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Analysis of Land Displacement Utilizing Sentinel-1 Satellite Imagery and InSAR Technique: A Case Study in Kern County, California

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Conflicts of interest
The author declares that there is no conflict of interest.

Abstract. This study investigates patterns of land displacement in Kern County, California, using Sentinel-1 satellite imagery and the Interferometric Synthetic Aperture Radar (InSAR) technique. A time-series analysis was performed to examine the temporal evolution of land displacement using the Small Baseline Subset (SBAS-InSAR) approach. The LicSAR (Comet Portal) and Liscbas toolbox were employed to analyze Sentinel-1 satellite data collected between 2014 and 2022. For the ascending orbit, the observation period spanned approximately 6.6 years, encompassing 256 images and 1,499 interferograms. The descending orbit covered around 7 years, with a network of 266 images and 954 interferograms. The data were decomposed into ascending and descending paths to identify both vertical and horizontal displacement patterns. An accuracy evaluation was conducted using 85 GPS stations in central California, revealing an RMSE of 1.89 and an R-squared value of 0.9 for the horizontal direction, and an RMSE of 2.4 with an R-squared value of 0.94 for the vertical direction, indicating a high level of accuracy. These results demonstrate the effectiveness of InSAR in capturing detailed land displacement patterns. This study also discusses the advantages and limitations of using InSAR for tracking land deformation and provides recommendations for future research.

Keywords: land displacement, Interferometric Synthetic Aperture Radar (InSAR), Sentinel-1, Kern County

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Анализ активности земной коры с использованием спутниковых изображений Sentinel-1 и технологии InSAR: исследование конкретного случая в округе Керн, Калифорния

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Заявление о конфликте интересов

Автор заявляет об отсутствии конфликта интересов.

Аннотация. Изучены закономерности смещения грунта в округе Керн, Калифорния с использованием спутниковых снимков Sentinel-1 и техники интерферометрического радара с синтезированной апертурой (InSAR). Для изучения динамики смещения грунта с применением подхода Small Baseline Subset (SBAS-InSAR) был выполнен анализ временных рядов. Для анализа спутниковых данных Sentinel-1, собранных в период с 2014 по 2022 г., использовалось программное обеспечение LicSAR (Comet Portal) и набор библиотек Liscbas. Для восходящей орбиты период наблюдения составил приблизительно 6,6 года. Набор данных для исследования включает 256 изображений и 1499 интерферограмм. Нисходящая орбита охватывала семилетний период, включала в себя 266 изображений и 954 интерферограммы. Данные были разложены на восходящие и нисходящие орбиты для определения как вертикальных, так и горизонтальных моделей смещения. Оценка точности была проведена с использованием 85 станций GPS в Центральной Калифорнии. Для горизонтальных моделей смещения RMSE составила 1,89 и значение R-квадрата 0,9, для вертикальных моделей смещения RMSE 2,4, R-квадрат 0,94, что указывает на высокий уровень точности. Эти результаты демонстрируют эффективность InSAR в составлении моделей активности земной коры. В представленном исследовании также обсуждаются преимущества и ограничения использования InSAR для отслеживания активности земной коры и даются рекомендации для будущих исследований в данной предметной области.

Ключевые слова: смещение Земли, интерферометрический синтезированный радиолокатор (InSAR), Sentinel-1, округ Керн.

Благодарности

Автор выражает искреннюю благодарность всем учреждениям и частным лицам, которые внесли свой вклад в завершение этого исследования. Особая благодарность команде LicSAR (портала Comet) и Liscbas toolbox за предоставление необходимых данных и техническую поддержку для анализа. Также выражает признательность департаменту водных ресурсов Калифорнии и Геологической службе США (USGS) за их ценную информацию и доступ к данным GPS, использованным в этом исследовании.

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Introduction

Land displacement and ground deformation present significant risks to infrastructure, natural resources, and communities, particularly in regions with extensive industrial activities such as oil and gas extraction [1]. The extraction of subsurface resources can lead to changes in land elevation, causing subsidence or uplift that may result in damage to roads, pipelines, buildings, and natural habitats [2]. Monitoring these patterns of displacement is crucial for understanding the impacts of industrial activities on the environment and for developing effective mitigation strategies to protect infrastructure and local communities [3].

Traditionally, ground-based monitoring techniques, such as leveling and GPS, have been used to measure land displacement. While these methods can provide accurate data, they are often limited in spatial coverage, labor-intensive, and costly when applied to large areas [4].The advent of satellite-based Interferometric Synthetic Aperture Radar (InSAR) technology has significantly improved the ability to monitor land displacement over wide geographic regions with high precision [5]. InSAR uses radar signals to detect changes in the Earth's surface, as shown in Figure 1, making it an effective tool for identifying even subtle shifts in terrain that would otherwise be difficult to detect with ground-based methods [6].

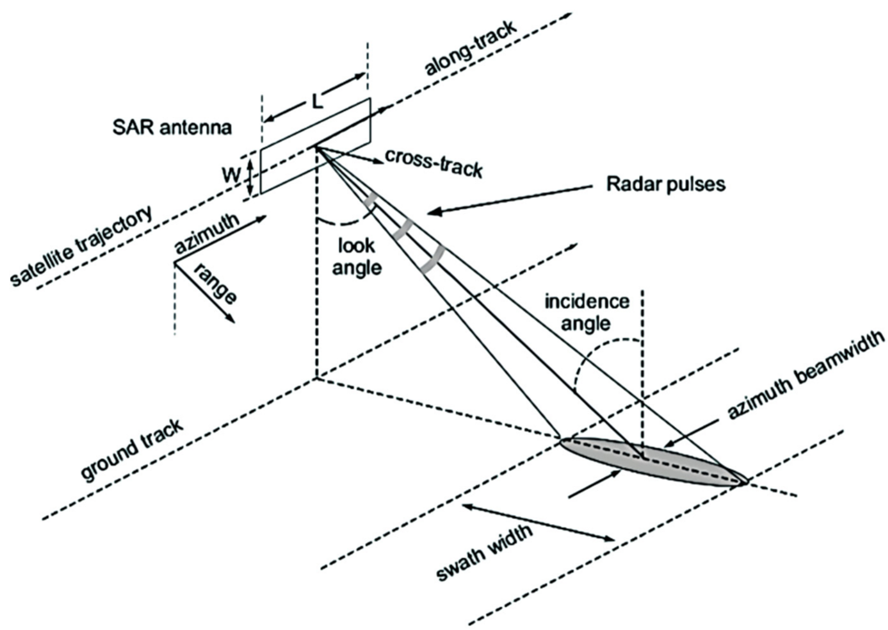

Figure 1. Geometry of Synthetic aperture radar
S o u r c e: made by A. Ferretti et al. [6]

Sentinel-1 satellite imagery, when combined with the Small Baseline Subset (SBAS-InSAR) approach, provides a robust solution for capturing both temporal and spatial variations in land displacement [7]. This study utilized Sentinel-1 satellite data and the SBAS-InSAR technique to investigate land displacement patterns in Kern County over an 8-year period from 2014 to 2022. By analyzing data from ascending and descending orbits, the study aimed to identify both vertical and East-West horizontal displacement components, providing a comprehensive view of ground deformation across the region. Figure 1 depicts the geometry of real aperture radar, which serves as the foundation for the InSAR technique. This research aims to demonstrate the effectiveness of InSAR technology for monitoring land displacement and to provide valuable insights into the impacts of such displacement on infrastructure and natural resources in Kern County. The findings contribute to a better understanding of ground deformation processes and offer data-driven guidance for managing and mitigating the effects of land displacement in affected areas.

1. Methodology

The Sentinel-1 satellite imagery, combined with the SBAS-InSAR approach, was employed to monitor land displacement in Kern County, California [7]. This technique enables continuous tracking of ground deformation, allowing for the analysis of long-term trends and sudden changes in the landscape. Sentinel-1 data were processed using the LiCSAR (Comet Portal) and LISCBAS toolbox to investigate land displacement over the 8-year observation period. The data were decomposed into ascending and descending orbits to identify both vertical and East-West horizontal displacement components, providing a detailed picture of ground deformation across the region.

1.1. Case Study Kern County

Kern County is situated in the southern portion of the Great Valley in California, bordered by the Coast Ranges, Sierra Nevada, and Transverse Ranges [8]. This unique geographic setting contributes to the complexity of land displacement observed in the region. The study area is depicted in Figure 2, which illustrates the monitored regions.

1.2. GPS

To ensure the accuracy and validation of the InSAR measurements, GPS stations were utilized. These GPS stations provided critical ground-based data that allowed for the comparison and validation of the displacement measurements obtained through the Sentinel-1 satellite data. This integration of GPS data is vital for confirming the reliability and precision of satellite-based displacement monitoring.

The GPS stations shown in Figure 3 cover a broad area across central California, including Kern County. They served as a key reference for evaluating the accuracy of the InSAR-derived displacement data, ensuring the robustness of the study's findings.

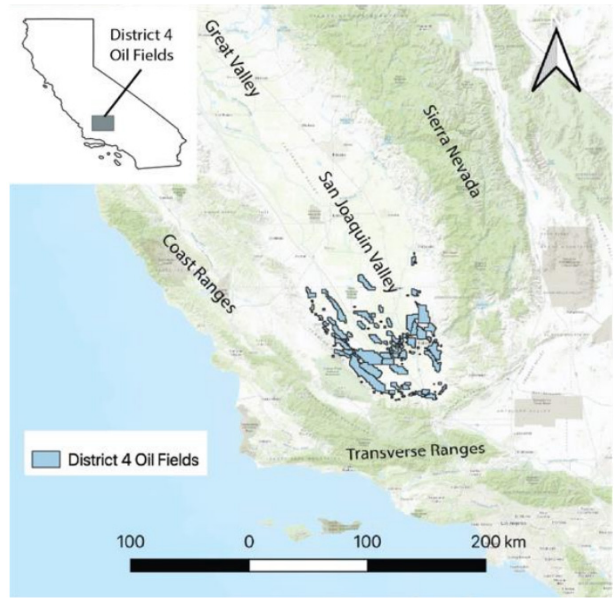

Figure 2. Kern County oil and gas fields
S o u r c e: made by K. Okamura, A. Quandt [8]

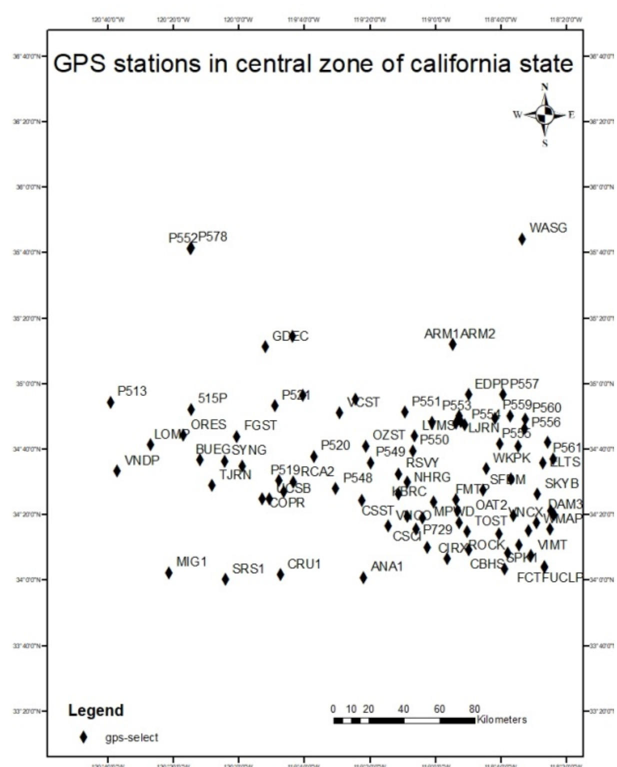

Figure 3. GPS stations in central zone of California
S o u r c e: made by J. Hatamiafkoueieh

1.3. Data Acquisition and Processing

The Sentinel-1 satellite imagery, combined with the SBAS-InSAR approach, was employed to monitor land displacement in Kern County, California [7].This technique enables continuous tracking of ground deformation, allowing for the analysis of long-term trends and sudden changes in the landscape. Sentinel-1 data were processed using the LiCSAR (Comet Portal) and LISCBAS toolbox to investigate land displacement over the 8-year observation period. The data were decomposed into ascending and descending orbits to identify both vertical and East-West horizontal displacement components, providing a detailed picture of ground deformation across the region.

1.4. Sentinel-1 Satellite Data Analysis

The Sentinel-1 satellite data were collected and processed using the SBAS-InSAR technique to monitor land displacement in Kern County, California, from 2014 to 2022. The LicSAR (Comet Portal) and Liscbas toolbox were employed to analyze the data. The ascending orbit (LiCSAR frame ID 137A_05534_131822) covered an observation period from January 31, 2015, to August 15, 2021, consisting of 256 images and 1.499 interferograms over approximately 6.6 years, as shown in Figure 4. The descending orbit (LiCSAR frame ID 144D_05501_131413) covered the period from November 8, 2014, to November 7, 2021, with 266 images and 954 interferograms over 7 years, as shown in Figure 5.

The acquisition interval was primarily 24 days before February 18, 2017, and reduced to 12 days afterward due to the increased observational capacity from the availability of Sentinel-1B, even though all the data were acquired by Sentinel-1A. It is worth noting that the acquisition start dates are not consistent for all frames because of the non-uniform observation strategy of Sentinel-1.

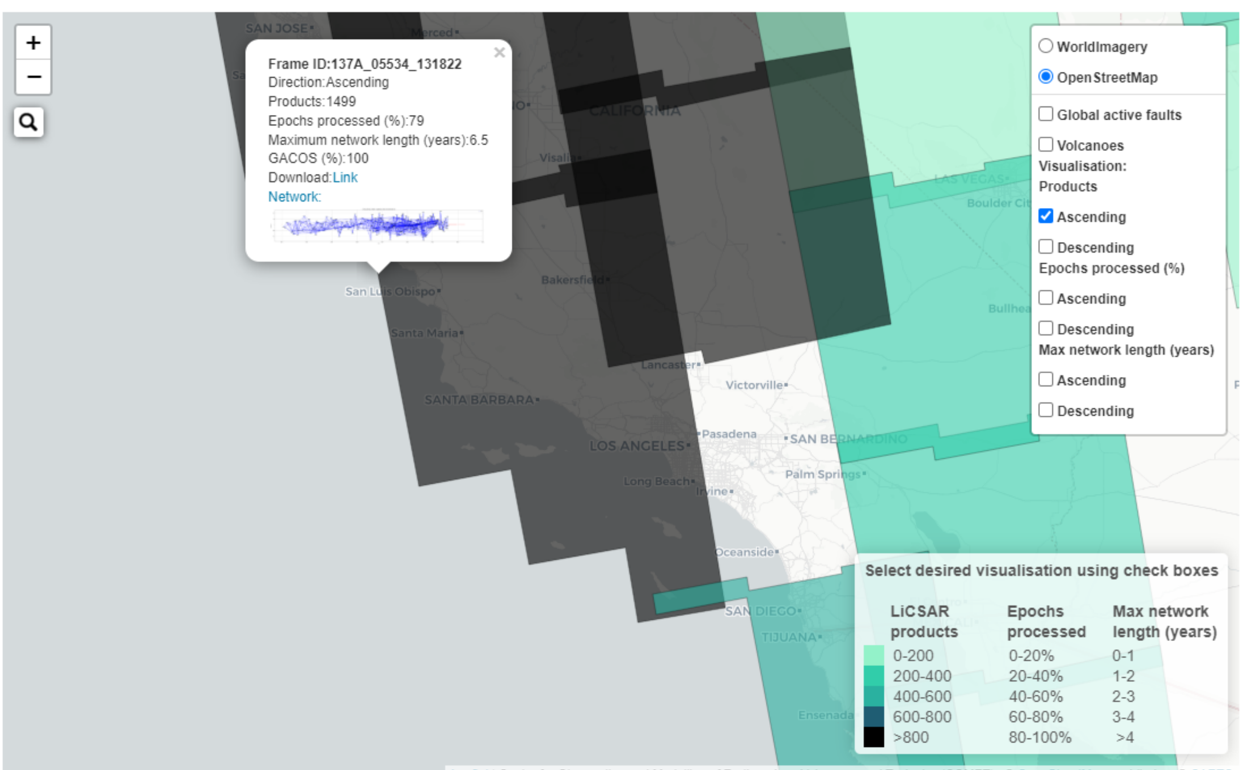

Figure 4. Ascending Orbit Frame Id 137a_05534_131822
S o u r c e: made by J. Hatamiafkoueieh

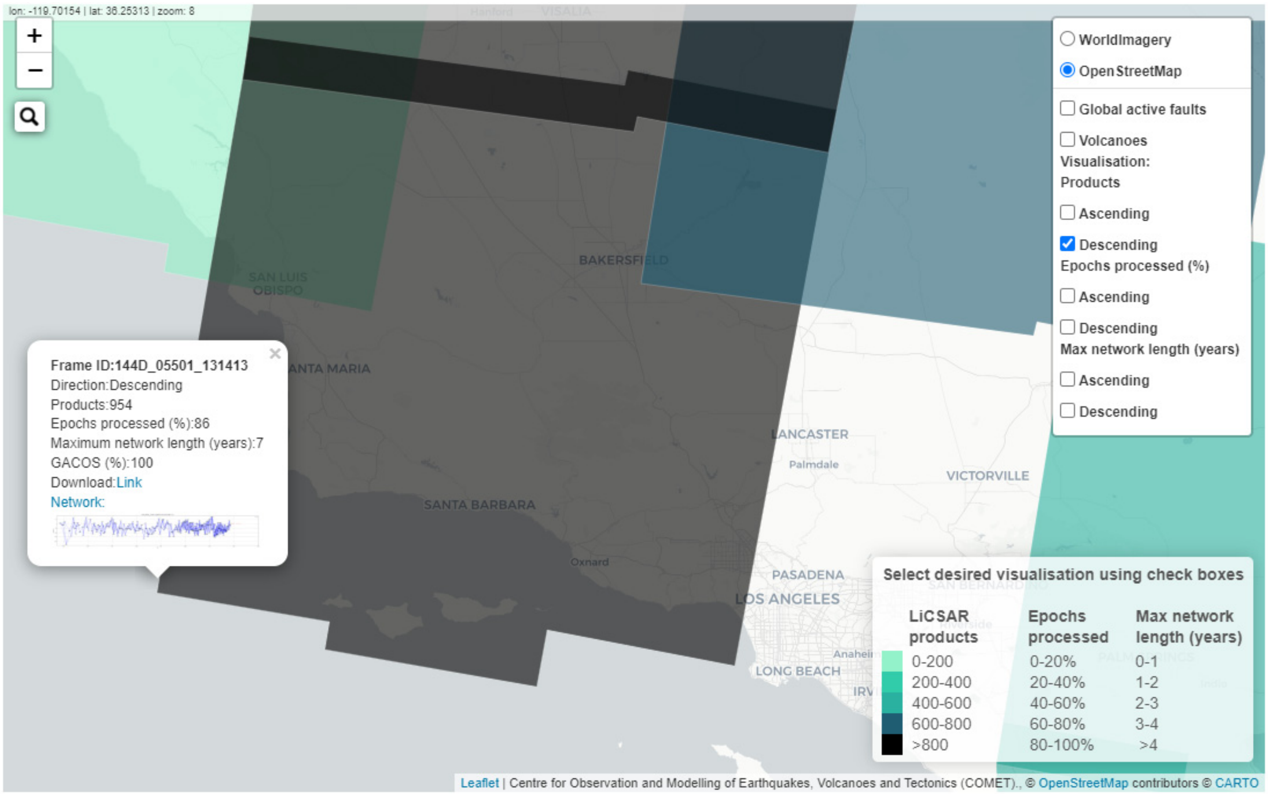

Figure 5. 131822 Descending Orbit Frame Id 144d_05501_131413
S o u r c e: made by J. Hatamiafkoueieh

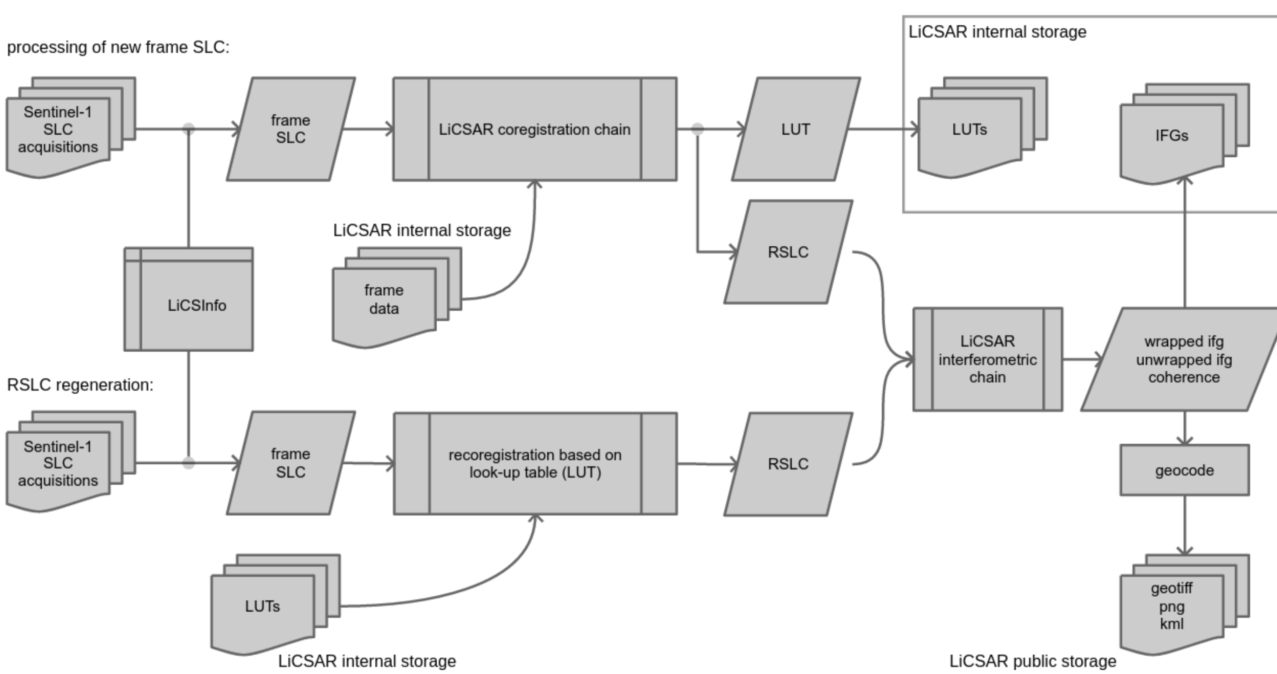

Figure 6. General flowchart of the LiCSAR processing chain
S o u r c e: made by Y. Morishita et al. [9]

1.5. The LiCSAR Processing Chain

The LiCSAR (Lithuania's SAR) Processing Chain was utilized for the processing of Sentinel-1 data[1] [9]. This automated workflow extracts and merges bursts covering a frame into Single Look Complex (SLC) mosaics for each acquisition epoch. The SLC mosaics are then coregistered and resampled to match the geometry of a primary SLC acquisition, which is determined during the initialization of the frame. The resampled SLC data are subsequently used to form interferometric products, including wrapped and unwrapped interferograms and coherence maps, by combining the new Resampled SLC (RSLC) with, by default, four preceding RSLCs. This process is designed for efficient batch processing in computer clusters, ensuring that large datasets are handled effectively [9]. Figure 6 shows the general flowchart of the LiCSAR processing chain.

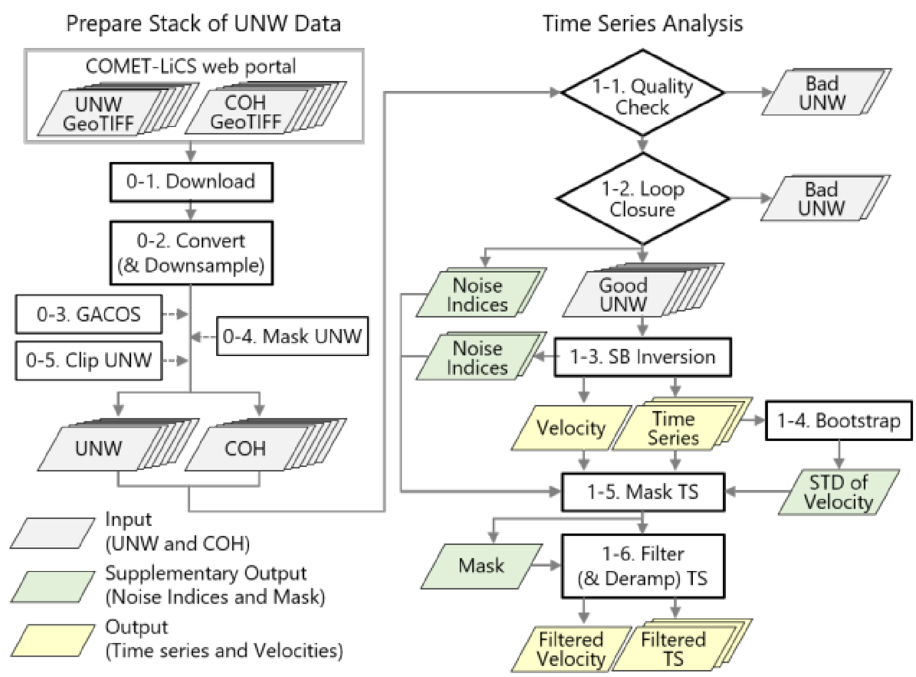

Figure 7. Workflow of LiCSBAS
S o u r c e: made by J. Hatamiafkoueieh

1.6. The LISCBAS toolbox

The LISCBAS (LiCS Basic Analysis Software) toolbox is another essential tool used for processing Sentinel-1 data and for monitoring ground displacement [10]. The toolbox provides a comprehensive workflow for InSAR data processing, facilitating the generation of high-quality displacement maps and time series. It is designed to manage the complexity of InSAR data processing, ensuring accurate and reliable results for ground deformation studies. The workflow of the LISCBAS toolbox is illustrated in Figure 7.

The data were decomposed into ascending and descending orbits to identify vertical and East-West horizontal displacement patterns. An accuracy evaluation was conducted using measurements from 85 GPS stations across central California [11]. The SBAS-InSAR technique, as processed through the LiCSAR and LISCBAS tools, proved

[1] LiCSAR Project Team. LiCSAR Processing Chain Documentation. 2018. Available from: https://comet.nerc.ac.uk/COMET-LiCSAR (accessed: 30.05.2024).

to be a robust method for detecting ground deformation, utilizing multiple satellite images taken over time to identify subtle changes in the Earth's surface. The dual-approach allowed for the decomposition of displacement vectors into vertical and East-West components, providing a more accurate representation of the deformation process.

2. Results and analysis

The SBAS-InSAR technique was instrumental in providing a comprehensive analysis of land displacement patterns in Kern County, identifying regions with significant deformation rates that required further investigation. This approach allowed for the detection of both subsidence and uplift trends across various areas, offering a clearer understanding of the deformation dynamics at play. To enhance the analysis, the SBAS-InSAR method was used to construct detailed connection networks for both the ascending and descending orbits. The connection network for the ascending orbit, as shown in Figure 8, illustrates the relationships between interferometric pairs generated during the observation period in a similar fashion, the connection network for the descending orbit, depicted in Figure 9, provides a complementary viewpoint.

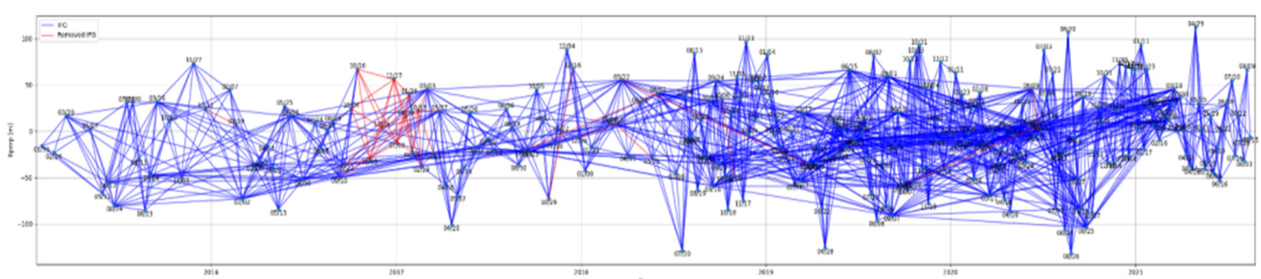

Figure 8. SBAS connection network of the Ascending
S o u r c e: made by J. Hatamiafkoueieh

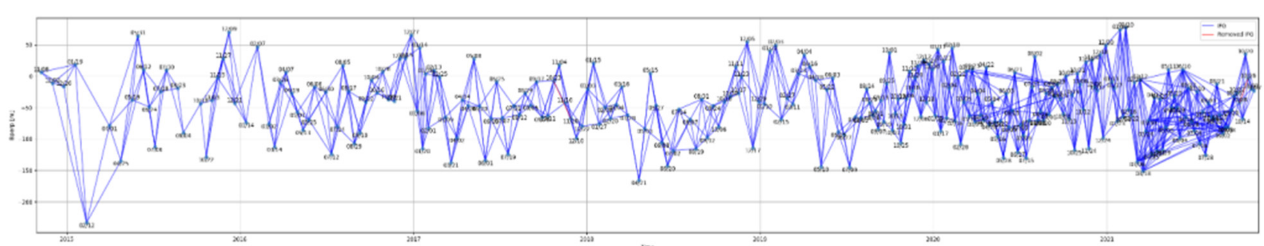

Figure 9. SBAS connection network of the Descending
S o u r c e: made by J. Hatamiafkoueieh

The decomposition of ascending and descending orbit data allowed for the separation of different deformation components occurring on the Earth's surface. Generally, ascending data is more sensitive to vertical deformation, while descending data better captures horizontal deformation. By analyzing both components, this study effectively identified the distinct types of deformation affecting the region, revealing displacement patterns in two primary directions: vertical, as shown in Figure 10 and horizontal (east-west), as shown in Figure 11.

The analysis revealed significant and varied patterns of land subsidence across multiple areas within Kern County, providing a comprehensive understanding of the spatial and temporal dynamics of ground displacement in the region. The most pronounced subsidence was detected in the South Belridge area, where ground displacement rates reached up to 20 mm per year, indicating severe subsurface deformation likely linked to intensive extraction activities and groundwater depletion. This high rate of subsidence suggests that the underlying geological structures in this region are particularly susceptible to changes resulting from human activities, such as oil and gas extraction, which can lead to the compaction of sediment layers and subsequent ground lowering.

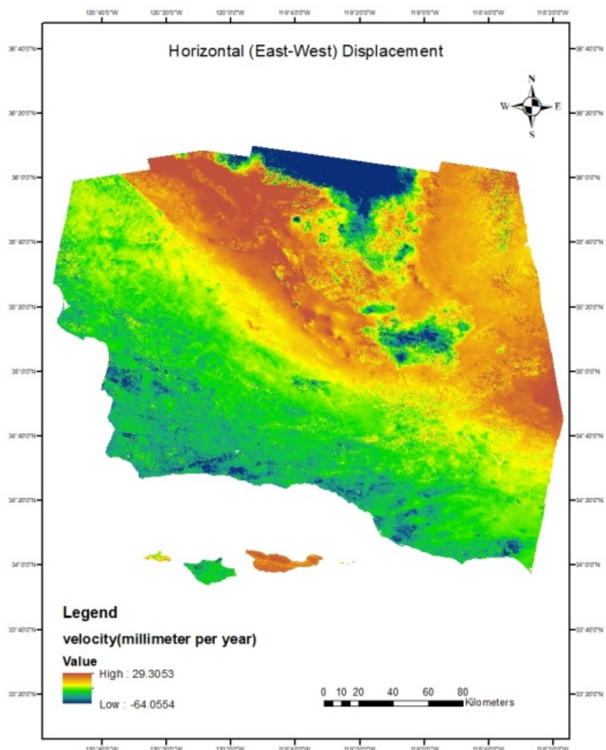

Figure 10. Descending Horizontal (East-West) Displacement Velocity Map
Source: made by J. Hatamiafkoueieh

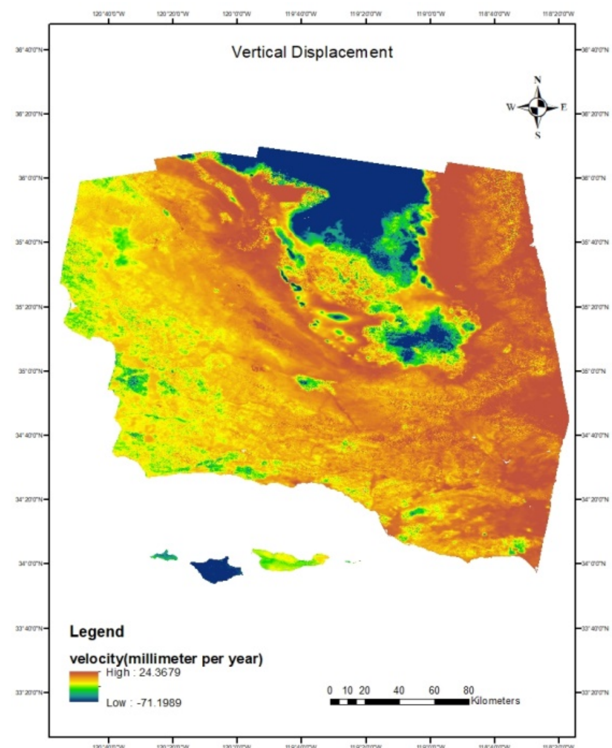

Figure 11. Vertical Displacement Velocity Map
Source: made by J. Hatamiafkoueieh

In contrast, the North Belridge and Lost Hills regions displayed subsidence rates ranging from 10-15 mm per year, which, although lower than the rates observed in South Belridge, still represent significant ground displacement over time. These rates of subsidence indicate that while the extraction activities in these areas may be less intensive or distributed differently, they still contribute to noticeable ground deformation. The continuous monitoring of these areas is essential, as even moderate subsidence can have long-term impacts on infrastructure, water resources, and overall land stability.

The Midway-Sunset region exhibited a more complex pattern of land subsidence, with moderate deformation rates that fluctuated throughout the observation period. These variations suggest that subsidence in this area might be influenced by a combination of factors, including variable extraction rates, groundwater management practices, and natural geological processes. The presence of fluctuating subsidence rates underscores the importance of long-term monitoring to capture the full extent of deformation dynamics and to understand the interplay between human activities and natural environmental factors.

Interestingly, the study also identified areas experiencing uplift, which is the opposite of subsidence. This phenomenon is likely attributed to natural aquifer recharge following periods of drought, causing the ground to rise as water is reintroduced into the subsurface layers. Such uplift suggests that the region's hydrogeological system is dynamic and responds to changes in water availability, highlighting the potential for land recovery in areas where extraction pressures are reduced or managed more sustainably.

Accuracy assessment

The accuracy evaluation of the InSAR data using GPS measurements demonstrated a strong correlation between the two data sets. The Root Mean Square Error (RMSE) and *R*-squared values for the east-west direction were 1.89 and 0.9, respectively, indicating a strong agreement between the SBAS-InSAR and GPS measurements. The results suggest that approximately 90% of the variation in the GPS data in the east-west direction can be explained by the SBAS-InSAR data, as shown in Figure 12, *a* — East-West Direction displacement and East-West Direction movement in GPS, where y represents the linear regression of the displacement data, and R^2 denotes the coefficient of determination, and in Figure 12, *b* — Vertical Direction displacement and vertical movement in GPS, where y represents the linear regression of the displacement data, and R^2 denotes the coefficient of determination.

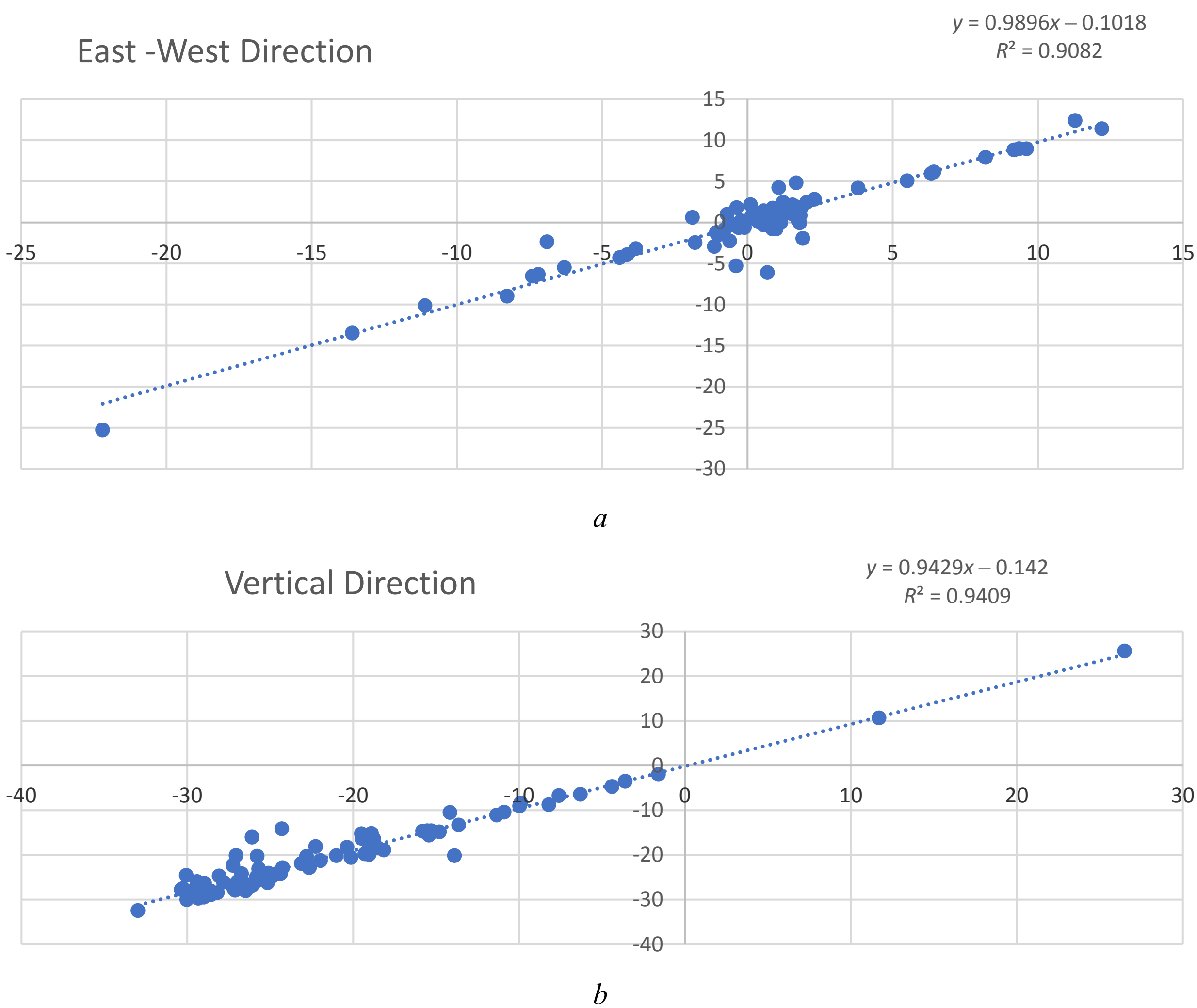

Figure 12. Chart of Registration Between SBAS INSAR And GPS:
a — East-West Direction; *b* — Vertical Direction
Source: made by J. Hatamiafkoueieh

In the vertical direction, the RMSE was 2.4, and the *R*-squared value was 0.94, signifying a high degree of accuracy in the InSAR data when compared to the GPS measurements. This means that around 94% of the variations in the GPS data in the vertical direction were captured by the SBAS-InSAR data. Together, the RMSE and *R*-squared values suggest that the InSAR technique is a reliable method for measuring ground deformation in both horizontal and vertical directions.

Conclusion

The findings of this study underscore the significant role of oil and gas extraction, groundwater pumping, and natural sedimentary compaction in contributing to land displacement in Kern County, particularly in the oil fields. The South Belridge region exhibited the highest rates of subsidence, reaching up to 20 mm per year, highlighting the critical impact of resource extraction activities on ground stability. These results are consistent with previous studies conducted in other oil-producing regions, where similar subsidence patterns have been linked to intense extraction activities, indicating that the extraction processes are a primary driver of land deformation. The integration of Sentinel-1 satellite imagery and the SBAS-InSAR technique proved highly effective in detecting land displacement at a high spatial resolution, allowing for a detailed analysis of subsidence patterns over time. By decomposing the displacement vectors into vertical and east-west components through the dual-orbit (ascending and descending) approach, this study offered a more accurate representation of the deformation processes occurring in Kern County. This method enabled the identification of not only subsidence but also uplift in certain areas, likely due to natural aquifer recharge following periods of drought, suggesting that natural geological processes also play a role in the observed deformation patterns. The study revealed a strong correlation between the spatial distribution of subsidence and the locations of active oil extraction wells, indicating that subsurface pressure changes from oil and gas production activities significantly influence land deformation. Groundwater extraction, which often accompanies oil production, also contributed to the observed subsidence rates. The North Belridge and Lost Hills fields experienced subsidence rates of 10–15 mm per year, while the Midway-Sunset field displayed more moderate and fluctuating displacement rates, further demonstrating the complex interplay between human activities and natural processes in influencing ground deformation.

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