CVEN 5301 Final Project

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1 Introduction

In the dynamic field of civil and environmental engineering, understanding and mitigating the impacts of ground deformation, specifically, subsidence and uplift—is crucial [9]. These phenomena not only threaten the integrity and longevity of infrastructure but also pose significant safety risks to the public [4]. With urbanization and natural landscapes being altered, the demand for innovative monitoring techniques has escalated [6]. Among these, Differential Synthetic Aperture Radar Interferometry (DInSAR) stands out for its precision and reliability in tracking ground movements [8].

Subsidence refers to the gradual settling or sudden sinking of the Earth's surface, primarily due to sub-surface movement of earth materials [6]. Uplift, conversely, involves the rise of the ground surface, which can occur due to natural geologic processes or human activities such as the extraction of underground resources [9]. Both phenomena can lead to considerable structural damage—from cracks in building foundations and roadways to severe instability in dams and levees [4].

The application of DInSAR technology offers an advanced approach to monitoring land displacement. It utilizes the phase differences in synthetic aperture radar (SAR) images captured at different times to meticulously measure the displacement of the ground. By employing SAR sensors aboard satellites, which emit radar pulses towards the Earth and capture the echoes, this technique can detect movements as minute as a few millimeters [8]. This capability makes DInSAR an invaluable tool for engineers and planners, providing them with the data needed to design more resilient infrastructure and implement effective mitigation strategies [6].

The scope of this project encompasses exploring the use of DInSAR technology to analyze subsidence and uplift phenomena in a high-risk area, San Joaquin Valley, California, USA. By integrating data from two Sentinel-1 images, selected with temporal proximity of almost a year, January - December of the year 2022, this study aims to map and quantify ground movements.

2 Methodology

1. Differential Synthetic Aperture Radar Interferometry (DInSAR):

The Differential Interferometric Synthetic Aperture Radar (DInSAR) technique is a remote sensing method used to detect and measure changes in the Earth's surface, particularly useful for studying ground deformation.

Synthetic Aperture Radar (SAR) is a type of radar system used in remote sensing that is capable of producing high-resolution images of the Earth's surface, irrespective of weather conditions or daylight. SAR systems emit microwave radar signals towards the Earth and capture the reflected signals to form images. A key feature of SAR is its ability to measure phase changes in the radar signal. As the radar satellite moves along its path, it continuously emits and receives signals, effectively synthesizing a larger aperture (radar antenna size), which enhances spatial resolution.

Interferometry involves the process of combining two or more SAR images of the same area taken at different times to produce an interferogram, a visual representation of the phase differences between the images [7]. These phase differences are sensitive to slight changes in distance between the satellite and the ground surface. By analyzing these phase differences, scientists can detect ground deformation—such as subsidence, uplift, or other geological changes—over time. The changes in phase are proportional to the movement of the ground, allowing for precise measurements of deformation in the order of a few millimeters to centimeters [5].

While DInSAR is a powerful tool for measuring earth surface dynamics, it has several limitations:

- **Atmospheric Effects:** The radar signal travels through the atmosphere twice (once down to the Earth and once back up to the satellite), and variations in atmospheric conditions (like humidity and temperature) can alter the signal's path, leading to errors in the phase measurement that can be misinterpreted as surface deformation.
- **Vegetation Cover:** Areas with dense vegetation can pose challenges for DInSAR because the radar waves may scatter multiple times before returning to the sensor, leading to a decrease in coherence between the radar images over time. This scattering can obscure the true ground motion and has been specifically noted to influence the polarimetric zero-baseline DInSAR phase diversity, impacting deformation studies [10].
- **Temporal and Spatial Decorrelation:** Decorrelation occurs when the interval between the acquisitions of the two SAR images is too long, leading to changes in the surface characteristics or geometry that affect the phase consistency. Similarly, spatial decorrelation can occur in areas with complex topography or surface textures that change between acquisitions.

2. Data Acquisition:

The focus area for subsidence and uplift monitoring is the San Joaquin Valley, Fig. 1, California. This region is known for significant ground movement due to extensive groundwater extraction, making it a critical area for ongoing geophysical monitoring.

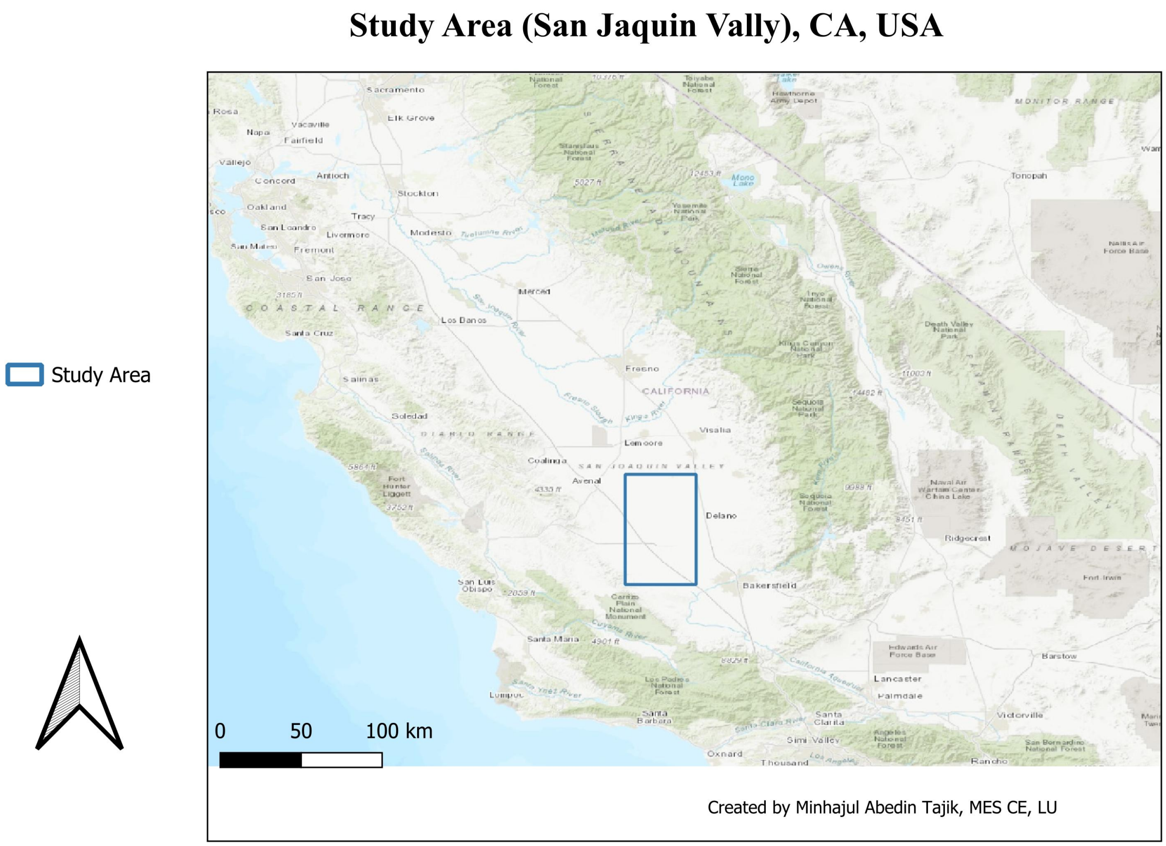

Figure 1: Study Area

For optimal coherence and to ensure the reliability of the interferometric analysis, images from perpendicular orbit tracks have been prioritized. This configuration helps in minimizing geometric distortions and maximizing the capture of vertical and horizontal ground motion.The specific time frame selected for this analysis spans from January 6 to December 20. This period was chosen to ensure minimal temporal decorrelation, thereby increasing the likelihood of obtaining accurate measurements of deformation. The proximity of acquisition dates between images reduces the effects of environmental changes on the observed data.Moreover, to ensure images have similar radar wavelength, polarization mode, and imaging geometry to reduce variations in radar signal characteristics, L1 single look complex (SLC), IW beam and polarization (VV+VH) were used for the analysis.

Sentinel-1 data for this project can be accessed through the Alaska Satellite Facility, a comprehensive portal providing free and open data from the Sentinel satellites. This platform can be reached at ASF Data Search, where users can download the necessary SAR images by selecting the specific area of interest and the relevant time frame.

3. Software and Processing:

The data processing for DInSAR is conducted using the Sentinel Application Platform (SNAP)[3], an open-source software developed by ESA. It offers a range of functionalities essential for DInSAR processing, such as data import, preprocessing (including radiometric calibration and speckle filtering), co-registration, interferogram generation, phase unwrapping, and visualization of deformation patterns.

The steps involved are:

1. **Data Import and Pre-processing:** This involves importing Sentinel-1 SAR images into SNAP, performing radiometric calibration to correct sensor-specific effects, and applying speckle filtering to reduce noise and enhance image quality.

2. **Co-registration:** The two Sentinel-1 images acquired at different times are aligned and co-registered to ensure pixel-to-pixel correspondence, using geometric correction methods to account for distortions.

3. **Interferogram Generation:** An interferogram is generated by computing the phase difference between the co-registered SAR images, which involves calculating the interferometric phase from the complex SAR data.

4. **Topographic Phase Removal:** This step uses a Digital Elevation Model (DEM) to remove the topographic phase component from the interferogram, compensating for variations in radar wave travel distances due to terrain elevation.

5. **Phase Unwrapping:** Phase unwrapping is performed to resolve phase ambiguities and reconstruct a continuous phase surface from the wrapped interferogram, ensuring accurate ground deformation measurements.

6. **Terrain Correction:** Transforms the coordinate system into a suitable one for overlaying on mapping services like Google Maps.

4. Analysis and Interpretation:

4.1. Interpreting the Differential Interferogram:

The differential interferogram generated from Sentinel-1 data provides a visual representation of ground deformation between two points in time. In the interferogram, each cycle of color change (often referred to as a fringe) corresponds to a relative motion of half the radar wavelength between the satellite and the ground surface.

- **Subsidence:** This is typically indicated by red fringes in the differential interferogram. Red fringes suggest that the ground has moved away from the satellite, indicating a sinking motion. Each red fringe represents a specific amount of downward movement, which is half the radar wavelength. The concentration and closeness of these fringes can indicate the rate and extent of subsidence.

- **Uplift:** Conversely, blue fringes indicate areas where there has been an upward movement of the ground towards the satellite. Like red fringes, each blue fringe represents a movement equal to half the radar wavelength upward.

The interpretation of these fringes allows to identify and monitor specific areas experiencing subsidence or uplift, thus providing valuable data for geophysical and environmental analysis.

4.2. Additional Analysis Techniques:

In addition to standard interferogram interpretation, additional techniques were utilized to quantify the amount of deformation more precisely:

- **Phase-to-Displacement Conversion:** This technique[2] involves converting the phase changes observed in the interferogram to actual displacement values, providing a quantitative measure of ground deformation. By using the known wavelength of the radar signal and the phase gradient across fringes, it is possible to calculate the exact amount of vertical displacement that has occurred. This quantitative analysis is crucial for understanding the severity and potential impacts of the observed deformation.

3 Results and Discussion

1. key findings:

Fig.2 represents the final interferogram (phase) of the analysis. We can clearly see the fringes are distributed across the study area which indicate significant displacement of the land in the area.

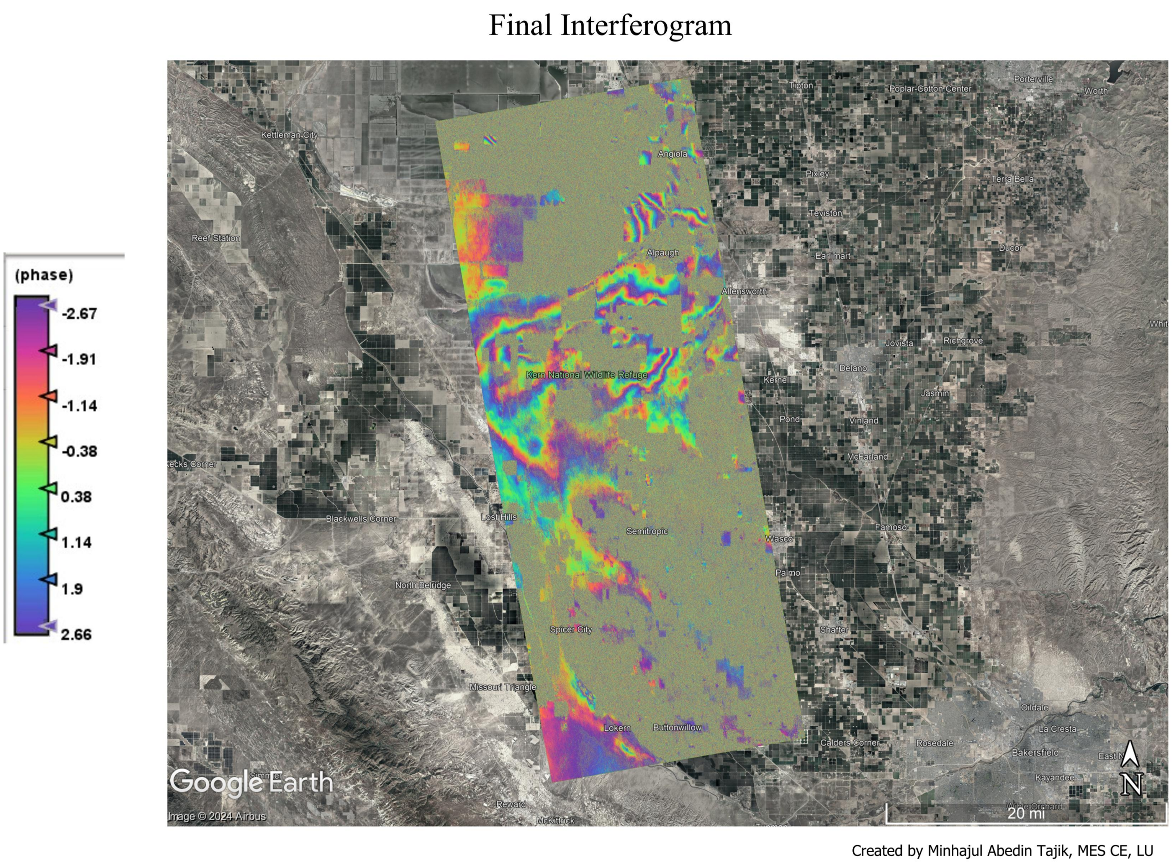

Figure 2: Final differential Interferogram

Fig.3 depicts the result of Phase-to-Displacement Conversion from Fig.2. It shows the actual displacement of the study area.

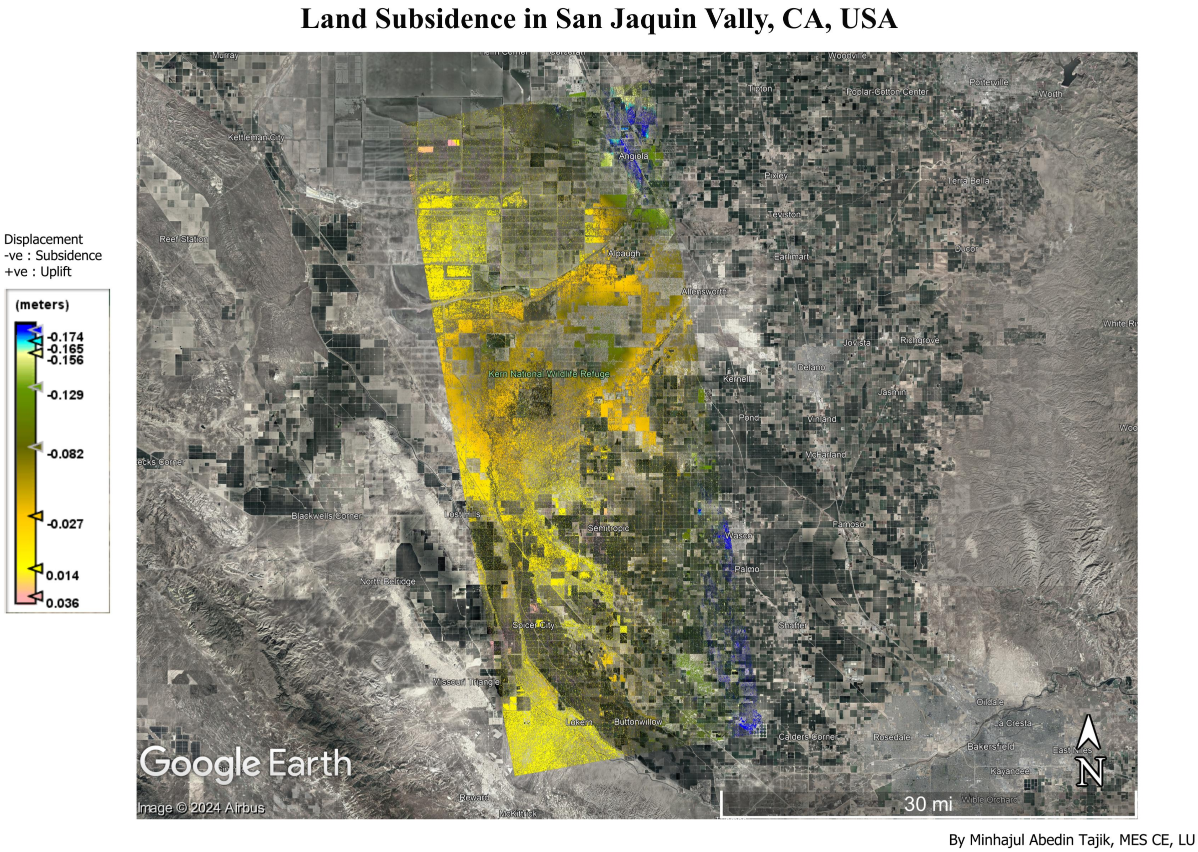

Figure 3: Land Deformation in Metric Units

2. Discussion:

As per the analysis the area has undergone the maximum subsidence, about 174 mm, in the North-Western portion. The area affected are Angiola, Wasko, and Palmo. Overall, the whole area had an mean subsidence of about 100mm. However, a little portions of the area have also been uplifted about 36 mm, which is not significant. The finding of the analysis also aligns with the study Land Subsidence in the San Joaquin Valley by USGS [1].

As per the the U.S. Geological Survey's web page[1] on land subsidence, the primary reason for land subsidence in the San Joaquin Valley is the extensive and long-term extraction of groundwater. This over-pumping has led to declines in groundwater levels, causing the aquifer system to compact and the land above it to sink. Historically significant subsidence has been recorded in this region due to these practices, compounded by periods of drought which further intensify groundwater use.

3. Limitation:

The analysis could be extended for the whole San Joaquin Valley, given more capable computational resources, as we had to compensate by subsiding the data. Other limitation may include:

- Atmospheric conditions (such as humidity and temperature variations) may have interfere with the accuracy of radar signals.
- Changes in land use and water management practices during the study period may affect the results, making it difficult to isolate the impacts of natural versus anthropogenic factors.

4 Conclusion

The study on land subsidence in the San Joaquin Valley, employing Differential Synthetic Aperture Radar Interferometry (DInSAR), has provided significant insights into the dynamic processes of ground deformation, particularly subsidence. The advanced DInSAR technique utilized synthetic aperture radar images to measure minute displacements in the Earth's surface, offering a precise tool for monitoring geological changes. The analysis confirmed substantial subsidence primarily due to extensive groundwater extraction, with the most affected areas experiencing varying degrees of land displacement. This study's findings underscore the critical nature of subsidence in the region, emphasizing the need for sustainable water management practices to mitigate further ground movement.

In conclusion, while DInSAR provides an invaluable framework for understanding and predicting subsidence patterns, it also highlights the necessity for integrating multiple data sources and advanced modeling techniques to enhance the accuracy and applicability of the findings in land management and urban planning strategies. The ongoing monitoring and analysis will be crucial in formulating effective mitigation and adaptation strategies to address the challenges posed by land subsidence in the San Joaquin Valley.

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