Monitoring land subsidence in southern Louisiana through InSAR & GPS: Challenges and future

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Abstract

Land subsidence in southern Louisiana arises from multiple processes occurring at different spatial and temporal scales. Past studies have attempted to measure subsidence with instruments such as GPS, leveling stations, and tide gauges, yet each technique had its own limitations in isolating contributions from different sources. In this study, we use SAR interferometry (InSAR) to provide dense measurements of subsidence from 2018-2021 using Sentinel-1 satellite data. Although data from the C-band Sentinel-1 provides good measurements over urban and developed areas, they are seriously limited due to a lack of coherence in the deltaic wetlands bordering the Gulf of Mexico in the state of Louisiana. Hence, a state-wide dense GPS network seems a viable option to provide accurate measurements in such areas. Future L-band SAR satellites such as NISAR are poised to provide denser measurements over the deltaic areas. In this study, we develop a framework to establish a region-wide GPS network in a way that captures the signal from multiple sources and also serve as ground truth for future InSAR measurements.

Introduction

Southern Louisiana is one of the hotspots for the increased threat of submergence and land loss due to modern-day sea level rise [Blum and Roberts, 2009]. The threat is further exacerbated by land subsidence on the coast due to factors such as soil consolidation, faulting, groundwater, and hydrocarbon extraction [Jones et al., 2016]. Subsidence from these factors occurs at different depths and is distributed with different spatial scales. Jankowski et al. [2017] reported subsidence of ~5mm/yr due to the consolidation of Holocene peat layers at a depth of 5-18 m. Using borehole pressure data, Mallman and Zoback [2007] reported localized subsidence of 3-10 mm/yr over oil and gas fields in southern Louisiana. Karegar et al. [2015] reported increased GPS horizontal motion of order >1mm/yr due to downslope slope motion on listric normal faults south of Baton Rouge.

To precisely measure the subsidence component from these multiple processes, we used Interferometric Synthetic Aperture Radar (InSAR), which provides ground motion measurements at a denser spatial scale. The technique measures the combined deep and shallow subsidence relative to a stable point in the scene yet largely relies on coherent returns from the targets on the ground. In an area with portions that are consistently inundated and heavily vegetated like coastal Louisiana, the technique has been demonstrated to work well in urban areas like New Orleans [Fig.1], but fails to provide measurements in key deltaic areas. In such cases, an effective option is to derive 3-dimensional non-relative measurements from GPS stations. A denser GPS network can well capture the spatially varying signal from multiple processes. However, GPS station bases are usually anchored deep into the soil at a depth of ~20m and thus cannot measure the subsidence occurring at shallow depths (0-20m) [Jankowski et al. 2017]. Therefore, using GPS along with InSAR can be complementary for delineating the subsidence due to deep and shallow processes.

On a SAR image, the pixels with stable returns are known as persistent scatterers (PS), and to capture the subsidence measurements precisely, well-distributed PS points are required throughout the SAR image. Although there are other InSAR processing algorithms that do not measure only PS points, even the most recent [Wang & Chen, 2022; Qu et al., 2020] cannot cover a significant portion of coastal Louisiana even at 1-km or poorer resolution because the C-band Sentinel-1 radar is not able to maintain InSAR coherence in the 12-day interval between acquisitions in many non-developed areas [J. Chen, private communication; Z. Lu, private communication]. Future L-Band SARs can be more sensitive to measurements over vegetated areas and can have more PS points in areas like Louisiana [Qu et al. 2015]. As more L-band SAR satellite-borne instruments become operational in the future (Ex:ALOS-4, NASA-ISRO Synthetic Aperture Radar (NISAR), ROSE-L), co-locating the GPS stations close to the areas of stable InSAR measurements (PS points) would help in delineating the deep and shallow subsidence contribution effectively. Setting up a GPS station network at a new location is a challenge as they need to be placed in sites with minimal disturbance, which are easily accessible, and at the same time maintain InSAR coherence for the 12-24 day orbit repeat period.

In this study, we processed 4 years of Sentinel-1 InSAR data from 2018-2021 covering southern Louisiana, and used the results to determine the locations of C-band PS points and inferred likely L-band PS points for the NISAR repeat orbit. We then use the InSAR results to find viable sites to set up GPS stations nearby. Hydrocarbon drilling was a major industry in southern Louisiana [Davis and Place, 1983], and the state has many abandoned oil and gas well sites which can be viable for locating GPS stations. We incorporate the well-site information into our framework as possible locations for establishing GPS stations.

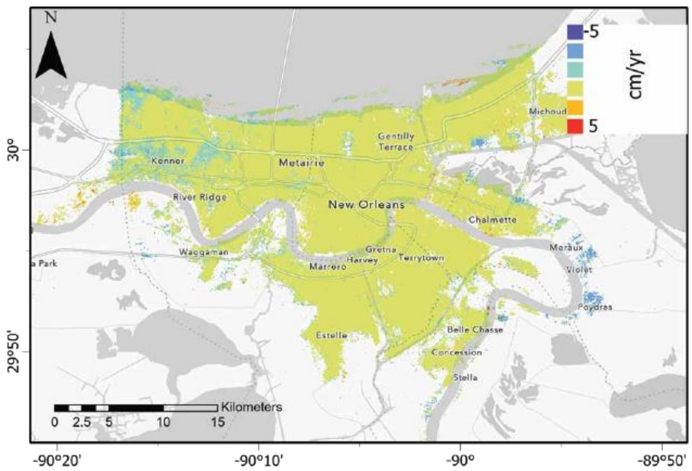

Figure 1 Subsidence rates from 4 years of InSAR data [Jan. 2018 – Dec. 2021] for the area around the city of New Orleans. Most of the urban area is stable except for some subsidence in the Michoud area.

Data

We use C-Band SAR single-look complexes (SLCs) from Sentinel-1A&B satellites in ascending pass configuration. More than 400 datasets spanning four frames are used for processing. Positional timeseries from 15 GPS stations in southern Louisiana are used to infer deep subsidence rates.

Methods

Sentinel-1 data are processed using a small baseline subset (SBAS) processing technique and inverted using a linear velocity model to get timeseries of deformation. Interferograms are processed using InSAR Scientific Computing Environment (ISCE) [Rosen et al. 2012] and timeseries processing has been implemented in MintPy [Yunjun et al. 2019]. We were able to get good returns on urban areas like New Orleans, where there are stable targets for InSAR processing, along the developed highways extending south towards the gulf, in isolated developed areas, and some PS points in wetlands. For some areas in southern Louisiana, especially in the Atchafalaya and Wax Lake Delta and nearby coastal wetlands and in Cameron Parish wetlands, InSAR is not able to maintain enough coherence and the interferograms were not properly unwrapped. Hence, we propose to provide calibration/validation data for InSAR in non-urban areas using a dense GPS network.

Given the complexity of the subsidence variability, to capture the subsidence and also serve as ground truth for future InSAR measurements, GPS stations have to be set up with consideration of their intended purpose, particularly if they are to be used long-term. We start by considering the site accessibility, and for that abandoned oil and gas wells can be viable sites for setting up GPS monitoring stations as they present minimal hurdles to access and owner permission. Next, to achieve our goal of placing GPS stations in close vicinity of stable InSAR measurements, we first determine pixels with stable returns on the ground in terms of Spatial Coherence (γ) and Amplitude dispersion (D_A) given as,

$$\gamma = \frac{E[u_1\, u_2]}{\sqrt{E[|u_1|^2]} * \sqrt{E[|u_2|^2]}}; \qquad D_A = \frac{\sigma_A}{\mu_A}$$

where u_1, u_2 are the complex representations of two SAR images forming the interferogram; E is the expected value computed in a window of pixels, and A and A are mean and standard deviations of the amplitude of all the interferograms in the stack.

The methodology is similar to identifying stable InSAR pixels as persistent scatters in other studies [Hooper et al. 2007; Crosetto et al. 2016], except we do not use phase criteria as many of our interferograms are not properly unwrapped. From the InSAR stack of interferograms, we take the dataset with high coherence over the four years, in our case June 2019 – June 2020. We generate an average spatial coherence map [Fig. 2a] for the dataset along with the Amplitude dispersion index [Fig. 2b]. For our analysis, we use a coherence threshold of >0.6 and an Amplitude Dispersion of <0.4 to choose our PS points. We generate a map of low Amplitude dispersion points overlapping areas of high coherence as PS points. From these, we only take points that have a nearby oil well within 1km. We refine the map using practical considerations such as choosing a site with stable foundation soil, not having large structures in the vicinity, and the ease of getting owners' permission. To ensure enough coverage with a minimal number of GPS stations, we divide the entire state into 5 km x 5 km grid cells and pick the best location in each grid.

Results

We identified 1332 PS points [Fig. 2c] over four InSAR data frames covering southern Louisiana and 1248 well sites [Fig. 2d] near them as viable sites for setting up GPS stations. Areas with high amplitude dispersion yet having significant coherence can be used to identify sites viable for setting up artificial corner reflectors for high coherence. The number of stations will further be downsized based on reliability and cost criteria [Mahapatra et al. 2015] producing a final location map. As next steps, to plan for the future L-band missions which should maintain higher coherence than the C-band, we will generate a new network of locations that should be able to support future missions that expand the InSAR-based subsidence measurements further from the developed parts of southern Louisiana.

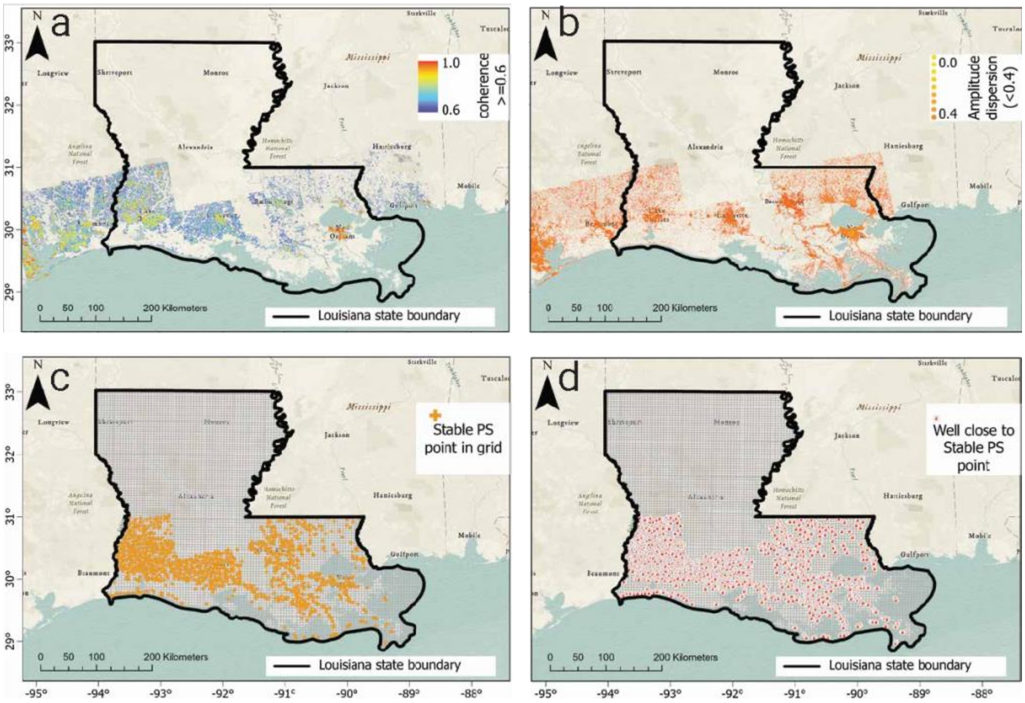

Figure 2 Location of InSAR (a) spatial coherence exceeding 0.6 and (b) amplitude dispersion below 0.4 for four Sentinel-1 SAR scenes over Southern Louisiana. (c) Points of stable InSAR return in each of uniformly divided 5kmx5km grids and (d) the location of the closest abandoned oil well site.

Summary and conclusions

The study provides a methodology for identifying locations at which to install GPS stations and to support expansion of the areas in which stable InSAR measurements of subsidence can be made in coastal Louisiana. The methodology mainly uses InSAR coherence and amplitude dispersion, making it free from the unwrapping issues faced during conventional InSAR processing. The GPS network can serve as ground truth for future InSAR measurements and can be used to separate deep and shallow components of subsidence. The study can also serve as a guide to incorporate site accessibility and reliability considerations into setting up a GPS station and can be applied to similar locations worldwide.

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