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Geodetic Deformation for Carbon Storage Monitoring: Observations, Modeling, and Inversion of Pore-pressure Evolution from InSAR/GNSS

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Summary

Reservoir pore pressure management is central to safe and effective CCUS operations because pressure buildup can affect caprock integrity, wellbore performance, and fault stability [Rutqvist, 2012]. Yet pressure measurements are typically sparse (well based) and may not provide fieldwide visibility of evolving pressure footprints, compartmentalization, or operational anomalies. Surface deformation from space geodesy provides an independent, low-cost, spatially continuous proxy for monitoring subsurface pressure change and therefore has strong potential as a MMV tool [Vasco et al., 2020].

We present a geodetic workflow that uses Sentinel-1 InSAR time series (and GNSS where available) to detect and quantify injection related deformation in multiple carbon storage site, interpret deformation observability across diverse geological settings, and connect deformation to pore pressure change using a poroelastic forward model. Across more than ten onshore CCUS and EOR projects with injection rates exceeding ~0.8 Mt/yr, we find that deformation observability is controlled by coupled geological and operational factors (e.g. reservoir depth and thickness, permeability/porosity, stiffness contrast, well spacing, and injection/production balance), rather than injection rate alone. Forward modeling calibrated against observations demonstrates that pressure changes on the order of a few MPa can produce millimeter scale surface deformation, which is resolvable by modern space geodetic methods. Building on these results, we outline an inversion framework to estimate time dependent pore-pressure evolution from geodetic observations. The goal is to enable pressure focused MMV products that support early detection of abnormal pressure behavior (e.g., localized pressure retention, unexpected pressure growth, or compartmentalization) and strengthen assurance of long-term storage integrity.

Theory / Method / Workflow

Geodetic measurements. We use the ISCE 2 software from JPL [Rosen et al., 2012] to process Sentinel-1 data [Torres et al., 2012; Fattahi et al., 2016] using a Small Baseline Subset (SBAS)

strategy [Bernardino et al., 2003] to generate unwrapped SAR interferograms [Chen and Zebker, 2001] and displacement time series over selected CCUS areas. Interferograms are formed using short temporal baselines and quality controlled by manual and statistical screening. Atmospheric delay and topographic phase contributions are mitigated using standard corrections where applicable. GNSS vertical and horizontal components are incorporated when available to improve sensitivity to 3D deformation and reduce trade-offs in interpretation.

Observability synthesis across sites. Each project is characterized by injection style (CCS vs. CO_2-EOR), injection/production balance, well spacing, reservoir depth/thickness, petrophysical properties (porosity/permeability), and lithology. Sites are grouped into response classes based on the maximum uplift rate: rapid, moderate, and stable/no detectable deformation. This classification provides practical guidance for when and where InSAR based MMV is likely to be effective.

Forward poroelastic modeling. To connect deformation to pore-pressure change, we apply a layered, axisymmetric poroelastic model based on a modified Geertsma formulation [Geertsma, 1973; Mehrabian and Abousleiman, 2015]. The model assumes a pressurized reservoir volume with radius R and thickness h and accounts for stiffness contrast between reservoir and overburden. For sites with published or operator reported pressure histories, we simulate surface deformation and adjust mechanical parameters within reasonable bounds to match observed deformation magnitude and footprint scale. This establishes pressure–deformation relations and provides physically grounds for inversion.

Proposed inversion for pore-pressure evolution. We propose a time-dependent inversion framework that estimates reservoir pore pressure change directly from displacement time series. Inversion minimizes misfit between observed and modeled deformation while enforcing constraints from reservoir geometry, injection history, and mechanical bounds. Output products are envisioned as: (1) best-estimate pressure-change maps/time series; (2) confidence intervals from uncertainty propagation; and (3) anomaly indicators for MMV decision support.

Results, Observations, Conclusions

Across the analyzed CCUS sites, we observe clear deformation at a subset of high injection rate projects, with uplift rates ranging from a few mm/yr to >10 mm/yr and with footprints that often collocate with injection wells. Other projects show no resolvable uplift above uncertainty despite comparable injection volumes, possibly caused by fast pressure dissipation, injection–production balancing, or higher observation noise. This outcome supports a key MMV message: deformation observability depends on the combined effects of reservoir geometry, petrophysics, and operations, not injection rate alone. Forward modeling calibrated to representative sites indicates that pressure changes on the order of ~1–2 MPa can generate mm-scale surface deformation (few mm to ~1 cm), which is detectable under favorable InSAR conditions (stable scattering, adequate time series length, and well-constrained uncertainty). This pressure range is operationally relevant because it can represent a substantial fraction of allowable pressure margin and can meaningfully influence effective stress, fault stability, and caprock integrity.

Geodetic time series (InSAR, GNSS or DAS where available) provide a scalable, cost-effective means to map CCUS deformation and support fieldwide MMV. Our Multi-site synthesis shows that deformation observability is governed by coupled geological and operational controls rather than one single injection rate. Layered poroelastic modeling demonstrates MPa scale pressure detection sensitivity and provides a pathway to quantitative pressure inference. A time-dependent

inversion framework is proposed to estimate pore-pressure evolution from geodetic deformation, enabling pressure focused MMV products and anomaly detection.

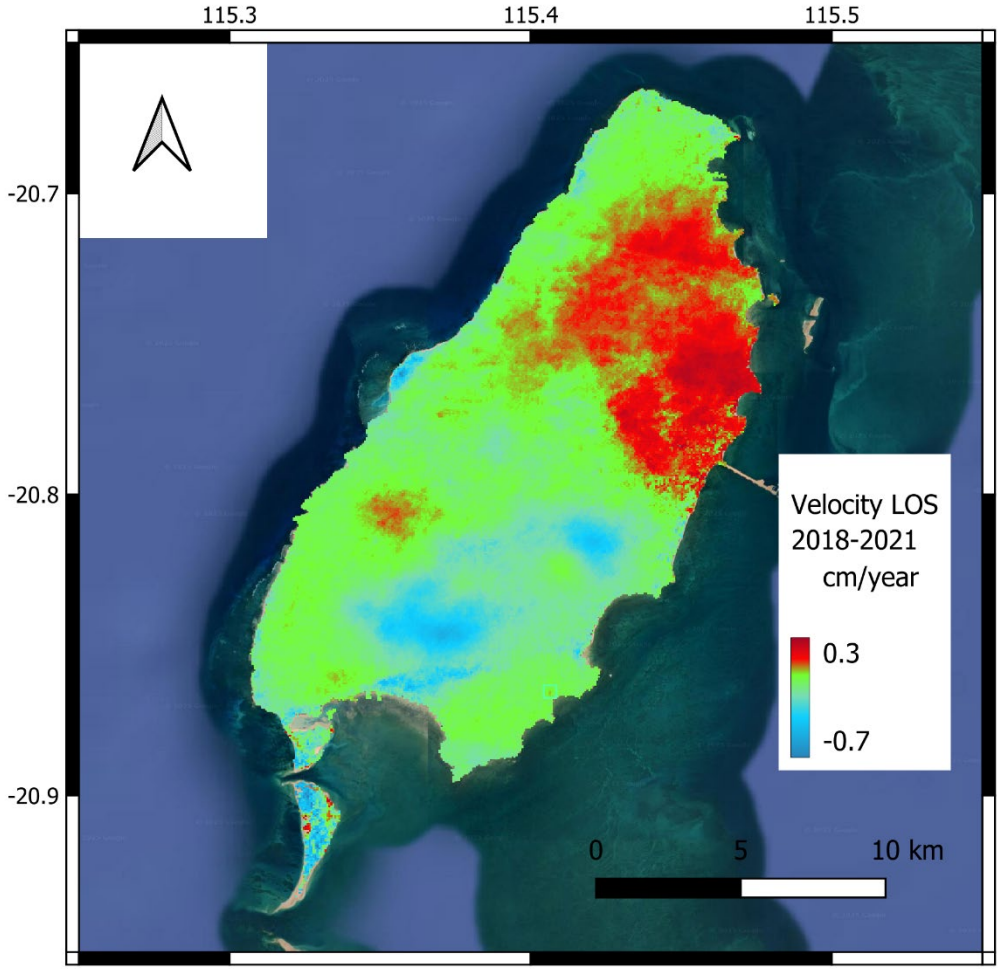


Figure 1. Observed Surface Deformation at the Gorgon CCUS project in Barrow Island, Australia. CO2 injection induced uplift over a wide area (5km by 10km) uplift. An average uplift rate of 3mm/yr was observed in the injection zone between 2018-2022.

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