The evolution and utility of modern satellite radar in the management of CCUS

Introduction

Underground gas storage (UGS) exploits geological voids (e.g. salt caverns, depleted O&G reservoirs) for the storage and retrieval of gases such as natural and hydrogen, and more recently for the more permanent storage of CO_2. Since development of the first UGS site in 1915 in Welland, Canada, approximately 925 facilities have been constructed globally with a working volume of around 4.93×10^8 m^3 (Manal, 2023). An issue with onshore UGS is the adverse geological side-effects of differential pressures operating within the cavern structure and supporting formations. These side-effects can result in wide-area subsidence or uplift at the ground surface (depending on injection or recovery) of cm/year magnitudes, consequential to operational infrastructure, well integrity, the surrounding environment, induced seismicity and fault reactivation (figure 1).

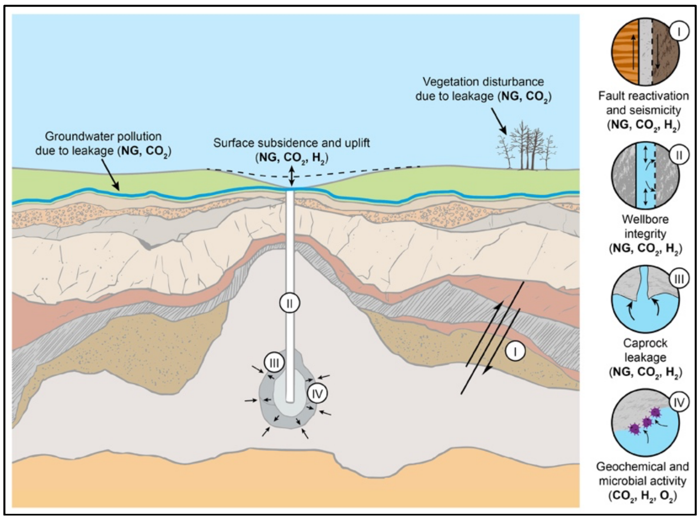

Figure 1: UGS geological side-effects (from Kaczmarek &Blachowski, 2025).

It can be advantageous or necessary to regularly measure the surface ground deformations caused by UGS for a number of reasons:

- Many authorities place mandatory limits on the allowed magnitude of ground disturbance and require forensic reporting.
- Ground movements (that reflect subterranean movements) can adversely affect well integrity, and so quantifying the evolution of the movement is valuable.
- Deformation at the ground surface can be useful in reflecting reservoir dynamics and behaviour, as well as revealing migration pathways and leakage by e.g. fault reactivation.
- Most UGS operations involve pipelines and other infrastructure that might be susceptible to ground movements.

However, obtaining measurements of ground movement using conventional ground-based instrumentation is expensive, labour-intensive, of coarse spatial resolution, and of relatively low precision. Conventional surveying does not fulfil all needs. Conversely, the revolutionary technology of satellite radar interferometry (InSAR) is able to map evolving surface deformation over wide areas, at high temporal and spatial resolution to mm/year precision at relatively low cost. Archives of satellite data uniquely allow retrospective analysis, and InSAR also has all the advantages of being totally non-invasive.

InSAR was first applied to CCS more than fifteen years ago (figure 2), but intervening regulation, policy and public opinion served to dissuade a significant operational roll-out, and InSAR technology was largely forgotten by the sector. Since then, new incentives have reviewed the landscape, not only in

CCS, but in underground gas storage generally; also in the availability and cost of InSAR, which is again either being used or under consideration.

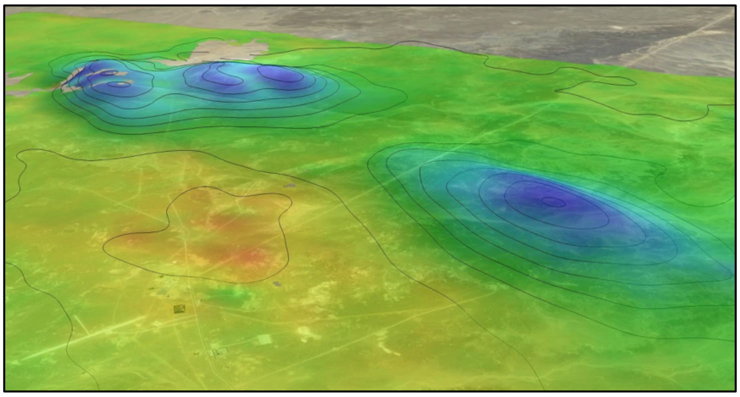

Figure 2: InSAR research on CCS application of ten years ago.
Isoview of mm/year ground displacements relating to CCS. Key aspects of cavern behaviour are reflected in the morphology of the deformation patterns (Thomas & Capes, 2011).

Method and/or Theory

InSAR works by the multi-temporal differencing of signal phase (not time), pixel by pixel, as it is received back by the antenna. The phase-differences relate to changes in signal-path length, and so by processing a stack of radar data acquired over time, ground velocities and displacements can be measured (Spaans & Hooper, 2016; Ferretti, et al, 2001) (Figure 2).

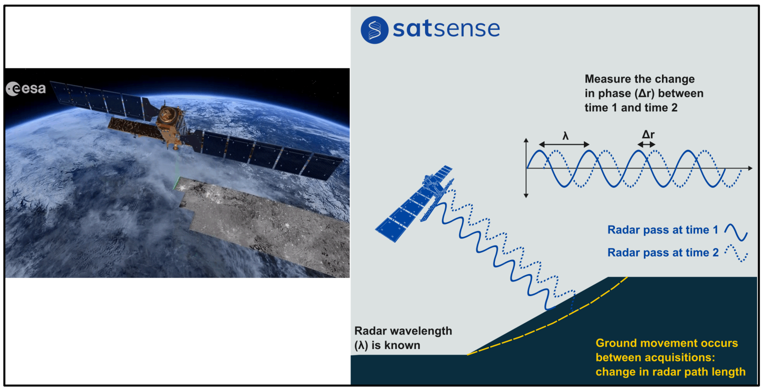

Figure 3: InSAR principles (credit SatSense Ltd., 2026).

InSAR evolution

In parallel with the development of UGS have been the improvements since 2010 in InSAR technology by way of satellites, processing algorithms and processing power. We now have several sources of high-quality open-source, radar data covering the Earth at a variety of resolutions and wavelengths, and an increasing number of commercially-driven very-high-resolution missions. Processing algorithms are now refined to a degree of accepted standardisation and precision (±1 mm/year, ±3-4 mm per measurement), and processing power has increased exponentially to the extent that many countries and even whole continents now have their own InSAR datasets – the largest geospatial datasets ever made. There are now many reputable InSAR service providers who can provide services customised to precise requirements in terms of historical analyses for baselining and ongoing monitoring at a frequency of choice.

Radar satellites for InSAR

The InSAR work on CCS of fifteen+ years ago was largely based upon Synthetic Aperture Radar (SAR) data collected by missions that were not specially designed for InSAR (ESA's ERS-1/2 and Envisat, Canada's RadarSat-1) – the possibility to exploit the data for InSAR being a serendipitous trade-off.

Limitations existed for operational services in terms of global coverage, temporal consistency of archives, >monthly repeat-cycles, orbit control, instrument noise, data dissemination, plus data from what were public-sector missions were only sold commercially. Today we have numerous SAR missions, both public (providing open-source data) and private, that provide high-quality, consistent data with nigh-global coverage. These 'new-generation' missions are specifically aimed at the requirements for operational services that can be relied on by users, not just now but for the foreseeable future. Table 1 below lists a representative sub-set of InSAR-compliant missions illustrating some of the key service parameters.

Table 1: Representative list of current InSAR-compliant SAR satellite mission relevant to CCS.

Mission	**Spatial resolution**	**Repeat-cycle**	**Ground velocity precision**	**Signal wavelength**	**Application**
Sentinel-1	20 m x 5 m	6 days	±1 mm/year	6 cm	Wide-area
TerraSAR-X	3 m x 3 m	11 days	±1 mm/year	3 cm	Infrastructure detail
Cosmo SkyMed	1 m x 1 m	4 days	±1 mm/year	3 cm	Infrastructure detail
NISAR	7 m x 8 m	12 days	±1 cm/year	24 cm	Wide-area, maps over vegetation

Fig 4: L to R Sentinel-1, TerraSAR-X, Cosmo SkyMed, NISAR (credit ESA, DLR, ASI, NASA, 2026).

InSAR processing algorithms

InSAR began by processing just two SAR images that bracket an event to produce an interferogram, incurring various noise that reduced displacement precision to decimetres. Now, whole archives of many hundreds of scenes spanning multi-year epochs are processed using techniques known as 'time-series InSAR'. The large number of samples (satellite acquisitions) enable statistical regression to improve precision by an order to millimetre-scale. Modern systems can know automatically alert users when an InSAR measurement point moves within pre-determined thresholds, e.g. begins accelerating. Using latest machine-learning and AI tools, researchers are now looking at the automated classification of InSAR time-series profiles for particular types of geological hazard (e.g. mining-related, fault reactivation, landslides, clay shrink-swell).

InSAR processing power

Computer processing power has of course increased exponentially. It used to take a month to process a single interferogram, and that was after waiting weeks for the SAR data to be distributed, where now SAR data can be acquired from the satellite operators within hours, and hundreds of scenes InSAR-processed for delivery within days. This enables reliable and timely reporting that easily be incorporated into operational workflows.

An example of the extraordinary advances in both processing power and modern InSAR-compliant missions is the EC's Copernicus *European Ground Motion Service* (EGMS) – an InSAR map of the entire continent comprising billions of measurement points with a ten-year history, updated annually and free to use (Figure 5). EGMS clearly demonstrates the maturity, validation and acceptance of the technology. Indeed, appreciating the clear benefits of InSAR, many other countries have now contracted their own dedicated InSAR mapping at national-scale, including the USA, New Zealand, Japan, UK, Denmark, Norway, Italy, France, Germany and The Netherlands.

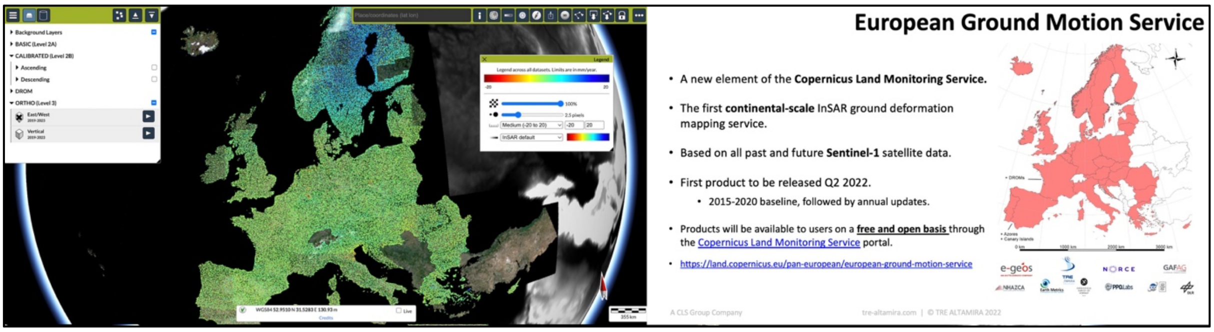

Figure 5: Copernicus European Ground Motion Service: EGMS 'Explorer' interface and detail. https://egms.land.copernicus.eu/

Conclusions

UGS operations can cause deformation at the ground surface that can reflect reservoir behaviour, but that can also have adverse consequences to operations. However, measuring such movements is fraught with difficulties on the ground. Modern InSAR offers a reliable cost-effective solution in its ability to non-invasively map ground motion over wide areas to mm/year precision in a way not possible by any other means. These advantages, together with significant cost and safety efficiencies, mean that InSAR should now be considered a standard tool in the box of the UGS operator. Furthermore, the use of InSAR shows a desire and openness to embrace advantageous cutting-edge technology, and a demonstration of regard for the wider environment.

References

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