Tracking Surface Displacement with Satellite InSAR. Another Environmental Factor Under Control

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Keywords: Displacement monitoring, satellite monitoring

ABSTRACT
The operation of geothermal fields involves the extraction and injection of fluids. This can induce changes in reservoir pressure and possibly deformation of the ground surface, thus creating an undesired consequence on third party assets or potentially hampering the operation itself. Surface displacement and subsidence mapping is typically addressed through repeat surveys and in-situ instrumentation. Satellite InSAR is changing this paradigm as it is possible to retrieve – by processing a stack of remotely sensed radar images – a map of the deformation that occurred over the site. The main advantage of satellite InSAR technology for geothermal field monitoring is two-fold. Firstly, in addition to monitoring the site itself, stability of the surrounding area (including slopes and infrastructures in the surrounding) can be tracked and easily updated weekly or bi-weekly. Secondly, both long- and short-term displacement trends can be captured (including historical analyses) providing a more complete picture of displacement behaviour over time. In this article, the application of InSAR as a provider of consistent and updated maps is discussed, and cases of comparison between volumetric changes in the reservoir and surface displacement are shared.

1. INTRODUCTION
The exploitation of subsurface resources, both when injecting and withdrawing fluids can impact the surface in terms of deformation. Geothermal fields pose many challenges, mainly associated to mass and energy transport in complex and heterogeneous media. While in oil & gas applications a poro-elastic model is generally sufficient to model the reservoir, the temperature changes typical of geothermal industry pose new challenges. In addition to the more conventional issues of reservoir structure, such as fault locations, permeability structure, etc., other variables such as heat fluxes and the heat-sealing capacity of the caprock are considered. The industry is reaching out to new techniques to implement robust and cost-effective reservoir models, such as inverse modelling and uncertainty analyses; all these theoretical and mathematical methods must be fed with precise input datasets coming from down-hole log data, hydrologic, geological and geophysical screenings.

Surface deformation monitoring is becoming an essential part of these datasets; in particular InSAR derived deformation maps provide a fully remote sensed appraisal of the eventual subsidence or uplift induced by the exploitation of the field. As the measurement can be repeated in time at a reasonable cost, such datasets can represent a first-level understanding of the subsurface activity. InSAR data had been used so far for a number of applications in this industry as a tool to provide surface displacement due to reservoir pressure changes at a millimetric resolution over large areas.

At the same time, as surface displacement mapping provides information to improve and condition the subsurface model – it provides a holistic view of the surface deformation scenario, potentially allowing an assessment of hazard generated on site (both on industrial premises and third-party assets).

This article discusses a brief description of InSAR methodology, together with a summary of the application of such data in a CO2 sequestration project at In Salah (an underground gas storage project in Italy) and a geothermal field in the USA.

2. INSAR DEFORMATION MAPS
InSAR estimates relative changes in ground surface by calculating phase differences between radar images acquired at different times. Several constellations of radar satellites can be used to feed the processing facilities; first constellations dates back to 1992, with more than 10 satellites now actively providing images to implement monitoring programmes (see Figure 1). Several processing paradigms can be applied on such data and it is out of the scope of this paper to provide an exhaustive dissertation on this matter. It is relevant to note, however, that modern processing methodologies can exploit multi-image data stacks to produce deformation maps of the surface sensitive at millimetre scale. Such maps rely on pixels within the radar imagery that consistently back-scatter in time towards the satellites (the so called Persistent Scatterers –PS) and they are treated as synthetic geodetic benchmarks to produce detailed deformation time series and deformation rates derived from those time series. PS can be buildings, fences, lampposts, transmission towers, rock outcrops, points aligned along roads and canals, etc., which serve as reflectors of the radar waves. Figure 2 shows the basic rationale behind the processing approach.
Figure 1: Synthetic Aperture Radar (SAR constellations); past and present available sensors.

Figure 2: Basic InSAR rationale

Figure 3: InSAR deformation maps during injection and withdrawal cycles. Peak to peak deformation: 2cm.
Figure 3 shows a typical result over an underground gas storage site; cycles of pressurization and depressurization of the reservoir are reflected as cycles of uplift (represented in blue) and subsidence (in red) on the surface. Green indicates general stability over time (no displacement). Time series analysis of the injected/extracted volumes, along with the time series of displacement of a PS over the reservoir, shows strong correlation between the two signals.

3. SUBSIDENCE AND UPLIFT AS A RESULT OF FLUID WITHDRAWAL AND INJECTION

InSAR is used as a tool to monitor the surface deformation induced by industrial activities which imply the movement of fluids underground. InSAR displacement maps provide information both for environmental analysis and production optimization; the latter is the main driver of the utilization of such methods in the oil & gas sector. Two examples are briefly discussed here. The first one refers to the largest CO₂ sequestration site in the world, the second describes the use of surface deformation to optimize the overburden model of a depleted gas field now used as a gas storage site.

3.1 CO₂ sequestration at In Salah - Algeria

The In Salah project is operated in a series of gas fields located in central South Algeria, where the global requirement to decrease the volume of CO₂ emitted in the atmosphere motivated the decision to re-inject captured CO₂ back into the reservoir. The size of the operation justified the industrialization of the process as the target was to avoid the emission of some 17 million tons of CO₂:

Three horizontal injection wells were drilled perpendicular to the stress field and more than 2.5 million tons of CO₂ had been stored underground by the end of 2008. Monitoring was undertaken to understand the gas plume dispersion together with the surface effect of such a massive injection.

Monitoring took place using several in-situ instruments, including geochemistry methods, geophones, micro-seismic sensors and a 3D time-lapse seismic survey was carried out. InSAR had been used to take advantage of its main features:

- Sensitivity to small-scale phenomena and the capacity of the system to detect subtle ground deformation in the range of a mm
- InSAR does not require any ground sensors thus allowing a non-biased assessment of the plume direction (uninfluenced by the position of the sensors)
- Ability to discriminate between vertical and horizontal east-west displacements

Surface uplift was measured over all three injection sites, where subsidence was present around production wells.

![Figure 4: In Salah rationale for CO₂ reinjection (Ringrose et al 2009)](image)

![Figure 5: Left – Vertical displacement [uplift shown in blue]. Right – horizontal displacement [eastward displacement shown in red, westward in blue].](image)
Figure 5 shows the deformation scenario related to the injection period (December 2003 – March 2007). It is possible to see the relative position of the gas field area (production area) with respect to the three injection wells used for CO\(_2\) sequestration; the thick black lines indicate the extent of each of the horizontal wells (KB-501, 502 and 503) within the reservoir. The depth of the target geological formation is around 2 km.

Forward and inverse modelling (Rutqvist et al, 2008) of the subsurface pressure increase explain the deformation pattern, thus confirming that the surface displacement map could be used as a simplistic assessment of the plume propagation.

As the main risk associated with CO\(_2\) sequestration is associated with leakages corresponding to injection wells, specific monitoring was installed and revealed an anomalous presence of CO\(_2\) at KB-502 wellhead (this was an old well drilled in the 80s). The leakage led to the decommissioning of the well in December 2008, and countermeasures were put in place to halt the leakage.

Seismic reflection data also suggested the presence of a northwest trending alignment; the same direction was identified (see the white dashed lines in Figure 5) as stress accumulation areas for horizontal displacement. This conclusion initiated a deeper analysis of the available datasets, in order to see if the double-lobed pattern of surface deformation detected above KB-502 could reveal something about a flow-related problem at depth. In fact, this behaviour suggested the opening of a tensile feature at depth (D.W. Vasco, 2010). The presence of a fault/fracture is confirmed by seismic data, and it is thought to be vertical or dipping at a very high angle; a few boundary considerations allow a geomechanical model to be constructed where the displacement might be explained by the opening of an extended tensile feature and volume change within the 20m thick reservoir interval (the model was built using several well-logs).

![Figure 6: Average damage zone dislocation Left – KB-502. Right – KB-503.](image)

Basically, in this experiment a forward model based on the elastic structure of the overburden is then solved through an inverse approach based on surface deformation data (D.W. Vasco, 2009). The same concept and approach was then implemented for both KB-502 and KB-503 wells.

To complement the exposed findings, Figure 7 shows the correlation between the amount of injected fluid and the surface deformation measured at KB-502.
Concluding, as a clear correlation between the fluid activity in the deep and the surface deformation is revealed, InSAR monitoring data can be used to assess injection performances and potentially complement other techniques to prevent well-failures.

3.2 Underground gas storage – Po plain, Italy

Underground gas storage (UGS) in depleted hydrocarbon reservoirs ensures continuity in energy supply across the seasons (with varying demand levels) and is common practice in Europe and North America. From a practical point of view, it involves the injection of natural gas during the summer and the withdrawal of the same operating gas throughout the winter; equating to pore pressure fluctuations at the reservoir level, resulting in potential displacement at the surface. The investigation of the relationship between the operating gas volume and the surface effect can improve understanding of the properties of the overburden and provide information on the environmental impact of underground gas storage. The field under inspection is located in the Po plain in Italy; at an operational level the gas overpressure (during injection) must not surpass 103% \( p_i \) (where \( p_i \) is the pore pressure prior to the field development).

The overall displacement scenario is represented in Figure 3. As can be expected, the cycles of gas injection and withdrawal induce uplift and subsidence cycles at the surface. In the analysed case, while the depth of the reservoir is around 800 m, the peak to peak deformation measured is around 2 cm. A simplistic initial analysis into the correlation of surface deformation and injected/extracted gas volumes is carried out by means of a simple 2D-deconvolution (see Figure 8).

The dense displacement information produced by InSAR analyses permits the investigation of the spatial distribution of the correlation between surface deformation and reservoir pressure changes.
Figure 9: Left – Correlation map of the injected/extracted volume and the cycle of deformation uplift/subsidence Right – Map of the ratio between induced displacement and gas volumes.

Left Figure 9 shows a map were the area just above the reservoir is highlighted (in purple); this is a set of points where the pattern of deformation correspond in shape to the gas injection.

Right Figure 9 implements a very simplistic but effective elastic model of the overburden: essentially, where there is a positive correlation, for each m³ of gas that is injected or extracted a corresponding displacement of 10 mm is observed over the reservoir. The map shows the behaviour of this “elastic” coefficient while moving away from the injector (and presumably from the centre of the reservoir).

Further, additional rigorous studies had been carried out exploiting such data in order to determine the possibility of increasing the reservoir pressure to 107% or 120% $p_i$. The overall idea is to calibrate the overburden model with InSAR data and use this model to infer the surface behaviour and caprock integrity in different (but more profitable) operative conditions.

A two-step model was created, where first a multi-phase flow simulation was calibrated with surface displacement data and subsequently a prediction based on a transversally isotropic poro-mechanical model is carried out (Teatini et al, 2011). Figure 10 shows the displacement data and the surface deformation estimated through the calibrated model.
The calibrated model is used to infer the behaviour of the reservoir whilst in different operative conditions (such as pressure at 107% or 120% $p_i$). In Figure 11 the trace of the gas pool is shown in yellow. The grey area represents the northward closure of the aquifer against the impermeable clay formation.

Also, in the framework of the same analysis, the calibrated model enables the prediction of potential of surface uplift/subsidence cycles when in different pressure condition. Figure 12 and Figure 13 show the predicted cycle of expected uplift and subsidence for the different operating conditions respectively, along with the expected distribution of maximum surface displacement.

Figure 10: InSAR measurement and calibrated geomechanical model

Figure 11: Left, predicted overall pressure change at 107% $p_i$ (left) or 120% $p_i$ (right)
Figure 12: Left – reservoir pressure cycles (past data and forecast in 107% $p_i$ and 120% $p_i$ conditions). Right, Cycles of displacement inferred with the model and the 107% $p_i$ (right-top [a]) or 120% $p_i$ (right-low [b]) UGS scenarios.

Figure 13: Peak to peak expected deformation when at 107% $p_i$ and 120% $p_i$ pressure scenario. Both vertical and horizontal components of the deformation are predicted.

Several findings were determined with this experiment:

- UGS is responsible for a land surface excursion of 8–10 mm over the last 5 years caused by a gas overpressure at the end of the injection phase equal to 103% $p_i$. This excursion is expected to increase to ∼15mm and ∼25mm with the gas overpressure of 107% $p_i$ and 120% $p_i$, respectively.

- The model calibration is consistent with the geomechanical characterisation of the basin as derived from previous experimental and modelling studies. In particular, the InSAR displacement maps are successfully matched with a loading unloading-reloading compressibility ratio equal to 4, perfectly in line with in situ marker expansions measured in other reservoirs of the same basin.
• The UGS 107% \( p_i \) and 120% \( p_i \) scenarios addressed in the present study are not expected to raise concern for the integrity of the surface man-made structures-infrastructures and the preservation of the natural environment. The differential displacements at the ground surface caused by the reservoir expansion and contraction are by far below the limits indicated in the literature to avoid structural instabilities.

4. MONITORING SURFACE DISPLACEMENT OVER GEOFIELD

While InSAR has been widely used in oil & gas to assess subsidence rates and implement new ways to optimize reservoir models, several experiments had been carried over geothermal areas.

The San Emidio geothermal field is located in Nevada, USA, and while the area is well known for its shallow hot water reservoir (boiling water found at \( \sim 30m \)) since the 60’s, the first binary geothermal field started operations in 1987 (Enave et al). As with many geothermal fields, San Emidio is located in a very active tectonic region where structural control has been widely studied; the area is dominated by a N-striking, w-dipping normal fault pattern. (Warren et al).

Figure 14: San Emidio Geothermal Area (SEGA), San Emidio fault (SEF) and Lake Range Fault (LRF). Production, injection and observation wells are also reported.

In 2009, U.S. Geothermal Inc. proposed a new paradigm for the application of monitoring techniques (https://www.energy.gov/sites/prod/files/2014/02/17/us_geothermal_san_emidio_peer2013.pdf) to develop new ways to identify and map Large Aperture Faults and assess the behaviour of wells intercepting Large Aperture Faults. Such investment should drive – in the scope of the project – increased productivity and reduced risk & environmental impact trough an improved model of the subsurface.

InSAR was implemented to provide precise (down to the millimetre) maps of the deformation all over the site, without the need to install on site instrumentation and incur site visits. InSAR results were integrated and calibrated with one GPS station located east of the Lake Range Fault and a few survey manual campaigns conducted in the region. See Figure 15 for an overall assessment of the capability of the system. The maps, colour coded with respect to the linear trend of deformation (velocity of deformation) are provided with a time series of displacement per each of the measurement point identified.
Figure 15: Displacement map over San Emidio area. Period covered 2003-2010. Left, vertical component of the deformation, right East-West component of the deformation

Surface displacement aligned along the main faults is clearly visible, both in terms of vertical and east-west displacement. The maps basically “draw” the effect of faults on the very surface.

Moreover, significant subsidence (vertical compaction) is detected around the production wells.

Figure 16: Correlation between the gravity field and subsidence pattern along a profile crossing the subsidence area.

The project, having implied several remote sensing techniques to provide an improved model of the reservoir, proved its effectiveness as it allowed the drilling and testing of several targets at minimum costs, while maintaining options for commercial production.

The same rationale was applied at The Geysers - the largest producing geothermal field in the world (active installed capacity is 900MW), located in California, in a complex tectonic environment. The scope of applying InSAR was essentially to identify, without the use of in situ instrumentation, displacement due to injection and fluid extraction. The area is well covered with survey data, but limited to a few measurement lines; the concept was to exploit the unicity of InSAR to provide spatially dense maps covering large areas. Figure 17 provides an overview of the displacement field (velocity of displacement) all over the area.
Figure 17: Displacement field (2011-2013) over an area containing the Geysers geothermal facilities. In red, the power plants.

Particular attention was devoted to two particular wells, previously abandoned and reopened in 2010 from an injector/producer pair (well Prati 32, in the centre of Figure 18).

Figure 18: Close caption of displacement field around the Enhanced Geothermal System (Prati 32). Horizontal injection well in blue, extraction in red.

Injection started in October 2011 with cycles of high-pressure (4000-4500 L/min) and low-pressure (1500 L/min) for almost 2 months. After that period injection pressure was established at nearly 3700 L/min). Micro-seismicity was also monitored in the area. A qualitative inspection of the correlation between injection rates, seismicity rates and surface displacement (all showing the same cyclic pattern) suggests a deeper analysis of the displacement scenario.

Figure 19: Time series of displacement, InSAR measurement point close to the Prati 32 injection well
5. CONCLUSIONS
The capacity of InSAR to complement other in situ measurements to deliver information about surface displacement has been successfully exploited in several industrial sectors, including mining and oil & gas. The correlation between industry driven pressure changes in (eventually deep) reservoirs and surface displacement has been demonstrated in several cases and the capacity of InSAR to support the geothermal industry in understanding the characteristics of the target reservoir and plume distribution is growing in importance. Finally, an interdisciplinary approach, which integrates geophysics, geomechanical engineering, subsurface hydrology,
remote sensing and numerical modelling prediction, allows for a broad characterisation of the geomechanical response to the injection and extraction of fluid in deep reservoirs.

6. REFERENCES


Philip Ringrose Mansour Atbi David Mason, Marianne Espinassous, Øyvind Myhrer, Martin Iding, Allan Mathieson, and Iain Wright (2009) Plume development around well KB-502 at the In Salah CO2 storage site. first break volume 27, January 2009


Mariana Eneva, Giacomo Falorni, William Teplow, Jessica Morgan, Greg Rhodes, and David Adams Surface deformation at the San Emidio geothermal field, Nevada, from satellite radar interferometry. Geothermal Resources Council Transactions 2011