PSMulti-interferogram InSAR Techniques for Monitoring Surface Deformation in CO_2 Sequestration*

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Abstract

The geological sequestration of CO_2 is rapidly becoming recognized as an effective tool for reducing GHG emissions. Although the scientific community will play a central role in demonstrating the feasibility of carbon capture and sequestration (CCS), it is perhaps even more important to convince public opinion that CCS does not pose a hazard to health and to the environment.

The role of pilot projects aimed at identifying reliable, accurate monitoring techniques is therefore fundamental. One of the most important initiatives to date is the In Salah Gas CO_2 Storage Assurance Joint Industry Project (JIP) which involves industry, governments and academia. Born from a Joint Venture between BP, Sonatrach and StatoilHydro, the JIP has been injecting CO_2 in Algeria since 2004 at a rate of almost 1 million tons of CO_2 per year with the stated goal of demonstrating best practices for CO_2 storage monitoring, integrity and verification technologies.

During the first stage of the project (2004-07) PSInSAR™, a multi-interferogram radar satellite technique for measuring ground movement, provided some of the most exciting and promising monitoring results. Injection of CO_2 into the saline aquifer caused changes in the fluid pressure field. This in turn produced an uplift of the ground surface, centered on the injection wells, of approximately 5 mm/yr that was precisely detected and measured by PSInSAR™. It is worth noting that these results were obtained using satellite data from one of the relatively older satellites.

Today, data from a new generation of satellites with significantly improved characteristics is being used in the second stage of the JIP to provide even more detailed monitoring information. The new sensors have a higher spatial resolution, lower revisiting times, and use a different wavelength. In preliminary findings the PSInSAR™ processing of data from the new sensors produces a density of points (Permanent Scatters - PS) for measuring surface deformation that is up to an order of magnitude higher than with the older data. In addition, an evolution of the PSInSAR™ algorithm which is set for release is also producing significant increases in the density of PS.

In this paper we will present some of the surface deformation results from the JIP and also show an example of an application of the updated PSInSAR™ algorithm to the Weyburn (Saskatchewan) area, in which the increase in the density of PS is well over an order of magnitude compared to the previous version.

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Introduction

The geological sequestration of CO_2 is rapidly becoming recognized as an effective tool for reducing GHG emissions. Measurement, monitoring and verification (MMV) activities of injected CO_2 therefore play a crucial role in this as they collect vital data on containment, seismic activity, leakage, and long-term storage among other things.

Satellite-based InSAR is gaining increasing attention for its unique technical features and cost-effectiveness. In particular, PSInSAR™, the most advanced InSAR technique, is capable of providing very precise 1D displacement measurements along the satellite line-of-site (LOS) and with a high spatial density (typically exceeding 100 measurement points/km^2) over large areas, by identifying and exploiting point targets present on the ground. PSInSAR™ has been used for numerous CCS, gas storage and reservoir monitoring applications (Vasco et al. 2008. Mathieson et al. 2009).

One of the most important CO_2 pilot projects currently under way is the In Salah Gas CO_2 Storage Assurance Joint Industry Project (JIP) in Algeria. Born from a Joint Venture between BP, Sonatrach and StatoilHydro, the JIP has been injecting CO_2 into a saline aquifer since 2004 at a rate of almost 1 million tons of CO_2 per year.

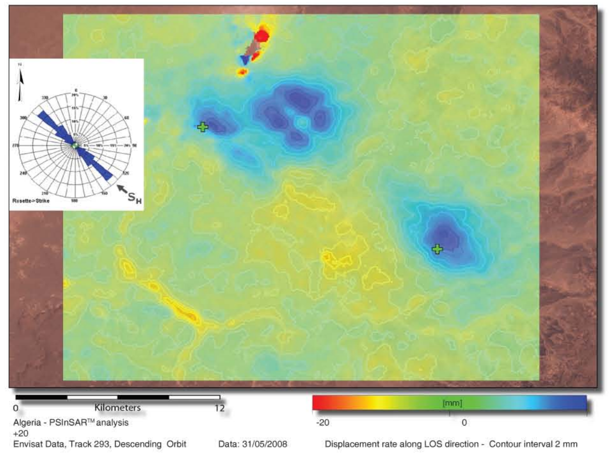
PSInSAR™ was part of a basket of technologies used to monitor the effects of CO_2 injection during the first stage of the project. The surface deformation results were unexpected and valuable (see Box 1). Injection of CO_2 caused changes in the fluid pressure field which in turn produced an uplift of the ground surface. The uplift formed bulges centred on the injection wells, and although deformation rates were only ca. 5 mm/yr, they were detected and precisely measured by PSInSAR™.

Additional factors are contributing to the increased use of InSAR: (a) the development of new algorithms, such as SqueeSAR™, which provides a significant increase in the spatial density of measurement points in rural areas and improves the quality of deformation time series (see box 4); (b) the availability of an increased number of satellites with higher spatial resolution (down to 1 m) and a higher temporal frequency of acquisition (see box 5) and; (c) the possibility to combine two or more data stacks acquired along different satellite orbits to estimate 2D or even 3D vectorial displacements rather than 1D measurements along the satellite LOS.

The examples presented here illustrate how PSInSAR™ and SqueeSAR™ can be used to measure the surface deformation produced by the subterranean storage of different types of gases and fluids.

CCS - In Salah, Algeria

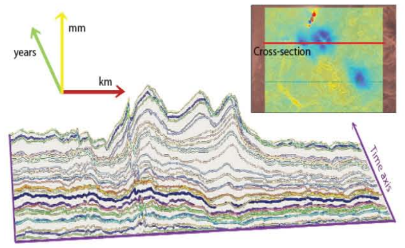
▪ BOX 1



Above: raster map and contour lines of maximum displacements measured along the satellite LOS compared to the strike of the main conductive fracture system (left inset, Iding and Ringrose, 2009; Vasco et. al., 2009).

▪ Ground surface deformation was not expected at In Salah prior to the start of CO_2 injection. However, PSInSAR™ monitoring revealed that within one month of injection a measurable amount of ground heave occurred. Up to 21 mm of uplift were measured after 3 years of injection.

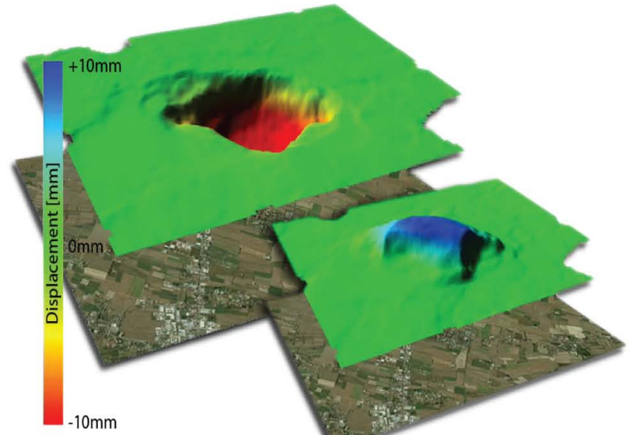
▪ The measured uplift was not uniformly centred on the injection wells. At one well uplift developed along two NW-SE trending subparallel lineations that correspond to previously unidentified faults (Ringrose et al., 2009). Uplift data was also instrumental in the reconstruction of the events that led to a minor CO_2 leak at a nearby appraisal well (Ringrose et al., 2009).



Right: evolution of LOS displacements along an E–W cross-section. Position of the cross-section represented in inset.

Gas Storage

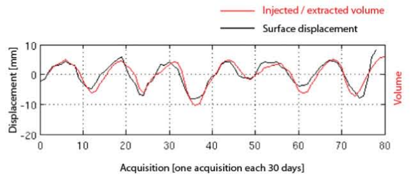
▪ BOX 2

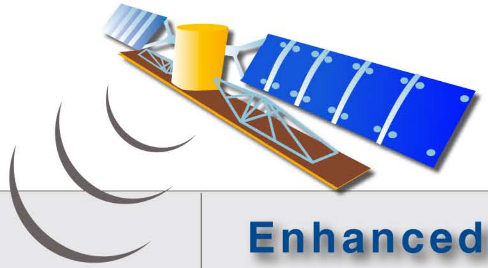


Above: two images taken from an animation showing the evolution of vertical displacement as gas is injected and extracted from the gas storage reservoir.

▪ Summer injection and winter withdrawal of gas in depleted hydrocarbon reservoirs often produce surface displacements. The extent of the displacements depends on the depth of the reservoir, the geomechanics of the overburden and the pore pressure changes induced by gas injection and / or extraction. The vertical displacements in this example show a very good correlation with the gas volume stored in the reservoir, allowing the setup and calibration of 3D fluid-dynamic models.

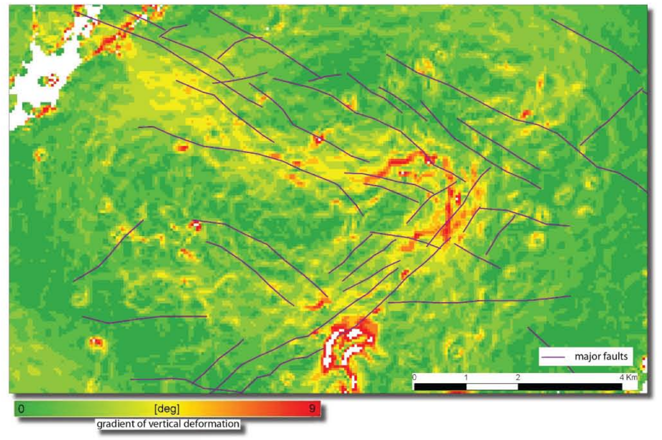
Below: comparison between vertical surface displacement measured with satellite data processing and injected / extracted gas volumes.





Reservoir Monitoring

▪ BOX 3

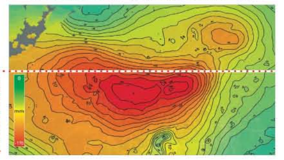


▪ The study area shown is an oil field in the Middle East, produced by water flooding. The area was monitored with satellite data over a period of about three years.

▪ The evolution of vertical displacements along E-W cross-sections of the oil field shows different displacement rates, delimited by faults reactivated by oil extraction.

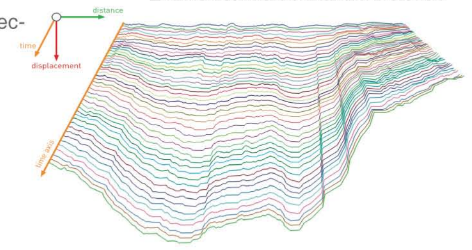
▪ The gradient field of cumulative vertical displacements is in good agreement with the orientation of the major fault systems.

■ SURFACE DISPLACEMENT FIELD



Above: gradient field of cumulative vertical deformation. Red areas indicate rapid changes in surface deformation velocity and are likely to correspond to active faults / fractures in the overburden.

■ VERTICAL SURFACE DISPLACEMENT EVOLUTION

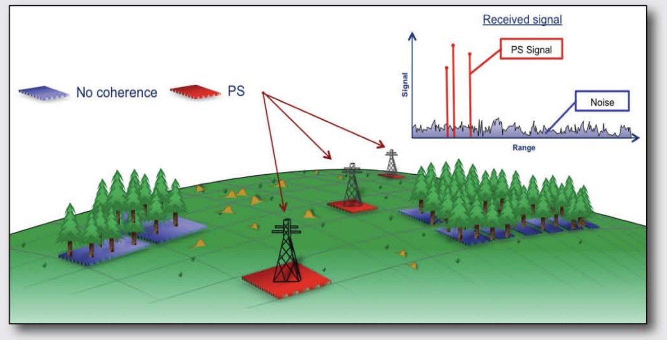


Right: evolution of surface profile over time along an E-W cross section. Each profile corresponds to one satellite acquisition.

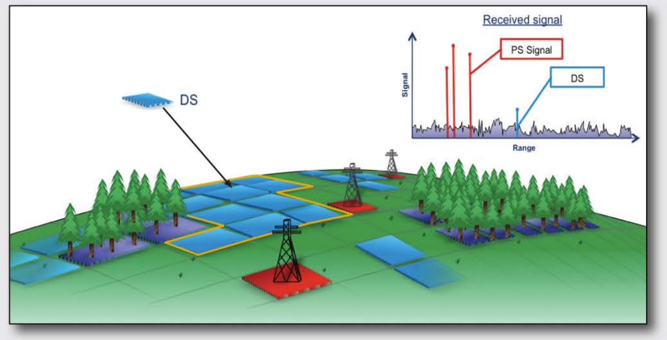
The Evolution of PSInSAR™: SqueeSAR™

▪ BOX 4

▪ The SqueeSAR™ algorithm, recently developed by TRE, enhances the density of ground points by exploiting the returns of 'distributed scatterers' (DS):

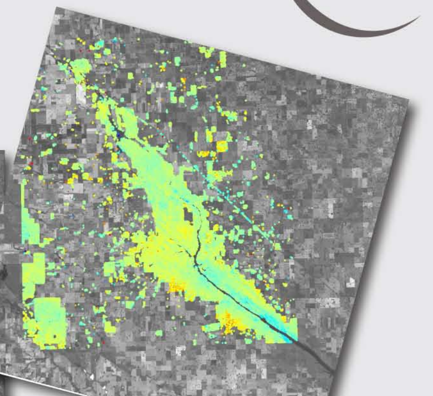


- Permanent Scatterers (PS) are ground points that consistently return a stable signal response to the satellite
- Data cannot be obtained from vegetated areas



- With SqueeSAR™ adjacent pixels are analyzed to identify those that exhibit a similar response - Distributed Scatterers
- DS usually correspond to outcrops, bare earth and homogeneous areas
- SqueeSAR™ includes both PS and DS

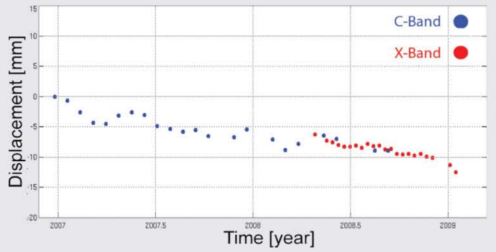
Above: PSInSAR™ analysis of the Weyburn area in Saskatchewan. PS were only identified in the town of Weyburn itself.



Above: An analysis of the same area with the new SqueeSAR™ algorithm led to the identification of over 1 million PS. Many of the PS appear to be located in rangeland.

Enhanced Spatial and Temporal Resolution of the New X-Band Satellites

▪ BOX 5



▪ The new X-band satellites have a significantly higher temporal sampling rate than C-band. Revisiting times can be as low as 4 days, compared to 24 or 35 days with C-band, leading to more effective monitoring of reservoirs.

▪ X-band satellites have a ground resolution of 3m x 3m or 1.5m x1.5m.

Conclusions

- Depending on reservoir depth, surface deformation data from SqueeSAR™ can be used in conjunction with other measurements to identify subsurface deformation constraints, help infer plume geometry and further define reservoir models for EOR, CCS and Gas Storage.
- Evidence of fault reactivation at the ground surface induced by reservoir exploitation can be detected, even in cases of millimetre-level displacements.
- Advances in the data processing algorithm (SqueeSAR™) have significantly increased measurement point densities in rural areas. Furthermore, X-band satellites with shorter repeat intervals and higher ground resolutions have also improved the spatial and temporal density of the results.
- SqueeSAR™ data are complementary to conventional approaches (geological, geophysical, geochemical investigations, core and log analysis, well testing, etc.) for the calibration of reservoir models.
- Compared to traditional surveying techniques (optical levelling, GPS, tiltmeters, etc.) SqueeSAR™ provides hundreds or thousands of measurement points per km^2 and offers high precision and low costs over long periods.

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