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Impact of high resolution radar imagery on reservoir monitoring

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Abstract

Surface deformation monitoring provides unique data for observing and measuring the performance of producing hydrocarbon reservoirs, for Enhanced Oil Recovery (EOR) and for Carbon Capture and Storage (CCS). To this end, radar interferometry (InSAR), particularly multi-interferogram Persistent Scatterer (PS) techniques, such as PSInSAR™, are innovative, valuable and cost-effective tools.
Depending on reservoir characteristics and depth, oil or gas production can induce surface subsidence or, in the cases of EOR and CCS, ground heave, potentially triggering fault reactivation and in some cases threatening well integrity.
Mapping the surface effects of fault reactivation, due to either fluid extraction or injection, usually requires the availability of hundreds of measurement points per square km with millimeter-level precision, which is time consuming and expensive to obtain using traditional monitoring techniques, but can be readily obtained with InSAR data. Moreover, advanced InSAR techniques developed in the last decade are capable of providing millimeter precision, comparable to optical leveling, and a high spatial density of displacement measurements over long periods of time, without the need for installing equipment or otherwise accessing the study area.
Until recently, a limitation to the application of InSAR was the relatively long revisiting time (24 or 35 days) of the previous generation of C-band satellites (ERS1-2, Envisat, Radarsat). However, a new generation of X-band radar satellites (TerraSAR-X and the COSMO-SkyMed constellation), which have been operational since 2008, are providing significant improvements. TerraSAR-X has a repeat cycle of 11 days, while the joint use

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of two sensors of the COSMO-SkyMed constellation have an effective repeat cycle of just 8 days. With the launch of the fourth satellite of the constellation, in 2010, COSMO-SkyMed will have an effective revisiting time of just 4 days, allowing "near real-time" applications. Indeed, by combining two acquisition geometries (e.g. data acquired along ascending and descending orbits), it will be possible, on average, to have a new scene over the area of interest every other day.

Additional advantages of the new X-band satellites are: a higher sensitivity to target displacement and a higher spatial resolution (the density of measurement points can be increased by an order of magnitude, possibly exceeding 2,500 PS/km^2).

In this paper, we present some examples of the application of X-band SAR data to reservoir monitoring. Special attention will be given to CCS projects where InSAR data could become a "standard" monitoring tool. The paper will highlight the technical features of the new sensors, the possible synergy between TerraSAR-X and COSMO-SkyMed data, as well as the importance of a careful analysis of atmospheric disturbances affecting SAR data covering the area of interest, in order to retrieve high quality displacement data. Finally, some conclusions will be drawn supporting recommendations about future CCS monitoring programs.

Keywords: InSAR; PSInSAR; CCS Monitoring; Reservoir Monitoring; Surface Displacement

1. Introduction

Surface deformation monitoring can provide valuable constraints on the dynamic behavior of a reservoir by allowing the evaluation of volume/pressure changes with time, as well as an estimation of reservoir permeability. Levelling campaigns, tiltmeters, GPS and InSAR are all geodetic techniques used to detect and monitor surface deformation phenomena. InSAR data from satellite radar sensors are gaining increasing attention for their unique technical features and cost-effectiveness. In particular, Permanent Scatterer InSAR (PSInSAR™) is an advanced InSAR technique capable of providing very precise 1D displacement measurements along the satellite line-of-sight (LOS) and high spatial density (typically exceeding 100 measurement points/sqkm) over large areas, by exploiting point-wise radar targets already available on ground. PSInSAR™ data have been already used successfully for environmental assessments, reservoir monitoring in CO_2 sequestration experiments and monitoring gas storage areas. Significant advances have further increased the quality and effectiveness of satellite reservoir monitoring: (a) the development of new InSAR algorithms, SqueeSAR™, which provides a significant increase in the spatial density of measurement points, as well as an improved time series quality of the deformation; (b) the availability of an increased number of satellites characterized by higher sensitivity to surface deformation, higher spatial resolution (down to 1m), as well as better temporal frequency of acquisition (typically a few days rather than monthly updates) and (c) the possibility to combine two or more data stacks acquired along different satellite orbits to estimate 3D vectorial displacements rather than 1D measurements along the satellite LOS. All three of the factors mentioned above have a positive impact on the application of satellite data for reservoir monitoring and CO_2 sequestration.Some specific examples are shown below.

2. Technology Overview

A thorough analysis of the InSAR technology is beyond the scope of this paper. Here we will simply recall some basic concepts and provide the reader with a quick introduction on satellite InSAR data.

Synthetic Aperture Radar Images

Because the illuminating source of radar sensors is microwave energy, radar signals are unaffected by darkness or clouds, in terms of visibility of the land surface. As clouds do not obstruct the passage of the signal through the medium, satellite platforms mounting Synthetic Aperture Radar (SAR) systems can function 24 hours per day, 365 days per year.
The sensors emit signals with a specific central frequency. Depending on the frequency of operation, radar systems are associated with specific bands of the electromagnetic spectrum. Those commonly used in InSAR applications are L-band (1-2 GHz, ~24 cm wavelength), C-band (5-6 GHz, ~6 cm wavelength), and X-band (8-12 GHz, ~3 cm wavelength). Since the relative bandwidth is typically very small, radar signals can be considered monochromatic (i.e. single-tone).
As the satellite circumnavigates the Earth, it emits millions of radar signals toward the Earth along the radar beam's line of sight (LOS), on a continuous basis. Using the signals reflected off the Earth's surface, also referred to as backscattered signals, processors on board the satellite integrate the returning signals to form a strip map. A SAR image is then a matrix of complex numbers where both amplitude and phase information are recorded. While amplitude data depends on the amount of energy backscattered by each resolution cell (image-pixel), phase information is related to the optical path between the phase centre of the radar antenna and the target on ground.

SAR Interferometry

Interferometric Synthetic Aperture Radar (InSAR), also referred to as SAR Interferometry, is the measurement of signal phase change, or interference, over time. When a point on the ground moves, the distance between the sensor and the point on the ground also changes and so the phase value recorded by a SAR flying along a fixed orbit will be affected, too. As a consequence, any displacement of a radar target along the satellite line of sight, creates a phase shift in the radar signal that can be detected by comparing the phase values of two SAR images acquired at different times. Figure 1 shows the relationship between ground movement and the corresponding shift in signal phase between two SAR signals acquired over the same area.
This simple concept can be used successfully only when the radar target on ground doesn't change its 'radar signature' with time, i.e. the radar return coming from a certain resolution cell should be identical in the two acquisitions, apart from a possible variation in range affecting all scattering centres belonging to the same image pixel. Whenever the radar signature of the target is constant in time, apparent phase variations between two satellite images acquired over the same area can be caused by actual ground displacement and/or by atmospheric effects that delay the electromagnetic wave propagation.
In the mid-90's, after extensive application of the InSAR technology, the atmospheric contribution to phase shift was found to be significant, particularly in tropical and temperate areas. Unfortunately, there is no method for removing the atmospheric component so users have to be aware of its effects. Thus, InSAR should only be used on the understanding that deformation measurements are prone to errors arising from atmospheric circumstances.

Permanent Scatterer Interferometry

Persistent Scatterer Interferometry (PSI) is the collective term used within the InSAR community to distinguish between single interferogram DInSAR and the second generation of InSAR technologies, of which there are but a few. The first of these to appear, in 1999, was PSInSAR™ (Permanent Scatterer InSAR, Ferretti et al 2001 [1]), an algorithm developed and patented by Politecnico di Milano and considered a real ice-breaker by the InSAR community.
The PS technique is an advanced form of InSAR based on the generation of multiple interferograms from a stack of radar images. As a minimum, 15 radar scenes are usually required for PS analysis to be performed , even though there are circumstances when analysis can be conducted with fewer images. However, it

should be noted that the higher the number of images used in analysis, the higher the accuracy of the results.

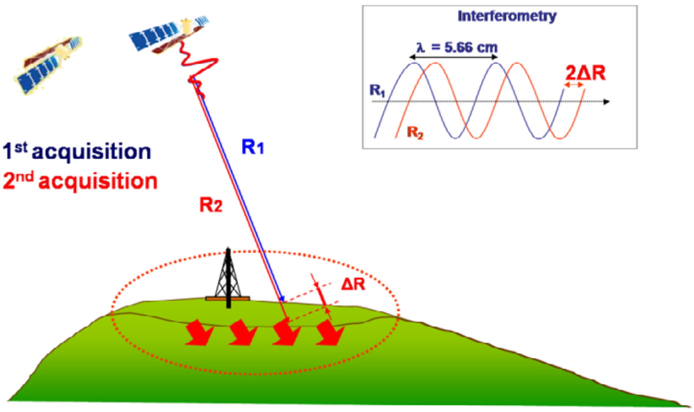

Figure 1: A schematic showing the relationship between ground displacement and signal phase shift. The numeric value of the wavelength λ is that used by the ERS satellite operated by the European Space Agency (ESA).

The main driver for the development of PSInSAR™ technology was the need to overcome the errors introduced into signal phase values by atmospheric artefacts. By examining multiple images, many interferograms are generated by selecting one of the scenes as a master to which the other scenes become slaves. Statistically-based tests are then conducted on all of the interferograms to identify, quantify and remove the atmospheric component. Having removed the atmospheric artefacts, the data that remain are upward and downward displacement values plus noise, which cannot be removed.
The process by which this is achieved involves searching the imagery and interferograms for pixels that display stable amplitude and coherent phase throughout every image of the data set. Thus a random sparse grid of point-like targets is generated across an area of interest on which the atmospheric correction procedure can be performed. Once these errors are removed, a history of motion can be created for each target. These targets are referred to as Permanent Scatterers. Objects that make good PS are varied and can be natural or man-made. Among the natural forms are: rock outcrops, hard un-vegetated Earth surfaces, and boulders. Among the man-made objects are: buildings, street lights, transmission towers, bridge parapets, above-ground pipelines, appurtenances on dams and roof structures, and any rectilinear structure that can create a dihedral signal reflection back to the satellite.
PS results can be accurately geocoded and integrated with other prior information in Geographic Information Systems (GIS), with individual time-series data and LOS velocities available for each measurement point (PS). Common to all differential interferometry applications, the results are computed with respect to a ground control point of known elevation and motion.

Precision

The most important factors impacting on data quality are: (1) spatial density of the PS (the lower the density, the higher the error bar); (2) quality of the radar targets (related to their Radar Cross Section); (3) climatic conditions at the time of the acquisitions; (4) distance between the measurement point (P) and the reference point (P0)
Table 1 is a chart showing precision values obtained from many analyses of data from the ERS, Envisat, and Radarsat-1 satellites acquired over different areas in Italy. Values refer to datasets where at least 2 years of data are available and the number of processed images exceeds 20. While the first two figures refer to the capability of measuring any range variation, the last three columns report the typical precision related to the positioning of the PS.

	Average Displacement Rate (LOS)	Single Measurement (LOS)	Easting	Northing	Elevation
Precision (1σ)	***1 mm/yr***	***5 mm***	***6 m***	***2m***	***1.5m***

Table 1: Typical values of precision for a PS <4km from the reference point (C-band data).

In particular, the accuracy of velocity measurements processed using InSAR datastacks is strongly dependent on the number of satellite images used. Given that satellites have varying orbital paths and 'repeat cycles', images over the same area of interest are acquired at different frequencies, ranging from 8 to 35 days. Hence, the minimum number of images required to perform an analysis with a certain accuracy can be obtained using the latest COSMO-SkyMed X-band satellites (acquiring every 8 days) much faster than Radarsat (RSAT, acquiring every 24 days). Figure 2 shows the relationship between the number of months of data acquisition and the standard deviation of the velocity measured. Data refer to statistical analysis carried out over thousands of SAR scenes acquired over Italy, but it should represent a reasonable benchmark for areas of interest at mid-latitudes. The new satellite platforms mouting X-band radar sensors (namely COSMO-SkyMed and TerraSAR-X) allow the user to achieve an accuracy of 1 mm/yr figure well before that of C-band sensors RADARSAT-1/2 and ENVISAT.

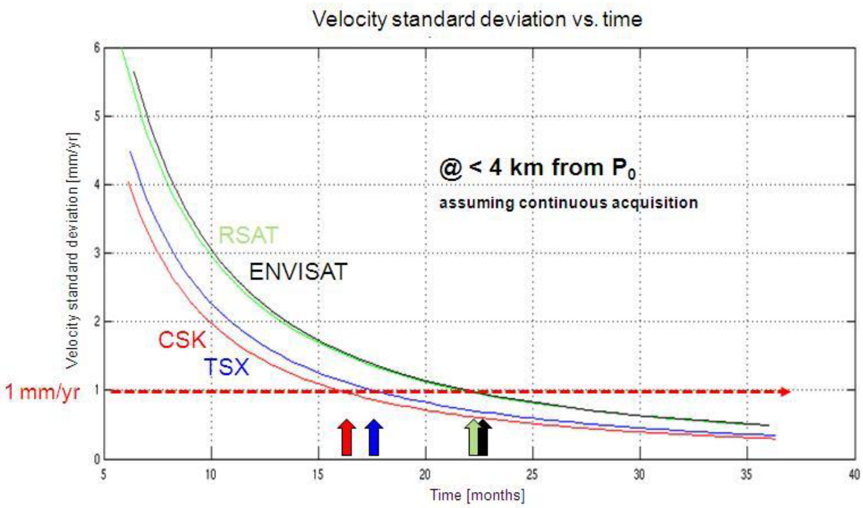

Figure 2: Precision of multi-interferogram InSAR measurements as a factor of satellite platform used and the number of months of data acquisition.

3. Applications

Surface deformation monitoring can provide valuable constraints on the dynamic behaviour of a reservoir by allowing the evaluation of volume/pressure changes with time, as well as an estimation of reservoir permeability and the monitoring of possible fault reactivation.

CCS Project

SqueeSAR™ observations associated with CO_2 injection data have been widely used to model fluid flow in reservoirs and estimate flow properties such as permeability.
In few words, the idea is to use the surface deformation measurements to infer volume/pressure changes due to CO_2 injection, then using the diffusive equation governing the fluid flow in a reservoir the permeability is estimated.

Such methodology has been successfully adopted to monitor the CCS in the InSalah project (in Algeria): the largely unexpected results well correlate with local geological observations and reservoir characteristics (Figure 3) (Mathieson et al. 2009 [2]).
The permeability estimated (Vasco et al. 2008 [3]) exhibits a privileged flow direction which is the same of the regional fault system, in contrast with the model, available before the analysis, based on a homogenous isotropic permeability distribution.
This result suggests that the pre-existing faults guide the flow of the injected CO_2 trough the reservoir. Such information is important especially for safety reason since it is mandatory to know precisely the spatial distribution of the injected CO_2.

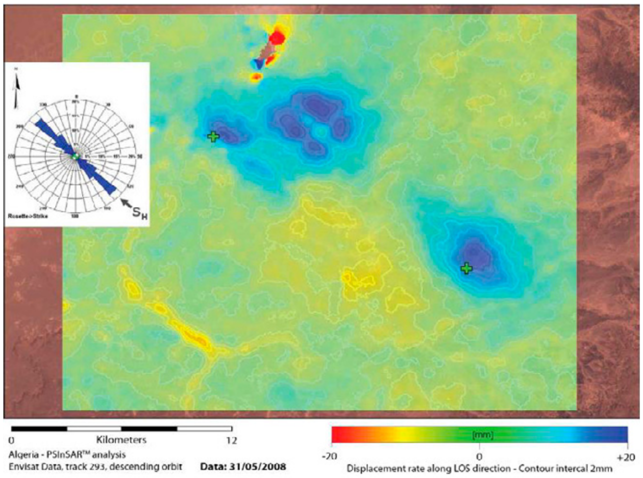

Figure 3:Raster image and contour lines of maximum displacements measured along satellite LOS compared to strike of the main conductive fracture system.

GAS Storage

Another possible application for the PSInSAR™ technique is the surface monitoring of gas storage area, summer injection and winter withdrawal of gas in depleted hydrocarbon reservoirs are responsible for surface displacements in UGS areas (Figure 4).

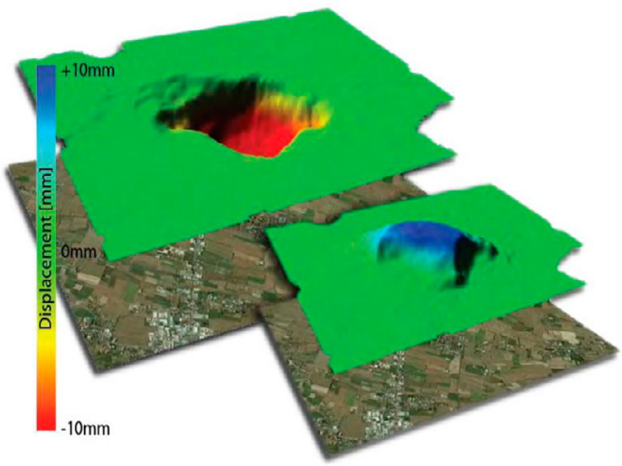

Figure 4:Two images taken from a movie showing the evolution of vertical surface displacement as gas is injected and extracted throughout the life cycle of the gas storage reservoir.

The extent and the maximum value of surface displacements depends on the depth of the reservoir, the rheology of the overburden and the pore pressure changes induced by gas injection and/or extraction. The vertical displacements in Figure 5 show a very good correlation with the gas volume stored in the reservoir, allowing the setup and calibration of 3D fluid-dynamic models. It's important to estimate the pressure changes induced by the injection/extraction activities especially to guarantee the integrity of the buildings present in the UGS area.

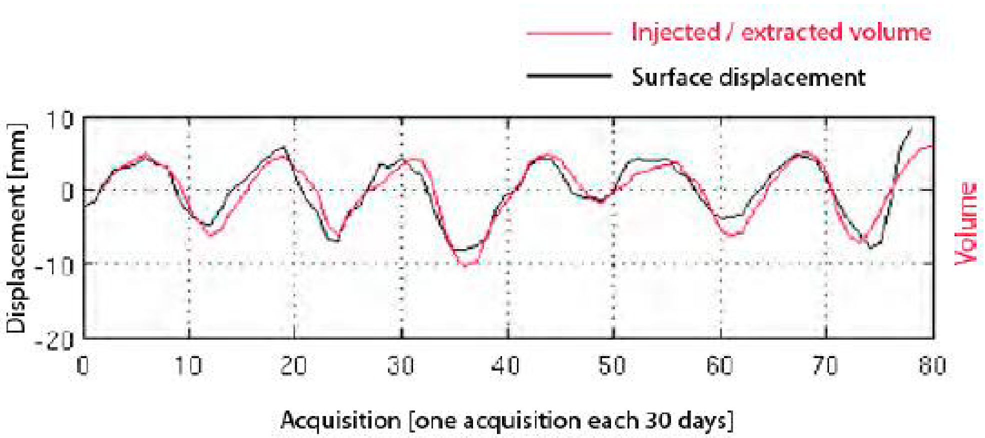

Figure 5:Comparison between vertical surface displacement measured with satellite data processing and injected/extracted gas volumes

4. Conclusions

Unlike traditional surveying techniques (optical levelling, GPS, tiltmeters, etc.) PSInSAR™ provides hundreds of measurement points per km^2 and offers high precision and low costs over long periods. For this reason satellite data represent an important tool for the calibration of reservoir models, which can be complementary to conventional approaches (geological, geophysical, geochemical investigations, core and log analysis, well testing, etc.). Moreover, displacement information can be used to monitor possible fault reactivation induced by reservoir exploitation, even in case of millimiter-level displacements (Vasco et al. 2010 [4]). The possibility to measure surface effects of the reservoir exploitation depends on the depth of the reservoir and on the rheology and heterogeneity of the overburden. Assessing depth limitations is not a simple process; our experience has shown that PSInSAR™ can be successfully applied in cases where reservoir depth is up to about 2000 m.

It's important to underline how advances in processing algorithm (SqueeSAR™) have significantly increased measurement point densities in non-urban areas. Furthermore, X-band satellites with faster repeat times and higher ground resolutions have also improved both temporal and special resolution of results.

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