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Use of Satellite Radar Data for Surface Deformation Monitoring: A Wrap-Up After 10 Years of Experimentation

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Abstract

Surface deformation monitoring can provide valuable information in assessing the environmental impact of activities, evaluating volume/pressure changes in a reservoir, as well as estimating other geophysical parameters. ENI and Stogit have been studying the use of Interferometric Synthetic Aperture Radar (InSAR) data for surface deformation monitoring since 2001. Based on almost 10 years of R&D and operational projects, this paper aims to summarise the strengths and weaknesses of this space geodetic tool, as well as providing an outlook on future developments in the up and down-stream activities.

During the last decade, satellite InSAR data have been gaining increasing attention for their unique technical features and cost-effectiveness. In particular, second-generation InSAR techniques (e.g. PSInSAR™) are capable of providing thousands of displacement measurements per sqkm at millimeter precision. Since 2001, ENI has financed projects based on InSAR data, first for environmental assessment and then for reservoir monitoring. In parallel, Stogit has used these techniques for the standard monitoring of gas storage fields. Projects and results have followed as a result of the development of InSAR technology. Radar data were first validated, compared with optical leveling surveys, integrated with GPS data, and then used for geophysical inversion, in both local and regional analyses. For some areas, data have been gathered by two different satellite platforms, providing unique datasets for a thorough analysis of different data sources. Long-time records of injected/extracted gas volumes, together with a multi-year displacement data set, have allow the calibration of fluid-dynamic and geo-mechanical models, that can be used to investigate the effects of increased working gas volumes, especially in overpressure conditions, in natural gas storage fields. In the authors' opinion, InSAR data will become a standard tool for reservoir monitoring in the next few years. The experience summarised in this paper can provide a useful contribution for petroleum engineers and the oil&gas community in general.

Introduction

Apart from the environmental impact of subsidence and uplift phenomena induced by fluid injection and/or extraction, recent reservoir optimisation techniques ask for timely information about many geophysical parameters, both downhole and on the surface. In particular, surface deformation measurements are lately gaining increasing attention within the reservoir engineer community, which is searching for new monitoring tools to complement seismic surveys. These monitoring technologies are relatively low in cost and their information adds significant value, if properly interpreted and integrated with more conventional data. One such technology – synthetic aperture radar interferometry (InSAR) - can provide high-quality, remotely acquired data about surface deformation affecting large areas. Since 2001, ENI has financed projects based on InSAR data, first for environmental assessment and then for reservoir monitoring. Environmental monitoring is legally obliged in Italy according to the Italian mining legislation. Oil, gas and mining companies must develop monitoring plans that should be approved by the Ministry of Environment and local administrations before the start of operations.

Initially, the request for InSAR analyses was simply a way to evaluate a new technology to complement conventional geodetic data from leveling networks and GPS stations. Indeed, in the late nineties, InSAR was a new space geodetic tool that had been used primarily by seismologists and volcanologists for research purposes, whose impact on reservoir engineering had still to be determined. The main question, at that time, was whether or not this technology could really provide precise and reliable estimates of surface deformation over large areas and allow the operator to obtain a data stream of geodetic measurements, correlated to other geophysical parameters of the reservoir, and be regularly updated.

It's important to point out that, rather than assessing the advantages and drawbacks of conventional InSAR analysis, ENI decided to test an advanced InSAR technology patented in 1999 by Politecnico di Milano (POLIMI) technical university,

called Permanent Scatterer InSAR (PSInSAR™), specifically designed to overcome most of the difficulties related to conventional InSAR analysis and claiming to become an operational tool for surface deformation monitoring. In 2000, POLIMI founded TRE, a spin-off company offering PSInSAR products and services to both the public and private sector and in 2001 TRE started providing ENI with radar data.
After a validation phase and a careful assessment of the PSInSAR technology using ground truth data, radar data have quickly become the reference tool for subsidence monitoring along hundreds of kilometers of coastal areas in Italy. In parallel, Stogit has used these techniques for the standard monitoring of gas storage fields, where both subsidence and uplift phenomena are carefully analysed to calibrate reservoir models.
As it will be discussed in the following sections, the main advantages of InSAR data, compared to conventional geodetic networks, are essentially related to the spatial density of measurement points, the temporal frequency of the observations, the precision and the limited cost, at least for the monitoring of large areas. Since the number of radar-mounted satellite platforms is increasing, as well as the accuracy of radar measurements, this source of information will probably become more and more common in projects related to reservoir monitoring and optimisation.

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 Permanent Scatterer (PS) InSAR, 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.

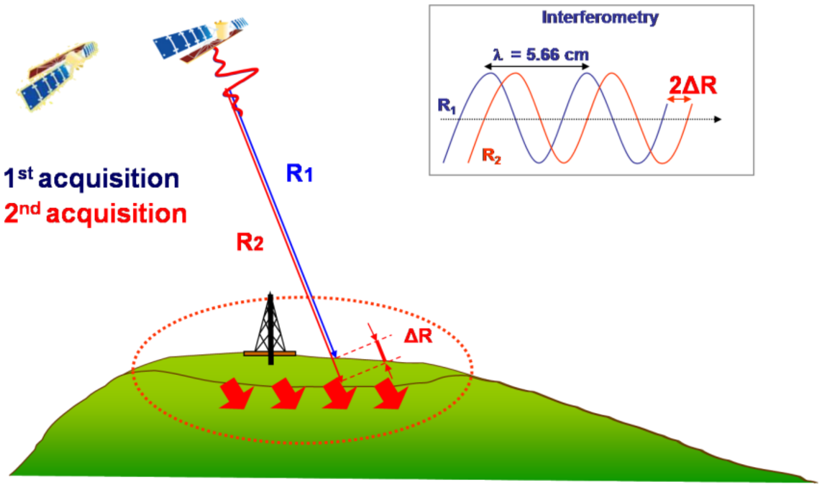

Figure 1: A schematic showing the relationship between ground displacement and signal phase shift. The numeric value of the wavelength λ is that used by the ERS satellite operated by the European Space Agency (ESA).

The main driver for the development of PSI technologies was the need to overcome the errors introduced into signal phase values by atmospheric artifacts. 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 artifacts, 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 (or Persistent) 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 (P_0)

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.

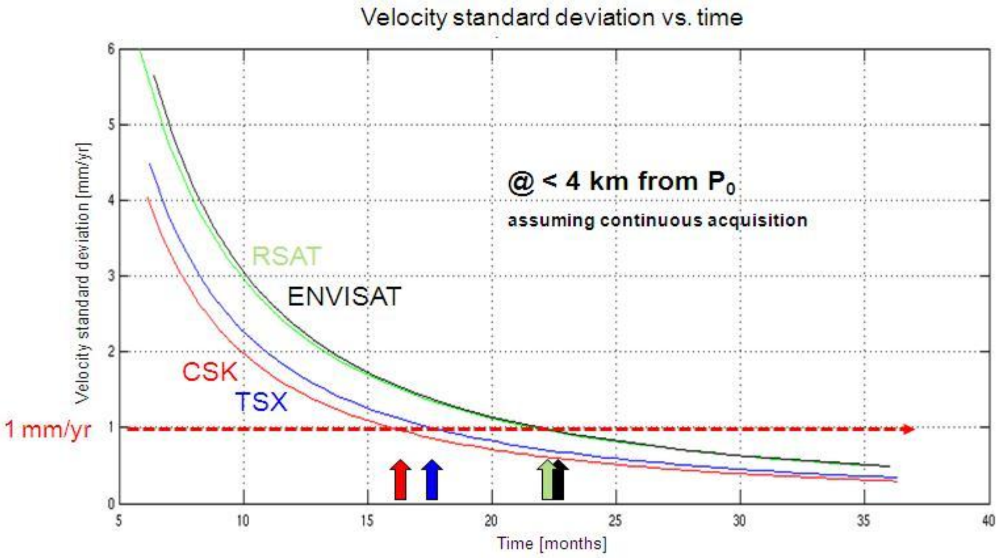

Figure 2: Precision of multi-interferogram InSAR measurements as a factor of satellite platform used and the number of months of data acquisition.

Satellite Radar Sensors

The family of satellites that carry, or will be carrying in the future, SAR sensors for commercial applications is illustrated in Figure 3. Other SAR-bearing satellites exist but are used exclusively for military applications.

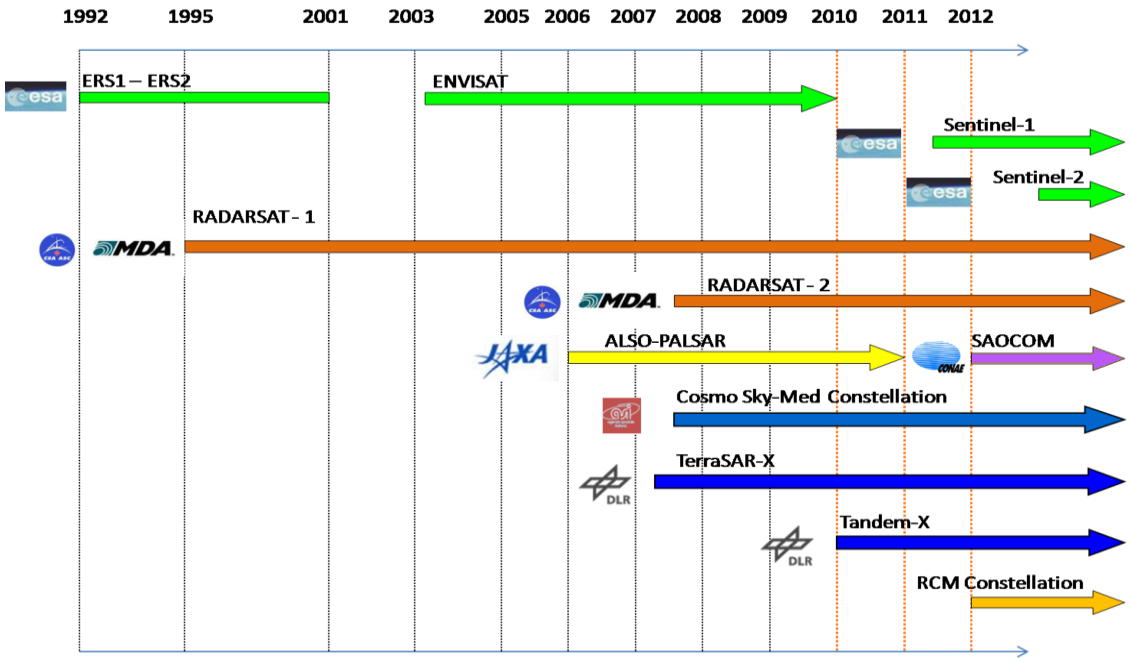

Figure 3: Satellite Radar Systems available now and into the future.

All satellites equipped with SAR sensors orbit the Earth on a near-polar orbit at an altitude ranging from 500 to 800 km above the Earth's surface, depending on the satellite platform hosting the SAR sensor. As clear from Figure 3, the number of radar data sources is steadily increasing, data redundancy is guaranteed for monitoring projects and historical InSAR datasets are available back to 1992, at least for areas where ERS data are available.

Results

As already mentioned, InSAR data were found to be extremely useful for monitoring large areas, at a reasonable cost. Figure 4 shows an example of PSInSAR analysis carried out over a coastal area in Italy, potentially affected by sudsidence phenomena. The colored dots correspond to InSAR measurement points for which it was possible to retrieve not only the average displacement rate, but also the time series of motion. As two independent acquisition geometries were available over the area of interest (one satellite orbiting from South to North, looking East and the second satellite orbiting from North to South, looking West) it was possible to estimate both vertical and East-West displacements as a function of time, for all measurement points shown in Figure 4. This kind of environmental monitoring is now routinely performed by ENI every year and results are carefully analysed to detect any acceleration or change in average trends. Every year, information on 2,000,000 PS, distributed along 500 km of coast is updated and integrated with permanent GPS stations data.

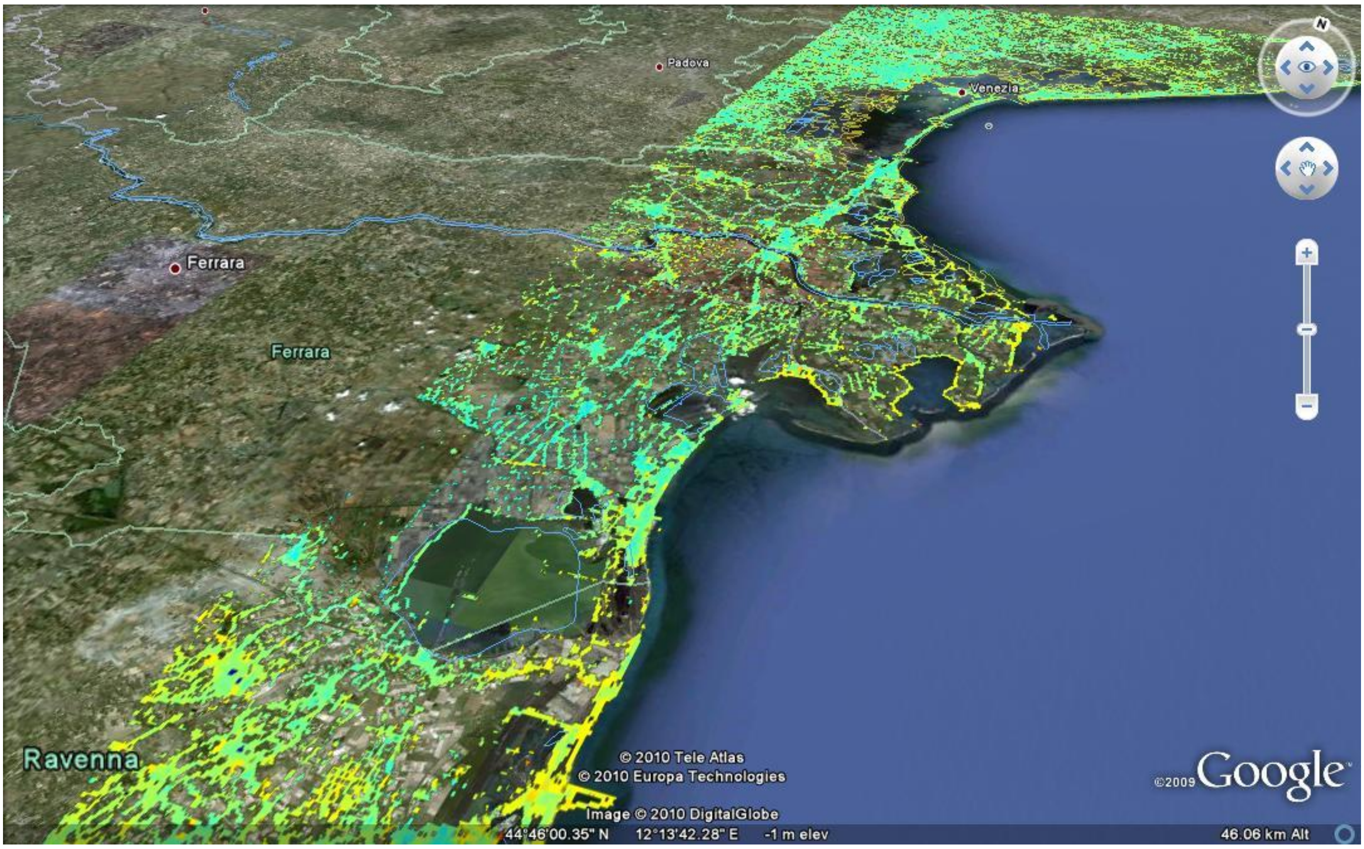

Figure 4: Example of PSInSAR analysis along a coastal area.

The density of measurement points detected depends on the sensor used for the analysis and on the terrain properties. For regional analyses in Italy RADARSAT-1 C-band data was used and PS density was found to exceed 1,000 PS/km^2 over urban areas.

As PS data became a more familiar measurement technology for ENI, opportunities emerged for its conjunctive use with Geographic Positioning Systems (GPS) in environmental monitoring projects. This was stimulated largely by the fact that the strengths of one technology were complemented by the weaknesses of the other. **Errore. L'origine riferimento non è stata trovata.** summarises some of the complementary features of both technologies.

PS	GPS
• Temporal sampling constrained by satellite repeat orbit cycle • Millimeter displacement accuracy in vertical direction • High density of measurement points • Cost effective, particularly over large areas • Site work rarely required	• Real time sampling • Centimetre displacement accuracy in vertical direction • Spatial positioning accuracy in millimeters • Low density of measurement points • Measuring stations have to be set up

Table 2: Comparison of PS and GPS technologies.

GPS data can be used successfully to calibrate PS results, as well as retrieving information about the North-South components of the displacement field affecting the area of interest. In fact, InSAR analysis cannot typically provide any information about North-South components of the 3D displacement vector.

As far as Stogit is concerned, it is well known that, due to the growing importance of natural gas for energy production, there is a growing interest to develop Underground Gas Storage (UGS) projects. 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 often show a very good correlation with the gas volume stored in the reservoir (Figure 5), allowing the setup and calibration of 3D fluid-dynamic models. This kind of reservoir modeling/optimisation technique is still under study, but results obtained so far are extremely promising.

Finally, an interesting future application could be the monitoring of CCS projects. In fact, the injection of CO_2 into geologic formations can induce deformation of the ground surface. PSInSAR observations associated with CO_2 injection data have been recently used by BP and Statoil to model fluid flow in the reservoir and to estimate flow properties such as permeability. The results correlate well with the local geology and the reservoir characteristics.

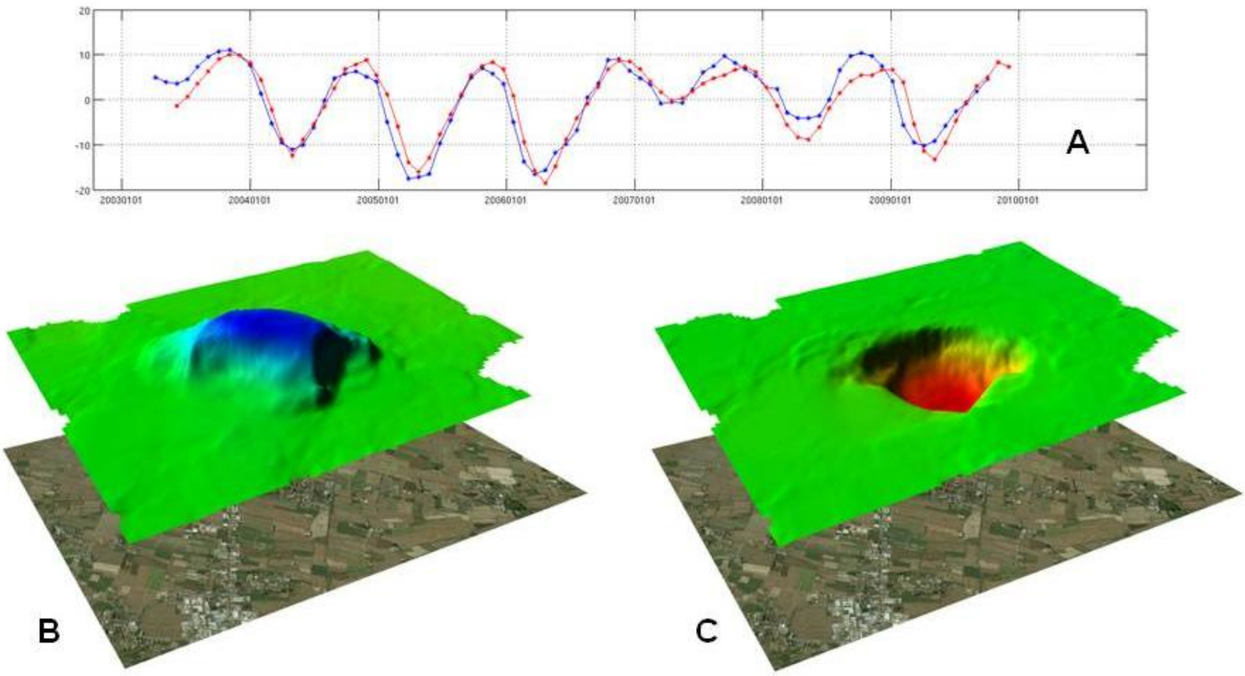

Figure 5: Surface deformation data over an Underground Gas Storage site. The area exhibits both uplift (B) and subsidence (C) phenomena as a function of the volume of gas injected or extracted. In (A) a time series of vertical deformation (in red) is compared to the gas volume stored in the reservoir (in blue).

Discussions and Future Applications

Based on ten years of experimentation, it can be said thatInSAR is not a *panacea* for all geodetic projects. There are situations where InSAR will produce poor results, or simply won't work. However, there are elements of the technology that make it unique among most measurement methods.
Table 3 summarizes some of its strengths and weaknesses.

Strengths	Weaknesses
• Non-intrusive and non-destructive	• Vegetation and erosion impede InSAR
• Millimeter precision	• Snow absorbs radar signals
• Historic analyses are possible, back to 1992	• Not suited for fast movement (>300mm/year)
• Cost effective, particularly over large areas	• Blind to movement parallel to satellite orbit
• High spatial density of measurement points	• Temporal sampling limited by repeat orbit cycles

Table 3: Summary of strengths and weaknesses of InSAR analysis.

As newer satellites, with higher levels of technology become operational, limitations associated with the technology become less significant. For example, the newer satellites invariably have much smaller resolutions cell sizes (3m x 3m for COSMO-SkyMed compared to 20m x 5m for Envisat), and shorter repeat orbit cycles (8 days for the COSMO-SkyMed constellation using 2 sensors compared to 35 days for Envisat). Such characteristics reduce the limitations of vegetation and temporal decorrelation.
Indeed, the recent launch of X-band satellites has significantly improved the ability and accuracy of monitoring ground surface deformation. X-band data are provided by the TerraSAR-X satellite (operated by Infoterra) and the COSMO-SkyMed (CSK) satellite constellation (operated by the Italian Space Agency). The advantages of X-band data are:

- An increased sensitivity to movement arising due to the shorter wavelength compared to C-band data (31mm, instead of 56mm with C-band).
- An increased spatial density of measurements produced by the higher resolution of the new satellites sensors (up to 1x1m cell resolution, instead of 20x5m with older satellites).
- Higher temporal sampling rates due to the significantly shorter satellite revisiting times (8-11 days versus 24-35 days for existing C-band satellites).

Last but not least, after ten years of PSInSAR analyses, TRE has recently introduced the “second-generation PSInSAR analysis” called SqueeSAR, that can further improve the results on both C-band and X-band datastacks by identifying, apart from the PS, the so called Distributed Scatterers (DS) and increasing significantly the spatial density of the measurement points.

Conclusions

Permanent Scatterer SAR Interferometry (PSInSAR) has proven highly valuable in monitoring subtle mm-scale surface deformation related to different phenomena either natural or anthropogenic (e.g. subsurface pressure changes due to fluid injection and hydrocarbon production). Unlike traditional surveying techniques (optical levelling, GPS, tiltmeters) PSInSAR provides hundreds of measurement points per sqkm and offers high precision and low costs over long periods. These features can be extremely important for environmental monitoring projects over thousands of sqkm of land.
Displacements are measured along satellite line of sight (LOS) but, by combining two independent acquisition geometries, vertical and E–W horizontal components can be computed having comparable precision.
The applicability of InSAR data is limited to onshore reservoirs. Moreover the possibility to measure surface effects of the reservoir exploitation depends on the depth of the reservoir and probably on the rheology and heterogeneity of the overburden. Assessing depth limitations is not a simple process; our experience has shown that InSAR data can be successfully applied in cases where reservoir depth is up to about 2000 m. Depending on the depth of a reservoir, the availability of surface displacements can become an essential tool for reservoir monitoring, supporting both surveying and modelling of the dynamic behaviour (volumetric change) of a reservoir.

Mnemonics Used

CSK	COSMO-SkyMed
DS	Distributed Scatterer
InSAR	Interferometric Synthetic Aperture Radar
LOS	Line Of Sight
POLIMI	Politecnico di Milano – Technical University
PS	Permanent (or Persistent) Scatterer
PSI	Persistent Scatterer Interferometry
PSInSAR	Permanent Scatterer InSAR (POLIMI international trademark)
SAR	Synthetic Aperture Radar
UGS	Underground Gas Storage

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