Retrieving surface deformation by PSInSAR™ technology: A powerful tool in reservoir monitoring

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1. Introduction

Remote sensing techniques have been widely used in recent decades to monitor Earth surface displacements related to seismic fault activity, volcanoes, landslides, aquifers and oil fields.

Two techniques in particular have provided interesting results: DInSAR (Differential Synthetic Aperture Radar Interferometry) and the subsequent PSInSAR™ technique (Permanent Scatters) (Ferretti et al., 2000, 2001), which was introduced by the Politecnico di Milano (POLIMI) in the late nineties, and later improved by Tele-Rilevamento Europa (TRE). Notable improvements to previously existing techniques include: the extension of the area that can be monitored (up to thousands of square kilometres) and the accuracy of the obtained measurements (deformation rates accurate to millimetres/year) (Colesanti et al., 2003, 2005; Hilley et al., 2004).

An important application of PSInSAR™ is in the field of reservoir monitoring. Constant and continuous measurement of surface deformation provides valuable information in determining dynamic reservoir behaviour and helps validate modelled changes in reservoir volume due to extraction or injection of fluid (Vasco et al., 2008; Ringrose et al., 2009). The millimetric precision of measurements of ground displacement obtained at hundreds of observation points per km² coupled with the cost-effectiveness of PSInSAR™ make it an attractive and most viable option for determining surface deformation, including the identification of potential fault reactivation due to reservoir exploitation.

This article presents an overview of the PSInSAR™ technique, processing methodology, interpretation of results, and their application for reservoir monitoring. Two historical case studies are also presented.

2. Methodology

To monitor surface deformation associated with fluid extraction from, or injection into, subsurface reservoirs, the following methodology is applied.
2.1. PSInSAR\textsuperscript{TM} technique

DInSAR is based on pixel-by-pixel computation of interferometric phase using two satellite radar acquisitions: such differential phase is a measurement of what has changed in the time interval between the two satellite acquisitions (ERS: 35 days, Envisat: 35 days, Radarsat: 24 days and TerraSAR-X: 11 days). Apparent phase variations between two satellite images can be caused by actual ground displacement or by atmospheric effects that delay electromagnetic wave propagation.

The PSInSAR\textsuperscript{TM} technique uses a temporally complete set of SAR scenes obtained over an identical target area. The approach is based on a few basic observations: atmospheric artefacts show strong spatial correlation within individual SAR acquisitions but are uncorrelated in time and, conversely, target motion is usually strongly correlated in time, exhibiting varying degrees of spatial correlation depending on the type of deformation (e.g. subsidence due to water pumping, fault displacements, localised sliding areas, collapsing buildings, etc.). Separating these phenomena, atmospheric effects are estimated and then removed by combining data from long time series of SAR images (such as those available in the ESA-ERS archive) which were acquired from late 1991. In order to improve the accuracy of ground displacement estimations, only scatterers minimally affected by temporal and geometrical decorrelations are selected for processing (Ferretti et al., 2000, 2001).

Differential phase contributions generated by atmospheric effects can be separated from stable ground signals (known as Permanent Scatterers, or PS) if the temporal span of SAR data is wide enough (typically about 30 images). Given the high spatial correlation of the APS (Atmospheric Phase Screen), even a sparsely populated grid of measurements allows a reasonable sampling of atmospheric phase contributions, provided a PS density of at least 3–4 PS/km\textsuperscript{2}. After the removal of the APS, sub-metre elevation accuracy is achievable and millimetric terrain displacements can be detected, through the exploitation of extensive temporal satellite data archives. In particular, target velocity in the line of sight (LOS) of the satellite can be estimated with an accuracy often greater than 0.1 mm/year, allowing accurate verification of deformation models—a key issue for risk assessment.

Results of multi-interferogram analysis are mapped, with individual time-series data and LOS velocities available for each PS (typical coordinate system used is WGS84). Common to all differential interferometry applications, the results are computed with respect to a ground control point (GCP) of known elevation and motion.

2.2. PS data post-processing

For each PS, PSInSAR\textsuperscript{TM} analysis provides the following outputs:

- average annual displacement rate, calculated for entire time period processed;
- displacement history.

As previously mentioned, displacements are measured along LOS of the satellite. The incidence angle (the angle drawn between an imaginary line from the centre of the Earth to the satellite, and the direction of propagation of the signal) ranges from 23\degree (ERS, Envisat) to 49\degree (Radarsat) depending on the satellite and acquisition mode. This means that displacement values measured along the LOS are influenced by vertical and horizontal components of displacement. Due to the orbital track of the satellite (approximately North–South), only East–West displacements can be detected.

PSInSAR\textsuperscript{TM} results can be easily viewed and managed in a GIS environment. The PSInSAR\textsuperscript{TM} technique produces a significantly increased number of ground PS targets compared to existing technologies. The following case histories are characterised by an average target spacing of 100 m. The two case studies presented in Section 3.2 exploit such distributions to better correlate surface deformation and volumetric changes in subsurface reservoirs. High spatial densities also allow the analysis of local and regional surface deformation trends, after appropriate post-processing of the data.

The key steps of post-processing are as listed:

- extraction of Easting and vertical components of displacement, by combining ascending and descending satellite tracks;
- data filtering to reduce noise;
- calculation of gradient field of vertical (LOS) displacements, in order to highlight trends and anomalies in the spatial distribution of data;
- evolution analysis of displacements along representative E–W cross-sections, in order to identify evidence of fault reactivation;
- comparison and integration of PSInSAR\textsuperscript{TM} results with other ground based surveillance data.

The extraction of Easting and vertical components is possible only when both ascending and descending satellite geometries are available. Each step of the post-processing procedure is briefly described in the following sections.

2.2.1. Easting and vertical displacement components

Satellites circumnavigate the Earth in polar orbits and therefore pass over an area of interest in two possible geometries: ascending (South to North) and descending (North to South). The PSInSAR\textsuperscript{TM} technique provides deformation rates along the satellite’s LOS: using only one geometry gives estimated displacement along the given LOS of the satellite, and is consequently not vertical. PSInSAR\textsuperscript{TM} results obtained from processing both ascending and descending datasets can be combined to give estimates of vertical and E–W movement.

Decomposition is performed using an XYZ Cartesian reference system where the three vectors correspond to the East–West, North–South and vertical directions. Ascending and descending datasets are compared and, where possible, identical PS are identified in both datasets. Velocity estimates are calculated for each dataset: \( V_a \) and \( V_d \).

In a Cartesian reference system, the velocity of a PS can be expressed as:

\[
\vec{V} = V_x \cdot \vec{s}_x + V_y \cdot \vec{s}_y + V_z \cdot \vec{s}_z,
\]

where \( V_x, V_y \) and \( V_z \) represent the velocity components \( \vec{V} \) along the E–W, N–S and vertical directions, respectively and \( \vec{s}_x, \vec{s}_y \) and \( \vec{s}_z \) are the vectors of the coordinate system.

Since the orbital path of the satellite is known, the LOS with respect to the XYZ coordinate system and the corresponding direction cosines of the velocity vectors \( V_a \) and \( V_d \) can be determined. It is then possible to write the following system:

\[
\begin{align*}
V_a &= V_x \cdot S_{axc} + V_y \cdot S_{ayc} + V_z \cdot S_{azc} \\
V_d &= V_x \cdot S_{adx} + V_y \cdot S_{ady} + V_z \cdot S_{adz}
\end{align*}
\]

where \( S_{axc}, S_{ayc}, S_{azc}, S_{adx}, S_{ady} \) and \( S_{adz} \) represent the direction cosines of the velocity vectors \( V_a \) and \( V_d \) (i.e. the cosine of the angles between the velocity vectors \( V_a \) and \( V_d \) measured along the satellite LOS, E–W, N–S and vertical directions).

Assuming that the orbital path of the satellite is approximately parallel to the meridian, the LOS sensitivity to motion in the N–S
direction is negligible, hence the equation can be rewritten to solve $V_a$ and $V_d$:

$$
\begin{align*}
V_a &= V_x \cdot S_{\text{asce}} + V_y \cdot S_{\text{asce}} \\
V_d &= V_x \cdot S_{\text{desce}} + V_y \cdot S_{\text{desce}}
\end{align*}
$$

Common targets are selected on a geographic basis: the area is divided into 50 m x 50 m cells and, under the hypothesis that all scatterers within a cell exhibit similar displacements, their velocities and time series are averaged resulting in ‘pseudo PS’. This operation is applied to both datasets, regulating the spatial distribution of the two datasets over a common grid. Cells that contain targets in both ascending and descending datasets are used to estimate vertical and E–W motion.

An example of annual ascending and descending displacement rates from a study conducted in the Middle East is shown in Fig. 1.

2.2.2. Data filtering

PS data are filtered spatially to reduce noise. In the examples presented in Section 3.2, filtering was applied to either LOS displacements, or to vertical and horizontal displacement components, depending on the datasets used. Each satellite acquisition was processed using ArcGIS following these steps:

- neighbourhood statistics and computation of mean values are applied to point displacement data; according to signal to noise ratio, different search radii (from 200 to 400 m) are used;
- a raster surface from cumulative displacement data is created; the obtained surfaces can be considered as isochronous displacement surfaces;
- a contour map showing the distribution of smoothed surface displacements is created.

Maps of the displacement field clearly show evolution on a regional scale, but do not necessarily highlight anomalies or trends that can be correlated with the geological setting of the study area. In order to extract more detailed information, the gradient field of displacements are calculated as described in the following section.

2.2.3. Gradient field of vertical displacements

After filtering, the gradient field of vertical displacements are computed, starting from the maximum displacement raster surface. ArcGIS surface analysis tools are applied. A map of the vertical displacement gradient can be used to highlight discontinuities in the spatial distribution of surface displacements, which could either be correlated to the reactivation of faults or to the structural control on fluid propagation.

2.2.4. Displacements along E–W cross-sections

A more detailed analysis of the displacement evolution can be carried out by analysing E–W cross-sections of displacement raster surfaces for each satellite acquisition. If fault reactivation has occurred due to field exploitation (whether by fluid injection or extraction), a discontinuity in the displacement profile is visible. This is particularly evident in Fig. 2 where millimetre differential displacements are visible.

![Fig. 1. Case history 1 (Middle East): detail of ascending LOS displacements (upper left), descending LOS displacements (upper right), vertical component (lower left) and Easting component (lower right). Vertical and Easting components have been calculated after resampling original LOS data on a common grid.](image)
2.2.5. Integration with conventional datasets

The integration of PSInSARTM data with conventional datasets such as geological, geophysical and geochemical surveys, core and log analysis allows the comparison of complementary datasets. As discussed in the following examples, PSInSAR™ data can be helpful in recognising faults that might not always be detected when conducting conventional surveys (e.g. seismic surveys) or when monitoring fluid propagation during the injection processes.

The format of outputted PSInSAR™ data enables its users to perform advanced processing within a GIS environment.

3. Results and discussion

3.1. The value of PSInSAR™ data for reservoir monitoring

Reservoir monitoring is based on an integrated approach, involving surface displacement measurements, geophysical investigations, geochemical monitoring, borehole measurements, etc. Both fluid injection and extraction operations cause volumetric changes in the reservoir, which can be manifested in surface movements. Moreover, field development operations can cause hydro-fracturing and fault reactivation; understanding fault and...
fracture properties is essential for realistic prediction of reservoir performance.

Key issues are:

- mapping fault-bounded reservoir compartments;
- inferring whether faults and fractures control fluid flow;
- construction of an accurate geomechanical model.

In order to use surface deformation measurements as a constraint in determining volumetric changes in a reservoir, high spatial resolution of displacement data is required. Moreover, depending on the extent of surface deformation, the detection of millimetric displacements may be necessary.

Tiltmeters, optical levelling systems and GPS are generally used to monitor surface displacements over time. Fig. 3 is a graph of both vertical and horizontal displacements obtained from GPS measurements at the Lost Hills Field (Brink et al., 2002). In this example, a general overview of the deformation field affecting the area is visible, but higher spatial distribution of displacement data is required to identify evidence of fault reactivation due to field exploitation. PSInSAR™ technique represents an alternative to traditional surface displacement measurement techniques, providing up to several thousands of point displacement measurements per km², each at a millimetric level.

3.2. Case histories

Two case histories are presented: the first features an EOR (Enhanced Oil Recovery) field, the second a CCS (Carbon Dioxide Capture and Storage) site. Both case studies regard onshore reservoirs.

3.2.1. Middle East

The study area regards an oil field in the Middle East, produced by water-flooding. About 500 injectors and producers have been drilled in order to exploit a heavily faulted and fractured carbonate reservoir (less than 2000 m deep).

Two sets of ascending Envisat and descending Radarsat data were processed covering a time interval of about three years. About 280,000 and 360,000 PS were detected respectively. For each PS, the annual average displacement rate and the displacement time series were calculated. The annual displacement rates in LOS for the descending geometry are shown in Fig. 4.

The estimation of the annual vertical and E–W horizontal displacement rates are shown in Figs. 5 and 6, respectively, while the cumulative displacement data for both the vertical and E–W horizontal directions (up to and including the latest available satellite acquisition) are shown in Fig. 7.

The gradient field of maximum vertical displacement obtained after data filtering, with major known fault locations overlain, is shown in Fig. 8. The faults delineated in Fig. 8 were interpreted at top reservoir, so relating surface features to these faults can only be indicative. Nevertheless, the correlation between maximal vertical gradients and identified faults is quite striking.

The evolution of vertical displacements along a selected E–W cross-sections of the study area is represented in Fig. 2. Each profile represents an isochronous cumulative vertical displacement line. Discontinuities in the displacement profiles have been interpreted as evidence of fault reactivation.

The area has been monitored with optical levelling and about 40 permanent GPS stations for many years, and upon integration of the two datasets, a good correlation between traditional measurement results and PSInSAR™ analysis was obtained. Nevertheless, the distribution of GPS benchmarks is not able to provide a detailed spatial distribution of surface displacements or detect anomalous features related to fault reactivation.

The key results of the analysis can be summarised as follows:

- the evolution of vertical displacements along E–W cross-sections of the oil field shows the presence of areas characterised by significantly different displacement rates, delimited by faults reactivated by oil field exploitation;
- the gradient field of cumulative vertical displacements during the time interval covered by the satellite data shows good agreement with major fault distribution;
- increased spatial and temporal resolutions of surface displacements enable a more refined geomechanical model of the reservoir, supporting modelling and risk analyses conducted.

![Fig. 4. Case history 1 (Middle East): average annual displacement rate measured along the satellite LOS (descending geometry).](image-url)
3.2.2. In Salah (Algeria)

The area of interest is In Salah, Algeria, where the largest onshore CO₂ storage project has been in operation since 2004 as part of a joint venture with BP, Sonatrach and Statoil Hydro. The CO₂ removed from production steam is re-injected via three horizontal injection wells into the water leg of the gas producing Krechba Carboniferous Sandstone reservoir (20 m thick) at a depth of around 1900 m (Ringrose et al., 2009; Raikes et al., 2008).

From a structural point of view, the main feature of the area is a gentle anticline with a NW–SE axis, associated with near vertical faults and associated fractures striking NW–SE. Although there is significant faulting within the Devonian, the faults die out in the Carboniferous and there is no evidence of faulting within the overburden above the field (Iding and Ringrose, 2009). At well scale, image logs (FMI) and core analysis show that the main conductive fracture system strikes NW–SE. The majority of faults are difficult to detect in the 3D seismic survey conducted in 1997 (Raikes et al., 2008; Ringrose et al., 2009); nevertheless a good understanding of the fault system is essential for predicting reservoir behaviour. The results of the PSInSAR™ analysis seem to provide helpful information in understanding the role of the fault and fracture system in CO₂ propagation.

PSInSAR™ analysis performed over the area using 30 Envisat images acquired between 12th July 2003 and 31st May 2008 identified more than 300,000 PS, with their respective displacement time series calculated. Only the descending geometry data

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**Fig. 5.** Case history 1 (Middle East): average annual vertical displacement rate.

**Fig. 6.** Case history 1 (Middle East): average annual E-W horizontal displacement rate.
set was available over the area so the annual displacement rate is estimated along the satellite LOS (Fig. 9). The satellite incidence angle was about 23°.

The PS results show a surface uplift rate of around 5 mm/year, caused by an increase in subsurface pressure. The cumulative displacement data along the satellite LOS, relevant to the latest available satellite acquisition, are shown in Fig. 10.

The uplift area, elongated NW–SE according to the main structural pattern at regional scale, can be interpreted as evidence of fracture related permeability anisotropy (Fig. 10). The subsidence in the SW highlights the presence of an eroding wadi, and has nothing to do with reservoir behaviour.

From a general point of view, according to the spatial distribution of the surface displacements, it is possible to indirectly infer that the CO₂ plume propagation is oriented in NW–SE direction. Forward and inverse modelling (Rutqvist et al., 2008) of the increase in subsurface pressure due to CO₂ injection demonstrates that the surface deformation is consistent with measured geomechanical data.

The maximum displacement values measured along the LOS are lower than 20 mm in five years; the cumulative differential displacements in the uplift area are not higher than 5 mm. No other conventional monitoring technique is capable of identifying mm-level surface displacement with the same spatial resolution.
Fig. 9. Case history 2 (In Salah, Algeria): average yearly displacement rate measured along the satellite LOS (descending geometry).

Fig. 10. Case history 2 (In Salah, Algeria): raster map and contour lines of maximum displacements measured along satellite LOS compared with the strike of the main conductive fracture system (left, Iding and Ringrose, 2009).
Fig. 11 shows the evolution of LOS displacements over time along an E–W cross-section of the field: the absence of spatial discontinuity means that probably no fault reactivation occurred. The only anomaly visible on the selected profile was correlated to the position of a single injection well and similar features were not detected along other E–W profiles just North or South of the said profile.

Different monitoring data have been used in the In Salah area to create a detailed reservoir characterisation and to reconstruct and model the most likely development of the CO2 plume. The plume has migrated in a NW direction over a two-year period (Ringrose et al., 2009); this direction is consistent with a preferred conductive fracture orientation highlighted in the displacement maps provided by PSInSAR™ analysis.

The key results of the analysis can be summarised as follows:

- the spatial distribution of surface displacements shows a good agreement with the major structural pattern (faults and anticline axis) and the strike of conductive fracture orientation (from FMI and cores);
- PSInSAR™ analysis provides helpful information in understanding the processes involved in CO2 migration and the role of the fault and fracture system in CO2 propagation.

4. Conclusions

Depending on the depth of a reservoir, the availability of surface displacements is an essential tool for reservoir monitoring, supporting both surveying and modelling of the dynamic behaviour (volumetric change) of a reservoir.

Permanent Scatterer SAR Interferometry (PSInSAR™) has proven highly valuable in monitoring subtle mm-scale surface deformation related to 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 km² and offers high precision and low costs over long periods.

Displacements are measured along the line of sight (LOS) of the satellite in both ascending (S–N) and descending (N–S) geometries. If both data set are available, vertical and E–W horizontal components can be computed.

The applicability of PSInSAR™ 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 PSInSAR™ can be successfully applied in cases where reservoir depth is up to about 2000 m. A further limitation of the PSInSAR™ technique is represented by the impossibility to measure horizontal displacements in N–S direction, which could infer the possibility to detect evidence of strike-slip faults depending on their orientation.

Interpretation of the two case studies from the literature demonstrated that

- evidence of fault reactivation at the ground surface induced by reservoir exploitation can be detected, even in cases of millimetre-level displacements;
- depending on reservoir depth, surface deformation data from PSInSAR™ can be used in conjunction with other measurements to constrain probable subsurface deformation and help infer plume geometry;
- PSInSAR™ data are complementary to conventional approaches (geological, geophysical, geochemical investigations, core and log analysis, well testing, etc.) for the calibration of reservoir models.

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References


