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Satellite Observations for CO2 Sequestration Studies

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SUMMARY

Knowledge of the structure controlling the flow of fluids within a reservoir is critical in many activities, such as hydrocarbon extraction and carbon capture sequestration (CCS). To this end, surface deformation are important observations that help in relating the ground motion to flow-related processes at depth. InSAR data from satellite radar sensors are gaining increasing attention for their unique technical features and cost-effectiveness. These data provide accurate displacement measurements along the satellite line-of-sight (LOS) and high spatial density (typically exceeding 100 measurement points/sqkm) over large areas, especially when advanced InSAR technique, such as PSInSAR™ are applied.
There are significant advantages in combining two or more data stacks acquired along different satellite orbits in order to estimate a 2D vectorial displacements (East-West and Vertical components). In this work we highlight the importance of using two components of displacement to better constraint an inversion for a distributed source model.

Introduction

Knowledge of the structure controlling the flow of fluids within a reservoir is critical in many activities, such as hydrocarbon extraction and carbon capture sequestration (CCS). To this end, surface deformations are important observations that help in estimating volume/pressure changes at the reservoir layer. Leveling 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. These data provide accurate displacement measurements along the satellite line-of-sight (LOS) and high spatial density (typically exceeding 100 measurement points/sqkm) over large areas, especially when advanced InSAR technique, such as PSInSAR™ are applied.
There are significant advantages in combining two or more data stacks acquired along different satellite orbits in order to estimate a 2D vectorial displacements (East-West and Vertical components). The utility of such data for reservoir monitoring and modeling has been proven during the InSalah Project, one of the three most important CCS projects globally.

2D displacement decomposition

Current SAR systems can only measure the projection of the actual surface motion vector along the system looking direction (Line Of Sight, LOS). However, one can combine the results obtained from the processing of an ascending and a descending datasets (when available) to estimate the East-West and vertical component of the motion. To better understand how the decomposition is performed, let us consider an X-Y-Z Cartesian reference system, where the three directions correspond to the East-West, North-South and Vertical directions. Consider the case in which 2 estimates of the velocity are available in 2 different directions, namely V_a and V_d. (see Figure 1).

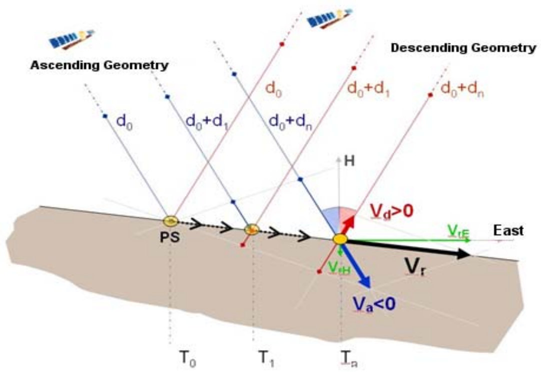


Figure 1*: Example of motion decomposition combining ascending and descending acquisition geometry.*

In general, in the Cartesian reference system X-Y-Z, the velocity of a target can be expressed as:

$$\vec{V} = V_x \cdot \vec{s}_x + V_z \cdot \vec{s}_z$$

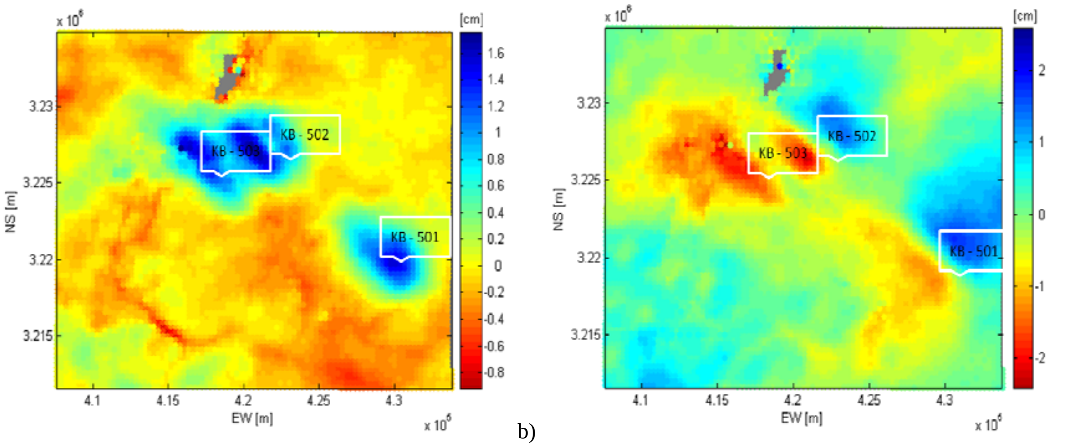
where V_x and V_z represent the component of the velocity V along the E-W and vertical directions, and .s_x, s_z the versors of the coordinate system. In the previous equation, due to the fact that the satellite orbit is almost parallel to the meridians, the LOS sensitivity to possible motion in the N-S direction is negligible (the direction cosine s_y is close to 0). Thanks to the knowledge of the satellite orbit, it is possible to estimate the orientation of the satellite Line of Sight with respect to the X-Y-Z coordinate system, and the corresponding direction cosines of the velocity vectors V_a and V_b. It is then possible to write the following system:

$$\begin{cases} V_a = V_x \cdot s_{xasce} + V_z \cdot s_{zasce} \\ V_d = V_x \cdot s_{xdesce} + V_z \cdot s_{zdesce} \end{cases}$$

that may be solved for V_x and V_z. The same approach can be applied to estimate the decomposed time-series of deformation as well.

Satellite monitoring for InSalah Project

We utilize InSAR observations gathered over a site of active CO2 storage to image ground motion induced by the injected fluid volume. The injected carbon dioxide is associated with the InSalah CO2 storage project located in Algeria, which has been operational since 2004. Given the estimates of deformation provided by the InSAR data, our aim is to relate the ground motion to flow-related processes at depth.
In previous works [1], [3], [4] only the LOS component of surface displacement was available to infer information at the reservoir layer. In this work, we were able to work with two displacement field components, East-West and Vertical.
For the Descending geometry, 41 radar reflection images from July 12, 2003 through March 19, 2007 have been processed by Tele-Rilevamento Europa (TRE) applying the PSInSAR™ algorithm in order to compensate for the atmospheric noise and provide surface displacement measurements with mill metric accuracy [2]. Unfortunately for the Ascending geometries there were too few images to apply the PSInSAR™ technique. It was possible to compute a single interferogram between two SAR images covering the same period of the Descending data-set. Thus no atmospheric noise compensation was feasible, with the effect of reducing the accuracy of the estimate of two components of displacement. In Figure 2 the cumulative Vertical and East-West displacement occurring from 2003 to 2007 is shown.



a) b)

Figure 2*: Cumulative Vertical (a) and East-West (b) displacement from 2004 to 2007.*

Looking at Figure 2 we notice how the deformation pattern in correspondence with well KB – 502 is different from the ones of wells KB – 501 and KB – 503. The vertical displacement over KB – 503 and KB – 501 is elongated in a north-northwesterly direction, suggesting preferential flow and volume changes at reservoir layer due to the injected CO2 [1]. Above injection well KB-502 there are, two lobes of uplift, suggestive of an opening of a tensile feature at depth [3]. In [1] and [3] the LOS displacement measurements have been already inverted for flow-related processes at the reservoir layer. In this work, we update our analysis having at our disposal the cumulative East-West and Vertical components of displacement, in particular we focus on well KB - 501.

Reservoir geomechanical characterization

The analysis carried out in [1], over well KB – 501, was based on the consideration that the reservoir is bounded above and below by lower permeability formations and contains natural gas. As a

consequence we expect that the twenty meters of Carboniferous sandstone, comprising the reservoir, will provide a stable conduit for the migration of the injected CO_2.
For this reason the model adopted, for the well under analysis, allows for volume changes within the 20 m thick reservoir interval, the elastic model for the overburden to use is provided by several well logs in the area [3].
Based on elastic theory, we divide our reservoir layer into a grid block so that to construct a linear system of equations mapping the two components of displacement, $\mathbf{u}_{EW}$ and $\mathbf{u}_V$, into volume change, $\mathbf{v}$:

$$\begin{cases} \mathbf{u}_{EW} = \mathbf{G}_{EW} \cdot \mathbf{v} \\ \mathbf{u}_V = \mathbf{G}_V \cdot \mathbf{v} \\ \mathbf{v} \geq \mathbf{0} \end{cases} \quad (3)$$

The elements of the matrices $\mathbf{G}_{EW}(i,j)$ and $\mathbf{G}_V(i,j)$ represent the sensitivity functions relating the j-th element of volume change grid block at location $\mathbf{x}_j$ to the i-th displacement measurement. Inequality constraints are incorporated into the linear inverse problem for volume change within the reservoir, under the assumption that the CO_2 injection only results in fluid volume increase. In [4] it was shown that the introduction of inequality constraint not only ensures a more physical solution but it also increases the spatial resolution of the estimates.

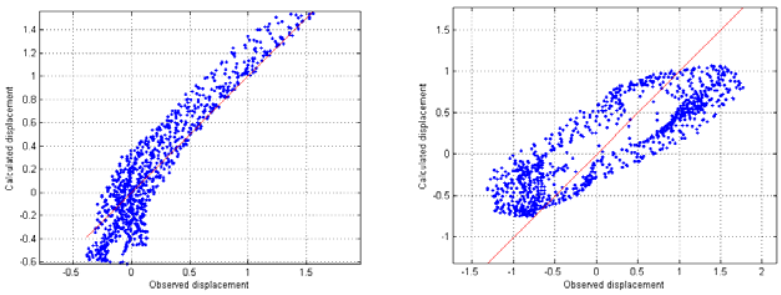


Figure 3 *Observed displacements plotted against displacement predicted by the inversion result for the Vertical component (a) and for the East-West component (b).*

In Figure 3 we plot the measured surface displacement and the displacement predicted using the estimated model parameters. It's evident that a model which contains only volume changes within the reservoir can explain the vertical component but not the horizontal. Thus, we generalized our model by allowing for the opening of an extended tensile feature representing a fault or, more likely, the opening of a damage zone at the reservoir depth. Through non-linear optimization we determined the dip angle, the strike angle and the location of the tensile structure. Then we divided it into a grid block of patches, each one 200 m long and 100 m width, in .order to solve for a linear problem:

$$\begin{cases} \mathbf{u}_{EW} = \mathbf{G}_{EW} \cdot \mathbf{v} + \mathbf{T}_{EW} \cdot \mathbf{d} \\ \mathbf{u}_V = \mathbf{G}_V \cdot \mathbf{v} + \mathbf{T}_V \cdot \mathbf{d} \\ \mathbf{v} \geq \mathbf{0} \\ \mathbf{d} \geq \mathbf{0} \end{cases} \quad (3)$$

where $\mathbf{d}$ represent the dislocation value of each fault patch; the elements of the matrices $\mathbf{T}_{EW}(i,j)$ and $\mathbf{T}_V(i,j)$ represent, instead, the sensitivity functions relating the dislocation of the
j-th fault patch to the i-th displacement measurement. To estimate all the sensitivity matrices we used a semi-analytic approach which allows for transversally anisotropic medium [5].

In Figure 4 we show the scatter plot between measured and calculated surface displacement for both the components, it's evident how the introduction of dislocation at the reservoir layer let it possible to fit, now, both the components.

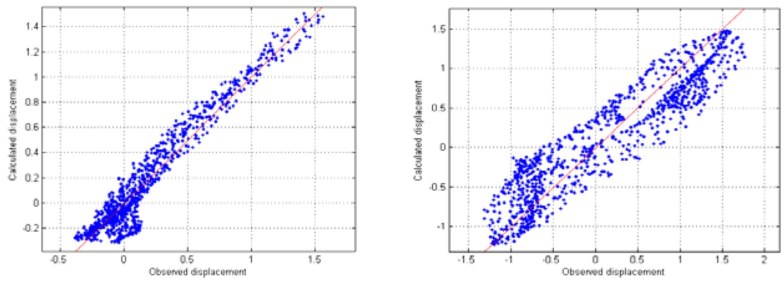


Figure 4 *Observed displacement plotted against displacement predicted by the inversion result for the Vertical component (a) and for the East-West component (b) when dislocation at the reservoir layer are allowed in the model.*

Conclusions

In this work we highlight the importance of using two components of displacement to better constraint an inversion for a distributed source model. Using only one component, the Line Of Sight one, it was possible to fit the data using a model based only on volume changes at the reservoir layer due to CO2 injection [1]. The introduction of a second component revealed the necessity to modify the model allowing for dislocation at the reservoir layer in order to fit both the components of displacement.

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