Inversion of time-lapse InSAR data for reservoir pressure monitoring: Example of the Kretchba field, Algeria

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Abstract

Time-lapse lapse interferometric synthetic aperture radar (InSAR) images provide accurate surface deformation over a large area and are sensitive to fluid injection/production at industrial scale. The quality and quantities of surface deformation time series open new opportunities for reservoir management. In this paper, we investigate the resolution of pore pressure change from InSAR highlighting some intrinsic features of such type of measurements (i.e. loss of resolution with distance to source). Depending on the relative ratio of the reservoir depth over the source length scales (e.g. reservoir extent), we propose two new robust inversion schemes consistently tackling the issue of loss of resolution without additional information: i) multipole moment decomposition for far-field case and ii) decomposition of the pore-pressure field change via Chebyshev series truncated at the order governed by the expected resolution.

The example of the Kretchba field illustrates our discussion. In particular, we show, using a far-field decomposition that the center of the pressure source remains in the reservoir layer around the KB501 injector and we recover quantitatively the direction of the flow anisotropy. We also discuss the direct inversion of the pore-pressure changes via Chebyshev decomposition. The requirement of a fast but accurate enough geomechanical model is emphasized in order to integrate time-lapse InSAR images with other conventional measurements for history matching purposes.

Introduction

Surface deformation measurement obtained via interferometric synthetic aperture radar (InSAR) is increasingly used in the context of reservoir monitoring (Arnaud, A. et al. (2009)). Time-lapse InSAR can provide surface displacement due to reservoir pressure changes at a millimetric resolution over a large area. Our goal is to review in detail the inversion of such surface displacement data. We believe that InSAR technology is a promising technique for reservoir management, if its advantages and drawbacks are properly understood – especially with respect to what details of the reservoir dynamics can be resolved and how.

In the course of this article, the Kretchba field operated by In Salah Gas, a joint venture between Sonatrach, BP and Statoil, will be used as an illustrating example. Large quantities of CO₂ (separated from the gas produced from that field) have been re-injected on the sides of the reservoir anticline below the water-gas contact since August 2004, in parallel with gas production in the central part of the anticline with the purpose of sequestering the greenhouse gas (Wright I.W. (2007)). This field example is very well documented and a large quantity of data is available (Mathieson, A. et al. (2010)). In particular, the desert terrain is very appropriate for InSAR (e.g. no seasonal changes of vegetation). 46 images from 2003 to February 2010 have been processed from the ENVISAT satellite. Synthetic Aperture Radar (SAR) images acquired by the ERS-1, ERS-2 and ENVISAT C-band satellites belonging to the European Space Agency (ESA), provide a wide coverage of 100 by 100 km, a high spatial resolution of 20 by 4 m and the availability of an extensive historical archive of SAR images beginning in 1991.
The information contained in each pixel of a SAR image consists of a complex number that can be represented by the amplitude and the phase components of the measured signal. The phase contains information related to the distance between the satellite sensor and the ground surface and it is used to estimate displacements through differential interferometry. The standard differential interferometry (DInSAR) methods compare two SAR images acquired at different moments in time over the same area, detecting ground surface deformations that have occurred between the acquisition dates of both images. DInSAR methods have limitations of temporal decorrelation – that is the loss of signal quality over longer periods and geometric decorrelation (i.e. the loss of coherence induced by subtly different viewing angles). These limitations have been partially resolved by the advanced DInSAR methods, the so-called Persistent Scatterers Interferometry (PSI) techniques. They make use of large sets of SAR images acquired at different moments in time over the same area, permitting observation of the temporal evolution of the displacement of every detected ground target with high precision and spatial resolution. The first PSI technique, called the Permanent Scatterers technique (PSInSAR\textsuperscript{TM}), was developed by Ferretti A. et al. (2001). Other authors have developed similar methods (Mora O. et al. (2003), Arnaud, A. et al. (2003), Werner, C. et al. (2003), Hooper, A. et al. (2004)).

Beyond the use of InSAR to detect possible abnormal movements such as aseismic fault reactivation due to injection or production, the quality and wide-area coverage of the time-lapse InSAR data fosters their use for quantitative reservoir management purposes. In particular, one is tempted to use these data to “image” reservoir pore-pressure changes over time as injection and production takes place in different parts of the field. A direct “brute force” inversion of surface deformation data to get reservoir pressure changes is however extremely ill-posed (i.e. very sensitive to noise and without a unique solution) therefore requiring the introduction of additional information (Fokker P. (2002), Du, J. and Olson, J.E. (2001), Morita N. (2003), Vasco, D.W. et al. (2000), Marchina P. (1996)) such as smoothing etc. We will review why such a direct inversion is not the best approach especially in light of the loss of resolution with distance intrinsic to elastostatic data such as InSAR surface displacement. Our goal is to quantify what is the information content of InSAR alone - i.e. without any additional information. This is a prerequisite in order to clearly understand the complementarity of InSAR with more conventional measurements made for reservoir management and history matching (e.g. bottom-hole pressure, breakthrough time etc.).

In particular, we test the use of far-field multipole moment decomposition in order to estimate macroscopic flow characteristics such as the pressure source center location, horizontal permeability anisotropy etc. from time lapse InSAR surrounding the KB501 injector at Kretchba. We also modify the classical full-field inversion of pore-pressure changes from surface displacement. We introduce a bi-dimensional Chebyshev decomposition of the reservoir pore-pressure field in order to properly take into account the constraint linked with the loss of resolution with distance therefore ensuring a robust inversion. The Kretchba field example will foster the discussion. In parallel with the analysis of time-lapse InSAR, we will also use the results of a large-scale dual porosity/dual permeability reservoir simulation of injection and production. This reservoir simulation has been history matched with well-head pressure and rates as well as CO\textsubscript{2} breakthrough time (Pamucku, Y. et al. (2010)). The results of this simulation are compared with the inversion of InSAR data.

**Ground movements due to reservoir pore-pressure changes**

The effect of fluid injection and production from subterranean formations on surface deformation (subsidence and uplift) is well-known in the oil and gas industry since the observation of massive subsidence over giant fields in the US in the first part of the twentieth century (Pratt, W.E. and Johnson, D.W. (1926)). The modeling of such effects can be traced back to the pioneering work of Geerstma, J. (1973). The prediction of the surface displacement at a point \( \mathbf{x} \) due to reservoir pressure changes can be written in terms of the following integral:

\[
\mathbf{u}_i(\mathbf{x}) = \iint_{\Omega_e} \epsilon(\mathbf{y}) \mathbf{U}_i(\mathbf{x},\mathbf{y}) \, d\mathbf{y} \quad i = 1, 2, 3 \quad (1)
\]

where \( \Omega_e \) is the domain which undergoes a volumetric eigenstrain \( \epsilon \) (i.e. a misfit of strain) due to a change in pore-pressure \( \Delta p \) with respect to the initial reservoir pressure:

\[
\epsilon(\mathbf{y}) = \frac{b \Delta p(\mathbf{y})}{3K} \quad (2)
\]

The reservoir Biot’s coefficient and drained moduli are denoted \( b \) and \( K \) respectively, while \( \mathbf{U}_i(\mathbf{x},\mathbf{y}) \) is the fundamental solution for the displacement in the \( i^{th} \) direction at the observation point \( \mathbf{x} \) produced by a unit infinitesimal center of dilation located in \( \mathbf{y} \).
Such a fundamental solution is known analytically only for simple domain such as the homogeneous isotropic and transverse isotropic half-space. Numerical solution for a layered medium is also possible. More generally, one can always use a numerical simulator to obtain such a fundamental solution. In the case of the homogeneous half-space, the fundamental solution only weakly depends on the Poisson’s ratio of the medium. We will use the homogeneous half-space model in the following discussion and explain its shortcomings at the end.

The reservoir properties (Biot’s coefficient and drained bulk moduli) may, in some cases, be poorly known. If it is the case it is then better to invert for the volumetric eigenstrain field in order to avoid any bias in the reconstructed pore-pressure field introduced by a poor geomechanical characterization. This is what we will do in the following, alternatively mentioning pore-pressure changes or volumetric eigenstrain as responsible for surface displacement, the two quantities being related by (2). One should also note that InSAR measures the displacement of the surface along the line of sight vector which is defined by the satellite trajectory. The only rigorous way to compare predictions to InSAR observations (i.e. without any assumptions on surface displacement) is to project the predicted displacement vector on the line of sight vector \( (v_t^{OS}) \): \( u^{InSAR}(x) = u_t(x) \cdot v_t^{OS} \). In the following, we simply denote \( u = u^{InSAR} \) the displacement predicted along the line of sight vector with positive displacement toward the satellite. Similarly, we will denote \( U(x, y) \) as the displacement along the line of sight vector at \( x \) due to an infinitesimal point source located in \( y \).

In view of the reconstruction from surface displacement of the reservoir pore-pressure changes, it is of prime importance to grasp the intrinsic behavior of the integral (1). The details of the shape of the reservoir get smoothed away very quickly due to the property of the elasticity equation (i.e. St Venant’s principle) such that the observed displacement may only depend on integrated quantities (e.g. total pressurized volume). It is indeed possible to show that for a reservoir with a maximum characteristic length \( l \) (e.g. reservoir horizontal extent), the displacement at point \( x \) located at a distance of more than twice the characteristic lengthscale of the reservoir center of mass \( c \) is strictly equal to the displacement induced by an infinitesimal center of dilation located at \( c \) with an intensity equal to the integrated pressurized volume. This result is often referred to as the far-field asymptote (Lecampion, B. et al. (2005)):

For any \( x \) such that \( r = \| x - c \| > 2l \)

\[
   u(x) = U(x, c) \times \iiint_{\Omega} \epsilon(y) \, dy + O \left( \frac{1}{r} \right)^2 \quad (3)
\]

This result is important to bear in mind in view of the reconstruction of pore-pressure changes from surface displacement. One will not be able to reconstruct details of the pore-pressure within the reservoir if the ratio between the depth \( d \) of the reservoir (i.e. putting \( d = r \) in the previous expression) and the pressure changes extent \( l \) within the reservoir is larger than 2. It is also important to note that such a far-field asymptote is intrinsic to elastostatic and does not depend on the complexity of the model: a layered medium will exhibit a similar loss of details with distance than a homogeneous half-space.

**Far-field Multipole Moment Expansion**

In reality, such a ratio \( r/l \) will evolve during the life of the reservoir: the length \( l \) will increase as more fluid is produced and/or injected, so that \( d/l \) will decrease with time and more details may become resolvable from surface displacement data. Recognizing that the surface observations are always outside the reservoir, it is interesting to investigate a multipole moment expansion of the original integral (1) for a point located in the far-field with respect to the reservoir. Such a far-field multipole expansion is similar to a Taylor expansion and reads for any point \( x \) away from the reservoir (See (Lecampion, B. and Peirce, A. (2007)) for more details in the case of fractures):

\[
   u(x) = \sum_{k, \ell, m=0}^{\infty} \frac{1}{k!\ell!m!} \frac{\partial^{k+\ell+m} u(k, l, m)}{\partial y_1^k \partial y_2^\ell \partial y_3^m} \bigg|_{y=c} \times \iiint_{\Omega} (y_1 - c_1)^k (y_2 - c_2)^\ell (y_3 - c_3)^m \epsilon(y) \, dy \quad (4)
\]

One can always truncate such a series expansion at a given order. In particular, the zeroth order term correspond to the far-field asymptote (3). As the observation point moves closer to the pressurized volume, more and more terms in the series are needed to represent the displacement at the observation point which corresponds to the fact that more and more details of the source affect the displacement (Lecampion, B. and Peirce, A. (2007)). The coefficients of this series correspond to the harmonic moment of the
pressurized volume \( M_{klm} = \iiint_{\Omega} (y_1 - c_1)^k(y_2 - c_2)^l(y_3 - c_3)^m \epsilon(y) \, dy \). These harmonic moments are integrated characteristic of the finite source. The zeroth order term corresponds to the volume of the pressurized reservoir, the first order term to the location of the center of mass of the pressurized reservoir, the second order terms relate to the length scales in the different directions etc. The validity of the expansion truncated at a given order depends on the same ratio \( r/l \) previously defined for the far-field asymptote. In the case where the observation point is located in the near-field of the source (e.g. \( r < l \)), such a Taylor expansion requires an infinite number of terms to converge and is thus of limited interest. However, as previously mentioned, for InSAR reservoir monitoring, one will in most cases be in between the far-field (\( r > 2l \)) and the near-field limit (\( r < l \)) such that the use of such a series expansion truncated at a conveniently small order can become useful. This is particularly true for the case where the fundamental solution \( U(x, y) \) is known in analytical form (e.g. the homogenous half-space). The forward model is then extremely fast and suitable for an inversion scheme.

For a truncation at a given order \( N \), the prediction of all the measured displacements stacked in a column vector \( \mathbf{u} \) are linearly related to the vector of the harmonic moments of the source \( \mathbf{M}_N \) whose size depends on the truncation order

\[
\mathbf{u} = \mathbf{E}_N(\mathbf{c}) \cdot \mathbf{M}_N \quad (5)
\]

One row of the matrix \( \mathbf{E}_N(\mathbf{c}) \) contains the different derivatives of the series expansion (4) estimated at a given observation point. This observation matrix depends non-linearly on the center \( \mathbf{c} \) of the pressurized volume. Due to the low computational burden of the multipole decomposition, one can therefore invert for both the location of the finite source center and the harmonic moments of the source.

**InSAR data processing at Kretchba**

Let’s now briefly review the processing of InSAR data. The Stable Point Network technique (SPN) has been used for analysing the motion of the Kretchba field from InSAR images. The SPN technique has been used to process the SAR images data set acquired by ENVISAT covering the temporal period from 2003 – 2010. The SPN technique is an advanced differential interferometric processing technique (Arnaud, A. et al. (2003), Duro, J. et al. (2005)). It is the result of several years of research projects in the DInSAR data analysis field carried out for the CNES (French Space Agency), ESA and Altamira Information SL. The SPN processing chain was the first advanced interferometric processor capable of merging the new ASAR data with the historical ERS-1/2 data (Arnaud, A. et al. (2003)). This technique uses the DIAPASON interferometric chain, developed by the French Space Agency (CNES) for all SAR data handling, e.g. co-registration work and interferogram generation.

Figure 1 gives an overview of the SPN processing chain: the SPN procedure generates three main products starting from a set of SLC SAR images: the subsidence rate that can be derived using a data set of at least 6 images, a map of height error, and finally, the displacement time series, which requires at least 20 images depending on the velocity of displacement with respect to the temporal separation of image acquisitions. An increase in the number of SAR images improves the quality of the measurements providing an error of 1mm/year for subsidence rates and 2 m for height errors. The basis of the SPN technique is the separation of the different components from the interferometric phase, \( \Phi_{\text{INTERF}} \): the topographic component, \( \Phi_{\text{Topo}} \), the movement component, \( \Phi_{\text{mov}} \), the atmospheric contribution, \( \Phi_{\text{APS}} \), and the noise component, \( \Phi_{\text{noise}} \):

\[
\Phi_{\text{INTERF}} = \Phi_{\text{Topo}} + \Phi_{\text{mov}} + \Phi_{\text{APS}} + \Phi_{\text{noise}}
\]

Hence, the SAR dataset is processed taking into account the physical behaviour of the characterized effects, considering the reflection of the radar signal and the acquisition geometry. Finally, the atmospheric artefacts can be estimated and removed from all the interferometric pairs as low spatial wavelength effects (Hanssen, R.F. (2001)). A high frequency analysis of the data is then carried out in order to extract the profiles with the temporal evolution of the displacement for any point selected by the user.

The SPN algorithm can either work at full resolution (4 by 20 m for Envisat) selecting the measurement points by analysing the amplitude of the set of SAR images, or at reduced resolution (e.g. 40 by 40 m) selecting the pixels or ground surface Persistent Scatterers (PS) by interferometric coherence. In this case, the full resolution Envisat data was used and pixels were selecting using both an analysis of the amplitude and interferometric coherence.
Multipole inversion of surface uplift around the KB501 injector

We now use the multipole moment decomposition previously introduced to invert time-lapse InSAR measurements recorded around the KB501 CO₂ injector at Kretchba from the beginning of the injection at the end of July 2004 up to February 2010. We will use a subset of the InSAR scatter data within a zone up to 5 kilometers from the location of the KB501 injector (see Figure 4).

A signal-to-noise ratio defined as the ratio between the mean and the standard deviation of the cumulative displacement of all the data around KB501 is useful to grasp when ground motion event starts to be visible around KB501. We can see on Figure 2 that such a ratio becomes larger than 0.15 in the middle of 2005 (a bit less than a year after the start of the injection). All the results that will be discussed thereafter are from the analysis of time-lapse images from May 2005 to February 2010.

We use a classical Bayesian inversion scheme (Tarantola, A. (2005)) to invert for the location of the source center and the harmonic moments of source from the scatter InSAR data. Due to the non-linear dependence of the prediction on the source center location, we use a non-linear optimization scheme on the center location while the harmonic moments for a given source center are obtained by a pseudo-inverse scheme of the matrix $E_{\varepsilon}(\varepsilon)$ of eq. (5) using a singular value decomposition. Moreover, we perform such an inversion scheme at different time for different order of truncation of the multipole moment decomposition from the zeroth (a single harmonic moment) up to the fourth order (35 harmonic moments). We use the Bayesian Information Criteria (BIC) to compare the results of the inversion obtained with the different orders in order to choose the best “model” (i.e. the model with the highest likelihood and the lowest number of model parameters): $IC = -log \hat{n}_k + k \log N_d$, where $\hat{n}$ is the mode of the posterior pdf for model $k$ which has $k$ parameters, $N_d$ is the number of data points. A lower BIC for model A compared to model B favors model A. We do not input any a-priori information on the harmonic moments; however, the center of the source is a-priori correlated with the location of the horizontal injector. We use the center of the horizontal section of the KB501 well as the a-priori for the center of the source location. The pressure disturbance may migrate upward in the cap-rock with time while its migration downward is less likely. We therefore use a skewed Gaussian pdf to represent the uncertainty on the vertical coordinates of the source, while the uncertainty on the horizontal location of the center is modeled by a Gaussian pdf with standard deviation of 200 meters from the center location.

Comparison between different orders of the decomposition

Figure 3 displays the evolution with time of the Bayesian Information Criteria (BIC) for the five different orders of truncation. It is interesting to note that as soon as the displacements are sufficiently larger than noise, the third and fourth order are always the best models and the gap with the lower order truncation steadily increases with time. This indicates that we see more than the far-field effect. One also has to note that the third and fourth order gives completely similar results both in terms of fit and in terms of the values of the harmonic moment estimated. We will only discuss the results obtained with this high order series in the following. A comparison between data and the best prediction can be grasped on Figure 4 for the June 2009 image.

Flow characteristics from the multipole moment inversion

First of all, it is important to note that the source center obtained from the inversion remains within the reservoir layer as can be seen on Figure 5. This indicates that most (if not all) of the pressure disturbance due to the injection remains in the reservoir layer and has not severely migrated upward. We can however note a horizontal shift of about 1.3 kilometer from the horizontal section of KB501 used for the injection. Such a shift was obviously not visible on the history matched reservoir simulation available. Interestingly, this horizontal shift does not significantly vary with time.

It is interesting to note the relatively good linear correlation between the estimation of the first-order moment $M_x$ and the cumulated injected volume for the different dates of the InSAR images (Figure 6). This was to be expected as the size and magnitude of the pore pressure changes directly depends on the injected volume.

The second order moments typically captures the length-scales of the source in different directions, therefore possibly detecting anisotropy. This is the case here. We have plotted in Figure 7 the ratio of the eigenvalues of the horizontal second order moment matrix $M_{\parallel} = [M_{xx}, M_{xy}; M_{xy}, M_{yy}]$. This ratio appears to increase with time indicating an increasing horizontal anisotropy. However, it is interesting to note that if we compute a similar ratio from the results of the history matched reservoir simulation of this injection, we obtain a higher ratio (about 9) which remains relatively constant. The ratio obtained from the reservoir simulation is obviously intrinsically related to the horizontal permeability anisotropy input in the model. The direction and magnitude of the permeability anisotropy used in the model was obtained by standard analysis of FMI images, and calibrated using bottom-hole pressures, production rates and arrival times. It appears therefore that the permeability direction of anisotropy
(obtained from the geometry of fractures) is more constrained than its magnitude.

We can also compute the orientation with respect to North of the eigenvector of the horizontal second order moment matrix $\mathbf{M}_H$. It indicates the direction of the horizontal anisotropy of the source. This direction actually corresponds well to the known direction of the natural fractures in Kretchba (North 135°) as can be seen on Figure 8. The results of the inversion also compare well with the same direction calculated from the reservoir simulation results.

It is also interesting to compare the first order moment $M_o$ estimated from INSAR and the one computed from the reservoir simulation results. In the case of the reservoir simulation, without making any assumption on the Biot’s coefficient and moduli of the reservoir, we may compute the following zero order moment: $\bar{\mu}_o = \iiint_{\Omega} \Delta p(x') \, dx'$. In Figure 9 we have plotted the ratio $\bar{\mu}_o/M_o/3$ which in principle should be equal to $K/b$. If one assumes a Biot’s coefficient of unity which for a fractured reservoir at large scale is realistic, one in principle should recover the drained bulk moduli of the reservoir. The results depicted in Figure 9 are of the right order of magnitude but increase with time. Several causes can possibly explain such a puzzling result. First, in the case of fractured reservoir such as Kretchba it is possible that the large scale drained moduli exhibits a non-linear dependence with effective stress. However, one would expect a decrease of the drained moduli with a decrease of the effective stress (i.e. open fractures render the material more compliant at large scale) which is clearly not the case. One has also to recall that the moment decomposition was performed for a homogeneous isotropic half-space. In the case of a harder or softer overburden, the well known arching phenomena can have a prominent effect on the extension and magnitude of surface displacement. The forward model used here does not account for any arching such that the inversion results (e.g. first order moment etc.) may be polluted by such a forward “model error”. Finally, it may also be possible that we are in a near-field situation where higher orders terms (i.e. higher than fourth) are needed in the multipole moment decomposition in order to obtain convergence. The use of the fourth order series may not be sufficient and the inversion results may be polluted. However, one has to remember that the results for the third and fourth orders are strictly similar, which hints to convergence of the serie.

It is important to emphasize how the use of the multipole moment decomposition has allowed us to estimate macroscopic characteristic of the flow within the reservoir such as horizontal anisotropy, center of mass location, first order moment (pressurized volume) at a very low computational cost. Moreover, the inversion of displacement data using such decomposition is stable and robust.

**Full-field inversion of ground motion at the Kretchba field**

We have seen that the moment decomposition was able to provide relevant information with respect to the injection around KB501. The fact that a high order expansion was needed to reproduce the measured displacement means that resolution of finer details of the pore-pressure field may be possible. We now revisit a full-field inversion of the eigenstrain field from surface displacement.

**Discretization of the reservoir**

It is common practice in reservoir engineering to discretize the reservoir using pillar grids. The displacement on the surface can thus be numerically estimated as a function of each cell pore-pressure changes after discretization of eq.(1) as:

\[
 u(x) = \sum_{j=1,N\text{grid}} \epsilon_j \iiint_{\text{Cell}_j} u(x,y) \, dy
\]  

where $N\text{grid}$ is the number of grid cell and $\epsilon_j = \frac{h \, \Delta p_j}{3 \, K}$ is the volumetric eigenstrain in cell $j$ directly function of the pore-pressure changes. Such a discretization directly leads to a linear system relating surface displacement at a number of measurements points to eigenstrain (and thus pore-pressure changes) in the reservoir grid cell $u = A \cdot e$, where $A$ is a rectangular observation matrix containing the effect of a unit volumetric eigenstrain in each cell on the surface displacement at each measurements point. Such a discretization is typically done when inverting InSAR data but is far from adequate if one does not take into account the intrinsic loss of information with the observation distance rooted in the far-field asymptote. The far-field asymptote indeed allows estimating the minimum size of a cell in the grid on which pore-pressure changes can be resolved from surface measurements. Denoting by $h$ the grid-size lengthscale, we obtain that one can resolve pore-pressure changes within a grid only if the ratio $d/h$ is lower than two – where $d$ is the reservoir mean depth. Such a ratio provides a optimistic estimate of the minimum grid-size one should use: $h_{\text{min}} \sim d/2$. In the case where the grid size is smaller than such a limit –which is almost always the case – the direct
We prefer to decouple the intrinsic problem of the loss of resolution from the size of the grid, mostly in order to keep the same grid between the reservoir simulator on which transport is solved and the grid used for InSAR inversion. We thus decompose the pore-pressure field using a 2D Chebyshev polynomial series over the reservoir grid. A horizontal bi-dimensional decomposition is sufficient in the case of Kretchba as the reservoir is thin (~20 to 40 meters) compared to the reservoir extent and depth. The order of the Chebyshev decomposition can be directly chosen from the minimum size \( h_{\text{min}} \) of the pore-pressure changes that can be resolved. We truncate the Chebyshev series at order 16, which corresponds for the extent of the reservoir grid used to a resolution of approximately 1.1km (~reservoir depth/2 as one can expects). Being a linear combination of polynomials, the Chebyshev series directly imposes smoothness of the solution, while guaranteeing that every “shape” of pressure distribution can be represented by a suitably long series. It is worthwhile to note that such a Chebyshev decomposition of the pore-pressure field condenses the information that is resolvable by InSAR. The dimension of the linear system linking the weight of the Chebyshev decomposition and the observation is also much smaller than the original system linking the volumetric eigenstrain in each cell to the measured displacement (16 coefficient vs. n 1000’s of cells). It is also important to note that when using the reservoir grid, one implicitly assumes no pore-pressure disturbance outside the reservoir and an undrained response of the surrounding medium.

The Southern part of the Kretchba field

We will focus on the southern part of the Kretchba field containing all the production wells and the KB501 injector. We do not investigate the northern part of the field where the effect of CO\(_2\) injection from the KB502 and KB503 wells have been discussed in other works (Vasco, D.W. et al. (2008)). The inversion of the Chebyshev coefficients of the decomposition is done for each time-lapse InSAR images independently. Figure 10 displays the measurement and prediction of the January 2010 image. The match is always within the measurement error (i.e. 2.5 mm). Similarly to the inversion of KB501 data, we actually image the eigenstrain field \( \epsilon \) and not directly the pore-pressure changes. Assuming again a value of one for the reservoir Biot’s coefficient, we estimate a ball-park figure of the drained bulk moduli by taking the covariance between the vector of the eigenstrain inverted from InSAR and the vector of pore-pressure changes in all the cells of the reservoir. This is done for each time-frame. The time evolution of such a macroscopic drained bulk moduli identified from InSAR and the reservoir simulation results can be seen on Figure 11. It is interesting to note that this estimated bulk moduli remains constant and is of the order of magnitude of the drained bulk moduli of such a naturally fractured reservoir (Zou, J. et al. (2011)). This constant value appears more realistic than the one obtained from the multipole moment decomposition (Figure 9), hinting again that in the case of Kretchba, one may be in an intermediate to near-field case. The estimate of such a modulus allows scaling the results of the inversion for an easier comparison of the pore-pressure field with the reservoir simulation predictions.

Having such a modulus in hand, we can compare the reservoir pore pressure change from the inversion of InSAR data and the reservoir simulation results. Figure 12 displays both fields for January 16, 2010. We clearly see that the match is far from perfect although the location of the pressure spikes associated with KB501 and to a lesser extent to the southern injector KB1 are captured. The other drops associated with production are not as visible. The geometry and magnitude of the pressure spike associated with KB501 is much larger than the prediction from the reservoir simulation. A similar observation holds for the producer wells. This mismatch is most probably due to the simplifying assumption of a homogeneous overburden while inverting the InSAR data. In reality, a stiffer overburden (compared to the reservoir) will lower the maximum surface displacement from an injector and widely spread the impact of the pore-pressure disturbance horizontally. The inversion presented here is thus most probably polluted by the modeling error associated with the hypothesis of a homogeneous half-space. Moreover, it appears from advanced geo-mechanical modeling that the reservoir compliance non-linearly depends on the effective stress such that the response of the producing zone differs strongly from the injection area around KB501 (Zou, J. et al. (2011)).

Relevance for Reservoir Management

From the results presented previously, it is clear that time-lapse InSAR data provide useful information for history matching of a reservoir model. The overall response of the surface displacement is linked at the first order to the produced and injected volume and these can be clearly captured by the inversion of time-lapse InSAR data. However, as usual, the difficulty is in the details. The details of the pressure source carried by the displacement field are smoothed out with distance, thereby intrinsically limiting the information content of elastostatic data such as ground motion from InSAR. In some ideal cases where the ratio between reservoir depth and horizontal extent is smaller than one, the spatial shape of the eigenstrain field can be reconstructed, although at
a resolution coarser than the typical reservoir grid. In other cases, macroscopic characterisitics of the flow dynamics can still be estimated (e.g. source intensity, anisotropy etc.). The inversion of InSAR data alone is not to capture the absolute value of the pore-pressure changes in the absence of a proper geomechanical characterization. The quality of the geomechanical characterization affects to the first order the conversion of the eigenstrain field into pore-pressure changes using eq. (2).

It is interesting to note that, in the case where a history-matched reservoir simulation is available, the order of magnitude of the reservoir moduli can be estimated from InSAR and reservoir simulation prediction. In practice, one obviously needs to have an independent geomechanical characterization (elastic properties) in order to quantitatively link reservoir pore-pressure changes to surface displacement. We have not done so here in order to grasp what can be obtained from InSAR alone. We believe this a pre-requisite in order to understand the real information content of InSAR.

It is clear that the combination of InSAR with downhole pressure gauges and others typical data (production logging etc.) will surely make possible to better constrain the measurement of the pore-pressure changes associated with production and injection. Time-lapse InSAR also appears complementary to 4D seismic surveys which are typically more sensitive to saturation changes than pore-pressure changes. It would thus make sense to integrate time-lapse InSAR observations with other conventional measurements in a history matching workflow. Ultimately, time-lapse InSAR data provide either integrated quantities on the pore-pressure disturbance using the far-field multipole moment decomposition in the case of far to intermediate field configuration ($d/l > 1$) or a reconstruction of the pore-pressure at a resolution coarser than the reservoir simulator grid ($\sim d/2$). These quantities can be integrated in a history matching scheme such as Extended/Ensemble Bayesian Kalman Filter or any other type of algorithm dedicated for that purpose. Without entering into too much detail with respect to the computational burden of such techniques, it is clear that ideally the inversion of InSAR data between two time-lapse images should at most not exceed the computational burden of the reservoir simulator between these two dates. A requirement which will be fulfilled if the geomechanical forward model has the right amount of complexity and if a proper inversion scheme that recognizes the loss of information with distance are used. For example, the multipole moment inversion is very cheap computationally speaking - about 10 to 15 minutes for the inversion of one image with no code optimization- compared to a full 3D geomechanical model for which one forward computation may take hours, such that the inversion of one InSAR image may take days. On the other hand, the simple homogeneous half-space may not capture important structural heterogeneities affecting the surface response to the first order. The principal difficulty thus lies in the choice of the right level of complexity required for the geomechanical model of the overburden. One has to strike a balance between simple but fast models and un-necessarily complex and slow to run models. The effect of arching due to the properties contrast between the reservoir and the overburden needs to be properly included in order to ultimately recover the proper spatial shape of the pore-pressure changes. This can be dealt with either a layered model – although the computational burden might be large even with spectral methods such as the one described in (Peirce, A. P. and Siebrits, E. (2001)) – or possibly via an adequate upscaling of the layering into an effective anisotropic medium akin to the Backus average used in seismic.

**Conclusions**

The Kretchba field is ideal for InSAR monitoring: desert terrain, large injection and production therefore high signal to noise ratio of the satellite data. Even in this ideal case, we have seen that the quantitative use of such data requires much more than “brute force” inversion. The intrinsic loss of resolution with distance associated with quasi-static elasticity will always be present and must be properly acknowledged in order to provide relevant answers to the reservoir engineer. Such a loss of resolution can however be properly tackled and quantitative features recovered depending on the reservoir configuration.

It is particularly important to distinguish three distinct configurations with respect to level of resolution on the pore-pressure disturbance that one might obtained from InSAR. For a reservoir of depth $d$ and a pressure disturbance of size $l$, i) in the far-field ($d > 2l$), such as early in the life of a field, one can only grasp the zeroth order moment of the pressure disturbance and its location, ii) in the intermediate field as $l$ approaches $d$, more and more harmonics moments of the source can be obtained (e.g. anisotropy) and iii) in the near field case ($l > d$), the pore pressure change in the reservoir can be imaged at a resolution equal to the half the reservoir depth ($d/2$). In the case of Kretchba, it appears that we are most probably in between an intermediate and near-field configuration. Depending on the configuration, different techniques must be used to ensure a robust inversion: either different order far-field multipole decomposition of the source integral (for intermediate and far-field cases) or by adequate Chebyshev decomposition of the pore-pressure field in the near-field case. Both techniques condense the right level of information content on the pore-pressure changes that may be recoverable from surface displacement data. It results in extremely robust inversion schemes without the need of strong a-priori information.

The question of how much details of the geology needs to be included in the geomechanical model has been partly discussed with respect to the well-known arching effect (properties contrast of the reservoir and overburden). It definitely requires more work. It
is possible that because the surface displacement induced by downhole fluid pressurization are not sensitive to small scale features, a homogenized medium may be effective to properly relate reservoir pore-pressure changes and induced surface displacement at a low computational cost – a requirement for the integration of InSAR data in any history matching scheme for reservoir management.

References


Figure 1: Main flow chart of the Stable Point Network processing chain.

Figure 2: Mean over standard deviation of all InSAR data points for the different time-lapse images around KB501. Such a "signal-to-noise" ratio increases as more fluid is injected with time.
Figure 3: Evolution of the Bayesian Information Criterion with time during the injection at KB501 for five different orders of truncation of the multipole series.

Figure 4: Cumulative displacement around KB501 from December 2003 to January 2010: InSAR data (left) and best prediction from the inversion using the fourth order multipole moment decomposition (right). The InSAR data presented here are scattered data with minimal processing.
Figure 5: Locations of the center of the source estimated from the inversion of InSAR images from 2005 to 2010

Figure 6: Cumulated injected volume versus estimated first order moment from time-lapse InSAR images (Correlation of 0.62).
Figure 7: Ratio of the eigenvalue of the horizontal second order moments matrix around KB501 inverted from InSAR images at different dates. The horizontal anisotropy appears to grow with time.

Figure 8: Direction of the horizontal anisotropy of the source with respect to North defined as the principal vector of the 2nd order horizontal moments matrix.
Figure 9: Ratio of the pore-pressure first order moment computed from reservoir simulation results over the estimated eigenstrain first order moment inverted from time-lapse InSAR images. This ratio should be theoretically equal to $K/b$.

Figure 10: Cumulative surface displacement along the line of sight vector from December 2003 to the 16th January 2010: InSAR data (left) and best prediction from the InSAR inversion (right).
Figure 11: Estimate of the drained bulk moduli from the standard deviation of the pore-pressure field changes from the reservoir simulation and the eigenstrain field inverted from InSAR (assuming b=1) for the different dates where InSAR is available. Note that at early time after the start of the injection, the low signal-to-noise of InSAR affect the results.

Figure 12: Reservoir pressure changes (from the initial state) in January 2010: history-matched ECLIPSE simulation (left) and results of the inversion of InSAR data scaled by the large scale drained moduli previously identified.