Monitoring the fate of injected CO$_2$ using geodetic techniques

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Abstract

Geodetic methods comprise one class of geophysical data that are sensitive to changes in effective pressure within operating reservoirs, albeit indirectly through induced deformation. Geodetic observations, which have observation intervals that vary from seconds to days, weeks, or months, generally provide more frequent sampling compared to existing geophysical methodologies (such as seismic time-lapse monitoring), which typically invoke repeat times of months to years. These differences in sampling intervals are primarily due to the extensive effort, and hence cost, of conducting geophysical field operations, which often precludes executing a large number of surveys. Satellite-based interferometric synthetic aperture radar (InSAR) is cost effective and used in many applications, including monitoring the injection of carbon dioxide (CO$_2$) for both long-term storage and enhanced oil production.

An application to the geologic sequestration of CO$_2$ in Algeria revealed northwest migration along a fault/fracture zone intersected by the injection well. A study in a Texas field demonstrated that enhanced oil recovery utilizing CO$_2$ leads to observable surface deformation that may be used to characterize the sequestered CO$_2$ and to estimate the pressure changes within the reservoir induced by injection and production.

Introduction

The injection of carbon dioxide (CO$_2$) into the subsurface, both for long-term storage of greenhouse gases and as a method for enhanced oil production, presents a number of unique challenges. In general, due to viscosity and density effects, the behavior of CO$_2$ in the subsurface can be very different from that of injected water. For example, gravitational forces can produce significant vertical movement, as observed at Sleipner. The associated fluid flow may be relatively rapid, and density effects can grow as fluids migrate upward. Such complicated behavior can be problematic for efforts such as geologic storage, where strict accounting and long-term stability are important, and in enhanced oil recovery (EOR) efforts due to the costs associated with injected CO$_2$.

Geophysical monitoring is critical in detecting deviations from the expected movement of injected CO$_2$. The monitoring requirements for geologic storage can be quite different from those for EOR. The sequestration of CO$_2$ is a long-term affair, and the well configuration is often fixed early, if not at the start of the effort. The injected volumes can be large, leading to significant changes in in-situ pore pressure and the stress field in and around the injection sites. Rapid sampling in time is required at the onset of injection in order to understand the fluid flow away from the well and to identify those regions to which the CO$_2$ is migrating. During EOR, the well geometry can be changing constantly due to evolving information and changes in production strategy. Therefore, frequent time-lapse imaging is highly desirable to maintain effective recovery of the oil in place. Seismic imaging and microseismic monitoring are two of the more common techniques for tracking the movement of CO$_2$ in the subsurface. However, seismic imaging can be expensive, and even though sparse permanent arrays are sometimes available, they are not commonly used for frequent time-lapse imaging. Microseismic methods can be cost effective, but the injection of CO$_2$ may not produce ample seismicity, and the events are only indirectly related to the injected fluids through changes in stress in the subsurface.

Geodetic techniques, in which displacements are measured at the earth’s surface or in the overburden above a reservoir, are another geophysical tool for monitoring injected CO$_2$. They typically have favorable temporal sampling, with observations gathered every few minutes to days or weeks apart. Geodetic observational methods are often cost effective in comparison with seismic surveys, particularly with the availability of interferometric synthetic aperture radar (InSAR) data from orbiting satellites (Ferretti, 2014). Observations of surface deformation do not provide the resolution of seismic reflection imaging, but they can be combined with other measurements and/or used with a detailed reservoir model to provide useful information on CO$_2$ movement.

In this paper, we outline how geodetic methods may be used to monitor the injection and storage of CO$_2$, and we provide two examples of recent monitoring efforts.

Observational methods

Overview. Most geodetic methods can be categorized roughly into point-measurement techniques (such as tilt and global navigation satellite systems [GNSS]) and scanning methods, of which InSAR and light detection and ranging (LiDAR) systems are prime examples (Eitel et al., 2016). A new technique that bridges these two classes of observation methods to some degree and is currently under active development utilizes fiber-optic cables for strain measurements (He et al., 2013). Point observation methods typically provide much better temporal resolution, with samples gathered seconds to minutes apart, at the expense of spatial density. Scanning systems, which send an electromagnetic signal to a target and record the return, provide excellent spatial sampling but are usually gathered at time intervals of days to months apart. Local LiDAR systems, such as those used for engineering applications, can be sampled at much higher rates approaching those of...
point methods. A third category of observations derives from time-lapse seismic monitoring (Landro and Stammeijer, 2004). Specifically, one may extract geodetic information from the movement of reflectors in the time interval between two seismic surveys and velocity variations due to stress changes (Tura et al., 2005; Hodgson et al., 2007; Staples et al., 2007). In what follows, we will outline two of the more commonly used techniques, InSAR and GNSS, in more detail.

**Synthetic aperture radar interferometry.** InSAR methods rely on the phase delay of a reflected microwave or radar wave to estimate the displacement of points on the earth’s surface (Figure 1). Both airborne and satellite-based systems are available, and the methodology is now well established and widely used to map deformation of the earth’s surface (Ferretti, 2014). The accuracy of InSAR measurements depends on a variety of factors, including spatial (i.e., the distance between subsequent satellite passes) and temporal (i.e., the time span between two acquisitions) baselines, satellite wavelength, land cover, and atmospheric conditions. To better understand the nature of InSAR observations, consider the phase of a pulse reflected from a point on the earth—a single pixel in a SAR image (Figure 1). The phase value \( \varphi \) of a pixel \( P \) of a radar image can be modeled as a mixture of four distinct contributions (Ferretti et al., 2001):

\[
\varphi(P) = \varphi + \frac{4\pi}{\lambda} r + a + n, \tag{1}
\]

where \( \varphi \) is the phase shift related to the location and to the reflectivity of all elementary scatterers within the resolution cell associated with pixel \( P \). The coefficient \( 4\pi / \lambda \) is the most significant contribution in any geometric application, as it is associated with the sensor-to-target distance or range \( r \). The term \( a \) is a propagation delay introduced by variations in the earth’s atmosphere. This quantity is often the main source of error and can compromise the quality of any distance estimate. The last term, \( n \), is a phase contribution related to system noise, such as thermal vibrations, quantization errors, etc. The phase values contained in a single SAR image are of little practical use, as it is impossible to separate the different contributions in equation 1 without prior information. The basic idea of SAR interferometry is to measure the phase change, or interference, over time between two radar images, generating an interferogram \( I \):

\[
I = \Delta\varphi(P) = \Delta\varphi + \frac{4\pi}{\lambda} \Delta r + \Delta a + \Delta n. \tag{2}
\]

If we consider an idealized situation where the noise is negligible and the surface character and atmospheric conditions are constant between the two SAR acquisitions, equation 2 reduces to

\[
I = \Delta\varphi(P) = \frac{4\pi}{\lambda} \Delta r. \tag{3}
\]

Therefore, if a point on the ground moves during the time interval between the acquisition of the two radar images with similar geometry, the distance between the sensor and the target changes, creating a phase shift proportional to the displacement (Figure 1).

The literature on InSAR techniques and applications is vast, and several techniques have been developed to improve the calculation of range change. Two of the more promising approaches that have led to estimates with a precision of several millimeters are permanent or persistent scatterer techniques and small baseline analysis. Both methods use a sequence of interferograms to overcome the limitations of conventional InSAR analyses, namely phase decorrelation (i.e., possible changes in the radar signature over the area of interest, the term \( \Delta\varphi \) in equation 2) and atmospheric effects. The first method relies on identification of point-wise, coherent radar targets, often referred to as permanent or persistent scatterers (Ferretti et al., 2001). Permanent scatterers correspond to radar targets with relatively constant amplitudes and slowly varying phase that can be either natural or manmade. The small baseline subset (SBAS) method (Berardino et al., 2002; Lanari et al., 2004; Hooper, 2008; Samsonov et al., 2011; Samsonov and d’Oreye, 2012) selects many coherent interferograms acquired with small spatial and temporal baselines, solves for the deformation rates between subsequent SAR acquisitions, and then reconstructs time series of the cumulative displacements. Various deformation time series analysis software packages are available, including StaMPS (Hooper et al., 2012), GIAnT (Agram et al., 2013), and Parallel-SBAS (Casu et al., 2014).

**Global navigation satellite systems.** Originally developed by the U.S. Department of Defense, this technique relies on the triangulation of signals from orbiting satellites to estimate three-dimensional positions and displacements to the precision of a few millimeters (Figure 2). Other nations have deployed similar satellite navigation systems, and the combined suite of systems is known as GNSS. Several aspects of GNSS geodesy are similar to the InSAR technique (Hofmann-Wellenhof et al., 2007). Both techniques use coherent microwave signals, make phase

![Figure 1. Illustration of the estimation of displacement along the line of sight to the satellite, known as the range, from the phase shift between the reflected electromagnetic waves. R1 and R2 denote the ranges from two different satellite passes, acquisition 1 and 2. The inset shows the phase shift or waveform delay of the repeat pass R2 with respect to the initial pass R1. \( \lambda \) is the wavelength of the radar/microwave chirp sent from the satellite, 5.66 cm in this case.](https://example.com/fig1.png)
measurements on these signals, and suffer from noise associated with signal propagation through the atmosphere. Both techniques also require high-precision satellite orbits to be computed and available for the data analysis. Unlike InSAR, GNSS is an absolute positioning technique, using measurements of range to four or more satellites to uniquely define a point position on the earth’s surface. Another difference between InSAR and GPS is that fine time resolution is possible with global satellite systems. The high precision of GNSS position and displacement measurements reflects several characteristics of the system. For example, most of these systems use dual frequency measurements, allowing a first-order correction for ionospheric effects. The ability to make large numbers of range- and phase-change measurements to satellites simultaneously, over different viewing angles, allows a first-order correction for the atmospheric delay due to water vapor. Other effects that influence the position of a point on the earth’s surface at the millimeter to centimeter level, such as tides, ocean loading, and changes in earth orientation, are corrected during data analysis via models or measurements from other space geodetic techniques. The availability of GNSS has opened a host of geologic and geophysical applications, such as measurement of ground deformation associated with extraction or injection of fluids, including injection of CO₂. A number of technical books on the subject provide more detail, including Teunissen and Kleusberg (1998) and Hofmann-Wellenhof et al. (2007). Geophysical applications are reviewed in Dixon (1991), Bürgmann and Thatcher (2013), and Bock and Melgar (2016).

Data interpretation and inversion methods

Changes in the fluid volume within a reservoir leads to variations in the effective pressure, which is the difference between the total pressure and the fluid pressure, inducing deformation and stress changes within the reservoir and the surrounding rock. Under favorable conditions, the resulting stress and strain lead to observable surface deformation. To make use of these observations, we need to relate the surface deformation to reservoir processes. The forward problem entails computing the displacements in the overburden given a distribution of volume change within the reservoir. There are several levels of sophistication that can be used to formulate the forward problem. At the simplest level, we can relate the surface deformation directly to reservoir volume change without considering the specific fluid pressure changes that led to the volume change. Thus, we restrict ourselves to purely mechanical considerations and are not concerned with modeling the fluid flow leading to the volume change. This approach invokes the fewest model parameters, and, if we are interested in short time intervals, can usually be accomplished by using an elastic or poroelastic model for the overburden (Vasco et al., 2010). More sophisticated simulations of the fluid flow within the reservoir can also improve fidelity of the modeling, at the expense of introducing additional, often unknown, parameters such as reservoir permeability and porosity. The most advanced level involves modeling both the fluid flow and the deformation by using a coupled numerical simulator. The conceptual model, relating the deformation to volume changes in the reservoir, is similar to that applied in seismic source estimation and imaging. That is, though the source volume may undergo nonlinear deformation and strain, outside of the source region, the much smaller deformation of the surrounding rock can be described using methods from linear elasticity over the time interval between surveys (typically less than one month). In particular, one can use a Green’s function $G_i(x, y)$ or impulse response function to relate the displacements of the overburden $u_i(x)$ to the fractional volume change $\Delta \psi(y)$ within the reservoir:

$$u_i(x) = \int G_i(x, y) \Delta \psi(y) dy,$$

where $V$ is the reservoir volume (Rucci et al., 2013). The Green’s function depends on the elastic properties of the overburden, and the effort required for its computation depends on the complexity of the elastic model. There are analytic and semianalytic techniques for homogeneous half-space and layered models, respectively, and numerical finite-difference and finite-element methods may be applied to fully three-dimensional models.

The inverse problem consists of using observations of the deformation of the overburden to estimate volume change within the reservoir. This is a much more difficult task because of the loss of resolution with depth due to smoothing effects of the Green’s function in equation 4. However, an inversion of the deformation can be formulated as a least-squares minimization problem, and one can take advantage of the linearity of equation 4 to solve for the spatial distribution of the reservoir volume change (Rucci et al., 2013). Due to the difficulty of the inverse problem, it is important to devise appropriate regularization schemes to stabilize the process of estimating a solution. One particularly useful approach for volume changes induced by fluid extraction and injection into a reservoir is a regularization or penalty term that favors volume changes near known well locations (Vasco et al., 2010; Rucci et al., 2013; Vasco et al., 2019). Such a penalty term utilizes the fact that the effective pressure changes surrounding the well are driving the volume changes within the reservoir. Conventional regularization terms, such as model norm and roughness penalty functions, tend to produce excessively smoothed

Figure 2. Schematic map of a GNSS. The orbiting satellites are denoted by dots and their orbits by black paths. The red dots signify the satellites that are visible to a point of interest at the earth’s surface. The red lines represent the transmission paths from the satellites to that point.
solutions, exacerbating the loss of resolution with depth. Another way to regularize the inverse problem is via model parameterization that accounts for known aspects of the source. For example, if the fluid volume changes are restricted to a specific formation with known boundaries, one can incorporate that fact by restricting the source volume to that region. Similarly, if the deformation is thought to be due to an evolving fracture/fault zone, then the source change can be modeled as aperture changes distributed over the potential fracture/fault plane.

Applications

Carbon sequestration at In Salah, Algeria. The In Salah gas storage project sequestered excess CO₂ that was stripped from natural gas produced from three fields in Algeria (Mathieson et al., 2010; Ringrose et al., 2013). The reservoir itself is a roughly 20 m thick layer forming a gentle anticline, overlain by approximately 2 km of shale and sandstone (Figure 3). Beginning in 2004, the first of three horizontal wells began injecting CO₂ into the formation. Fortunately, observations from SAR satellites of the European Space Agency were available, as the satellite had been gathering data for several years prior to the start of injection. An early analysis revealed significant range change due to uplift over each of the three injectors (Figure 4). Interestingly, a double-lobed pattern, indicative of the opening of a narrow vertical feature (such as a fault or fracture), was observed over the injection well KB-502. This conclusion was supported at wells KB-502 and KB-503 by a later seismic survey that detected pushdown in a narrow fault/fracture zone due to the injected CO₂ (Gibson-Poole and Raikes, 2010), as shown in Figure 5.

Based on the suggestion of fault/fracture flow, the source of the uplift above well KB-502 was modeled as a vertical damage zone that responds to the injection of CO₂ by increases in aperture or fracture width. The trace of the fracture zone is plotted on top of the seismic pushdown in Figure 5. Using the modeling technique presented in equation 4, it is possible to formulate an inverse problem for the aperture changes of discrete patches of the fault/fracture zone as a function of time, indicative of the movement of CO₂ through the subsurface. That is, we can relate the InSAR range change $r(\mathbf{x}, t)$ at a location $\mathbf{x}$ on the earth’s surface.
surface to the aperture changes on rectangular patches over the vertical fracture:

\[ r(x, t) = \sum_{n=1}^{N} R_n(x) a_n(t) = R(x) \cdot a(t), \]

where \( R_n(x) \) is the integral of the projection of the Green’s function of the three displacement components along the look vector \( l \) taken over the fault/fracture patch \( P_n \):

\[ R_n(x) = \int_{P_n} l \cdot G(x, y) dV. \]

Given a set of range change measurements (roughly 300,000 observations at the In Salah site) (Figure 4), we can write the associated collection of linear constraints as a large system of equations for the aperture changes over the fault/fracture surface. The inverse problem entails solving this linear system for the aperture changes during each time interval. This is accomplished by using a least-squares approach in which we minimize the sum of the squares of the residuals. To stabilize the inverse problem, we introduce a term which penalizes aperture changes that are far from the known well location. This penalty function is based on the hypothesis that the aperture changes are driven by fluid pressure changes due to injection and that these changes are largest near the well itself. Therefore, we minimize the composite quadratic function in the aperture \( a(t) \):

\[ Q(a) = (d - Ma)^T (d - Ma) + a^T Da , \]

where \( d \) is the matrix of observed range changes, data \( M \) is a matrix with the \( j \)th row given by \( R(x_j) \) and a diagonal penalty matrix \( D \) that takes on large values for cells that are far from the injection well. The necessary equations for the minimum of the quadratic function \( Q(a) \), with respect to the components of the aperture vector \( a \), produces the desired linear system of equations.

Aperture changes for a selected set of time intervals, obtained by inverting the InSAR range changes above injection well KB-502, are shown in Figure 6. Note the northwest migration of \( \mathrm{CO}_2 \) for several kilometers from the injection well during the first two years of sequestration. Such rapid migration was validated by the relatively rapid appearance of \( \mathrm{CO}_2 \) at an unused well to the northwest (Mathieson et al., 2010; Ringrose et al., 2013) and by a subsequent seismic survey (Gibson-Poole and Raikes, 2010) as indicated by the narrow corridor of pushdown extending several kilometers northwest of the injection well (Figure 5). The stress changes associated with the migrating \( \mathrm{CO}_2 \) generated microearthquakes that were detected by an array of seismometers installed in 2009, well after the start of injection in KB-502. The vast majority of microseismic events are located at or below the injection well, supporting the conclusion that the \( \mathrm{CO}_2 \) remained at depth (Stork et al., 2015), as in the solution plotted in Figure 6. The restriction on the depth of the injected \( \mathrm{CO}_2 \) to within a few hundred meters of the injection well is also supported by coupled geomechanical modeling (Rinaldi and Rutqvist, 2013) and a stochastic inversion of the InSAR data (Ramirez and Foxall, 2014).

**Monitoring EOR at the Kelly-Snyder Field, Texas.** In addition to storage and long-term sequestration, \( \mathrm{CO}_2 \) may be injected to maintain or increase reservoir pressure and reduce viscosity, a technique for EOR. Monitoring of surface deformation in a field undergoing EOR provides a check on reservoir pressure changes and fluid pathways. Data analysis and modeling are similar to the procedures described earlier for carbon sequestration, with one significant difference: in actively producing fields, fluids are both injected and extracted concurrently. In addition, there are often

![Figure 6. Aperture change during six intervals since the start of injection at well KB-502. The horizontal axis signifies the distance to the northwest of the injection well, along the fracture trace indicated in Figure 5.](https://pubs.geoscienceworld.org/tle/article-pdf/39/1/29/4911002/tle39010029.pdf)
large numbers of injection and production wells. Hence, it is important to account for the various cumulative fluid fluxes and their relative contributions to reservoir pressure, which can involve complex bookkeeping and equation-of-state calculations.

Here, we describe an example from the west Texas Kelly-Snyder oil field (Figure 7), which is presented in more detail in Yang et al. (2015). The reservoir, which has an average depth of 2000 m, consists of subsurface limestone reef mounds, including the Pennsylvanian-age Cisco and Canyon formations (Yang et al., 2015). The field has been an important producer since the early 1950s. Production declines in the 1960s led to injection of water, followed by injection of CO\textsubscript{2} in the early 1970s. Injection of CO\textsubscript{2} increased significantly in the early 2000s, and a total of 100 megatons was injected into the field between 1972 and 2011. Data from the Japanese Aerospace Exploration Agency ALOS-1 SAR satellite, with a repeat time of 46 days, were gathered over the field. The data set consists of 13 SAR images collected between 2007 and 2011. These data were used to generate 53 interferograms. The SBS technique was used to generate a range change time series that measured up to 10 cm of uplift, closely centered on the reservoir (Figure 7).

The field operator provided injection and production data for the hundreds of wells operating in the field. The injected and produced volumes were summed in 500 × 500 m grid blocks (Figure 8). A matched asymptotic solution for reservoir pressure (Mathias et al., 2009), accounting for two-phase flow (supercritical CO\textsubscript{2} and water), was coupled with an analytic expression for surface deformation (Xu et al., 2012) in order to understand the flow and pressure distribution within the reservoir, and to establish the compatibility between the production/injection and the

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**Figure 7.** (a) Location map showing the position of the Kelly-Snyder Field in Texas. The color variations indicate the line-of-sight displacements from 8 January 2007 through 6 March 2011. (b) Injection wells for CO\textsubscript{2} (green circles) and water (blue circles) plotted on top of a map of the InSAR range changes over the field. From Yang et al. (2015), reprinted with permission according to STM guidelines by the *International Journal of Greenhouse Gas Control*.

**Figure 8.** Location of net injection points representing effective injected volumes of (a) CO\textsubscript{2} and (b) water. Circles represent injection wells, and triangles represent production wells. The injected and produced volumes correspond to conditions at 16 MPa and 41.5°C. From Yang et al. (2015), reprinted with permission according to STM guidelines by the *International Journal of Greenhouse Gas Control*.
observed range change (Yang et al., 2015). Thus, the approach uses a simplified method to compute the Green’s function for the forward modeling discussed earlier. The contribution from each effective block was summed to estimate the total fluid pressure changes caused by injection and production (Figure 9). Computation of the range change at the surface, due to the pressure distribution in Figure 9, required an estimate of the Young’s modulus of the half-space model. Estimates were obtained by conducting a series of inversions with varying values of Young’s modulus and finding the value that minimized the misfit (Figure 10). Given an optimal Young’s modulus, the pressure variations in Figure 9 were used to estimate the range change at the surface by using the method of Xu et al. (2012). The calculated range changes match the InSAR observations (Figure 11) with some exceptions south of the field, where there is a systematic residual of around 4 cm. The discrepancy may be due to atmosphere effects or effects of shallow aquifers in the region (Yang et al., 2015). The range change data at the Kelly-Snyder Field may also be used to invert for fluid pressure changes and to estimate spatial variations in reservoir permeability, as in Vasco et al. (2008).

**Discussion: Limitations and advancements**

Our examples provide two cases in which surface deformation is sufficient to provide constraints on fluid flow at depth. Another example related to CO₂ EOR is provided by the GNSS-based study of Karegar et al. (2015). While there are a large number of situations with detectible range changes, there are also notable areas in which injection and production do not generate significant surface deformation. The conditions for generating observable deformation are not yet understood, and the generation of stress changes in the subsurface due to injection and production can be complicated, as can be the relationship between seismicity and ground deformation (Shirzaei et al., 2016). Improved understanding will come with better modeling and accounting for the
variations in poroelastic properties within the earth. Furthermore, advancements in instrumentation and monitoring techniques should lead to improved detection, particularly for methods that provide observations at depth and do not rely on surface measurements. One class of methods is the time-lapse seismic time strains mentioned earlier (Hatchell and Bourne, 2005; Tura et al., 2005; Staples et al., 2007). These methods provide observations at locations where the strain is much larger than at the earth’s surface and have the potential to greatly enhance our resolution of pressure changes (Hodgson et al., 2007), as indicated in Figure 12. Another class of downhole observations that is just now undergoing active development is provided by fiber-optic cables and distributed strain sensing (He et al., 2013). This technology can provide observations where there are wells, extending measurements right into the areas of interest. It should be possible to combine such geodetic data with microseismicity to better understand processes such as fracture development.

Conclusions
Both the geologic sequestration of CO₂ and enhanced oil production utilizing CO₂ result in changes in effective pressure that may lead to observable surface deformation. Such observations provide information on subsurface fluid flow which, as demonstrated here, can provide the foundation for an inverse problem for reservoir volume change or aperture change on an evolving fracture. One can formulate these inverse problems in purely mechanical terms, without the need for reservoir simulation or coupled fluid flow and geomechanics. This reduces the number of unknown parameters to reservoir volume changes or aperture changes. The temporal resolution of geodetic data allows for rapid sampling and quick turnaround times for imaging.

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Data and materials availability
Data associated with this research are available and can be obtained by contacting the corresponding author.

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