GPS-based Monitoring of Surface Deformation Associated with CO₂ Injection at an Enhanced Oil Recovery Site

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Abstract

High precision GPS measurements have been used to measure surface deformation associated with CO₂ injection at an Enhanced Oil Recovery (EOR) field in South Texas. We describe a filtering procedure to reduce noise associated with seasonal hydrologic effects, achieving post-filter precisions of better than 2 mm and 3 mm in horizontal and

vertical components respectively. A model assuming uniform pressurization of a thin horizontal disc-shaped pressure source in an elastic half-space fits the surface deformation data quite well. The model predicts a location of the pressurized source consistent with injection locations, and suggests minimal horizontal migration of the CO₂ fluid during the test period. Our results suggest that a sparse network of dual frequency GPS receivers can be used to augment sub-surface data for Monitoring, Verification and Accounting (MVA) activities associated with Carbon Capture, Utilization and Storage, deriving independent constraints on pressure changes in the reservoir at depth as well as CO₂ plume migration.

1. Introduction

An important aspect of large scale Carbon Capture, Utilization and Storage (CCUS) is the ability to assess the fate of injected CO₂ and test for containment loss. These so-called Monitoring, Verification and Accounting (MVA) activities typically include active seismic and down-hole geophysical techniques for precise tracking of plume migration, all of which can be expensive. Since the economic viability of CCUS is impacted by the cost of MVA activities, development of lower cost approaches, including surface techniques, is desirable.

Injection of CO₂ or other fluid into a reservoir at depth increases fluid pressure in the reservoir, causing deformation in the overlying strata and inducing surface deformation. If the pressure change is large enough, the surface deformation may be measurable. In principle, the measured surface deformation can be inverted to estimate pressure changes at depth. With additional information on geomechanical properties, quantitative information on the mass of injected CO₂ as a function of time and its spatial variation can be obtained, allowing assessment of its subsequent fate (successful storage; migration)

(e.g., *Vasco et al.*, 2008 & 2010; *Rinaldi and Rutqvist*, 2013; *White et al.*, 2014). For example, upon initial injection, the surface above the injection point will be uplifted due to the pressure change; subsequent migration of the fluid away from the initial injection point would result in subsidence at that location unless additional fluid is injected. More generally, defining the time-variable surface deformation field in the vicinity of a reservoir being used for CO₂ storage has the potential to provide a wealth of useful MVA information. Over long periods (decades or centuries), chemical reactions that result in formation of mineral phases will result in pressure and volume reduction and subsidence, and could not be distinguished from migration of the fluid with this technique alone. On the other hand, surface deformation can be measured at relatively low cost, the interpretation is straightforward, and the technique gives useful information in the critical few years immediately following injection.

To date, most studies of surface deformation associated with CO₂ injection have used InSAR (Interferometric Synthetic Aperture Radar) (*Mathieson et al.*, 2009; *Klemm et al.*, 2010; *Tamburini et al.*, 2010; *Morris et al.*, 2011; *Shi et al.*, 2012; *Rohmer and Raucoules*, 2012; *Verdon et al.*, 2013). This technique works well in dry areas with little vegetation cover, but may be problematic in areas with variable atmospheric moisture or dense vegetation cover. In these conditions, the radar signal between successive satellite passes may be decorrelated and the phase change in the radar signal between the passes (the key observable for the InSAR technique) may be difficult to estimate. Temporal sampling may also be limited; depending on the satellite system used, there may be several days to more than a month between satellite passes.

GPS can be used in a high precision mode to estimate surface deformation. It is less

sensitive to atmospheric water vapor compared to InSAR, is not affected by vegetation (assuming the GPS satellites remain visible to the ground antenna), and can be done at relatively low cost. GPS also provides excellent temporal sampling. Although we average our data to once per day, in principle much higher sampling rates are possible.

We have tested this concept at an Enhanced Oil Recovery (EOR) site in Texas. Here we report initial results from that experiment. The reservoir was pressurized with CO₂ for about a year prior to significant extraction of oil, and the resulting pressure changes were measured with down-hole techniques, allowing a quantitative test of the GPS approach.

2. Site Characteristics

The oilfield for our test is located in southern Texas, and was discovered in the 1930's. Production peaked in the 1970's. As of 2011, the field had produced more than 500 million barrels of oil (*Davis et al.*, 2011). Like many oilfields in the region, it represents a structural-stratigraphic trap in the Oligocene-age Frio formation, a high porosity sandstone unit that has been faulted against a deep-seated salt dome. The reservoir includes two sandstone units: the Upper Frio (~60 m thick) and the Lower Frio (~ 200 m thick). The average depth of the reservoir is about 1600 m. Holocene through Miocene age clays, sandstones and shales are present from the surface to approximately 1400 m depth. Below the Miocene, approximately 200 m of Anahuac shale act as impermeable caprock to the Frio reservoir.

The field is divided into several sections by faults (Figure 1). These sealing faults are thought to be barriers to CO₂ movement, allowing faster build-up of pressure in the reservoir during EOR-related fluid injection (*Davis et al.*, 2011). One goal of our

experiment was to see if the GPS network had sufficient sensitivity to detect fluid migration across one or more of these faults.

The oilfield has been re-pressurized with both saline water and CO₂, the latter from both natural and industrial sources. CO₂ injection began in late 2010, and oil production began in early 2012, after approximately 14 months of CO₂ injection. Pressure in the injection interval zone was monitored by a pressure gauge at the bottom of one well. Average reservoir pressure was 2350 psi (pounds per square inch) (16.2 MPa) in December 2010, increasing to a maximum of 2850 psi (19.6 MPa) in March 2012, two months after the beginning of significant oil production. Pore fluid pressure in the injection zone thus increased by about 500 psi (3.5 MPa) after about 14 months of CO₂ injection.

3. Data Collection

Three continuously operating GPS sites (TEST-1, 2 and 3) were installed by the University of South Florida in October 2011, 11 months after CO₂ injection started but 3 months prior to significant oil production (Figure 3). TEST-1 and TEST-2 are located in the northern fault block, 728 m apart. TEST-3 is emplaced in a southern fault block, 1879 m from TEST-1 and 1239 m from TEST-2 (Figure 1). Each GPS station consists of four components (Figure 2): a dual frequency Trimble NetR9 GPS receiver, a stable monument (cement and rebar extending to approximately 1.5 m depth), a GPS antenna (choke-ring design), and a power supply. The latter consists of lead acid batteries recharged with solar panels during daylight hours. The antenna is mounted about 1.7 m above the ground surface in order to minimize multipath noise (*Johnson et al.*, 1995) and is covered with a radome.

4. Data Analysis

The general characteristics of the GPS system and its use for high precision geophysical applications are described in *Dixon* (1991). The Precise Point Positioning (PPP) technique uses un-differenced dual frequency pseudo-range and phase measurements from a single GPS receiver, together with external models, to define the position of the ground antenna phase center at the millimeter to centimeter level (*Zumberge et al.*, 1997). The resulting position time series record surface deformation associated with reservoir pressure changes, changes associated with hydrological and other surficial effects, and variations related to processing artifacts or other noise sources. Here we briefly describe procedures to reduce the effects of hydrological processes and noise in the GPS time series.

GPS raw data are processed using Jet Propulsion Laboratory's (JPL's) GIPSY/OASIS II software package (version 6.2) based on the PPP technique. JPL's precise satellite orbit and clock parameters together with an absolute GPS receiver and satellite antenna phase calibration model (*Schmid et al.*, 2007) are used to generate daily point position solutions.

Atmospheric effects associated with the ionosphere and troposphere introduce a time-variable delay in the propagation of the GPS signal from the satellite to the ground receiver and cause ray bending. The first-order effects of the ionosphere are corrected using the dual-frequency approach and a linear combination of the carrier phase measurements. *Hernandez-Pajares et al.* (2007) and *Petrie et al.* (2010) showed that higher-order ionospheric effects are less than 1 mm and hence can be ignored. Tropospheric effects are modeled using the Global Mapping Function model of *Boehm et al.* (2006) which maps the zenith troposphere delay to the elevation of each observation. *A priori* zenith tropospheric delays are estimated from a Global Pressure and Temperature model (*Boehm et al.*, 2007). The elevation cut-off angle is fixed to 7° , a compromise to better constrain

tropospheric effects but minimize errors due to multipath (e.g., *Elósegui et al.*, 1995; *King and Watson*, 2010).

Non-tidal atmospheric loading effects are believed to have a 1 to 2 mm level impact on the vertical component (*Tregoning and Watson*, 2009). These effects are removed using a global 2.5 degree displacement field computed from a model provided by the National Center for Environmental Protection. The effects of ocean loading, which can reach several mm in the vertical component for near-coastal sites, are corrected using the FES2004 model (*Lyard et al.*, 2006).

The single station ambiguity resolution algorithm of *Bertiger et al.* (2010) is adopted to solve integer ambiguities for each station.

The non-fiducial daily position time series generated by these procedures may be transformed into the IGB08 reference frame (*Rebischung et al.*, 2012) using JPL's X-files, a 7-parameter transformation. The IGB08 daily solutions can then be transformed to a North American plate-fixed frame (NA12) using a daily 7-parameter transformation calculated according to *Blewitt et al.* (2013). It is also possible to go directly from non-fiducial positions to NA12. With either approach, the transformed horizontal motions are in general agreement with motions expected for the stable interior of the North America plate, with exceptions noted in the next paragraph.

The resulting GPS time series exhibit strong seasonal changes which mainly reflect hydrological effects. Figure 4 shows the vertical component of the TEST-1 site compared to Total Water Storage (TWS) estimated from the Gravity Recovery And Climate Change (GRACE) mission, a satellite project managed by NASA and the German Aerospace

Center (*Tapley et al.*, 2004). The GRACE TWS field has a spatial resolution of ~ 100 km (*Landerer and Swenson*, 2012) and represents a regional signature of groundwater, surface water and soil moisture changes. The vertical component recorded by our TEST GPS stations and nearby GPS stations (see Figure 5) are influenced by this hydrologic signal. Recognizing surface deformation related to CO₂ injection in the presence of such dominant hydrological effects is clearly challenging. Here we describe a procedure for reducing the hydrological effects, in order to investigate subtler signals associated with CO₂ injection.

Consider a regional network of GPS stations within several hundred km of our local network. The position time series for both the regional and local networks record signal as well as noise from a variety of sources with varying amounts of temporal and spatial correlation. A common mode signal across the regional network likely includes regional hydrologic effects. We can therefore use data from the regional network to remove such Common Mode Effects (CME) from our local network, in effect defining a regional reference frame. This approach to regional filtering was first described by *Wdowinski et al.* (1997). Note that CME can include both common mode signals and common mode errors.

A network of 30 permanent GPS stations covering an area of $400 \text{ km} \times 300 \text{ km}$ currently operates near the study area, 24 of which recorded data during our observation period and are available for definition of the regional reference frame (Figure 5). The raw GPS data are publicly available through the Continuously Operating Reference System (CORS) website (<http://geodesy.noaa.gov/CORS/>).

One challenge to implementing such a regional filter in this area is that some stations may be also affected by local deformation (site-specific motion unrelated to regional hydrologic effects), for example by water pumping from a local well. To eliminate these stations from the regional reference frame, we performed a correlation analysis for the three components of the GPS displacement time series to find stations whose motions are highly correlated. These stations presumably exhibit CME within the study area, are less affected by local deformation sources (i.e., smaller site-specific motions), and can be used to define and remove CME. Figure 6 shows the stations having a correlation coefficient greater than 0.4 in the vertical component. These stations are used to identify regional CME. Recall that we distinguish common mode error and common mode signal. The common mode signal is mainly related to the response of the lithosphere to continental water storage, which exhibits a strong seasonal cycle, as reflected in the GRACE data. The common mode noise may reflect long wavelength un-modeled (residual) atmospheric effects, reference frame effects, and satellite orbital errors (*King et al.*, 2010). However, the CME may not be spatially uniform. To account for non-uniformity of CME, *Dong et al.* (2006) developed a spatio-temporal filtering approach based on principal component analysis. This approach has been successfully applied to extract CME in various GPS networks (*Savage* 1995; *Marquez-Azua and DeMets* 2004; *Tiampo et al.*, 2004, 2012).

We used principal component analysis based on the covariance analysis approach (*Dong et al.*, 2006) to spatially filter the CME including hydrological effects and regional noise in the GPS time series. Consider detrended and demeaned GPS time series ordered as columns in a displacement matrix $\mathbf{X}$. The rows in $\mathbf{X}$ represent displacements of one epoch (t_i) for all stations (n). $\mathbf{X}$ can be decomposed into a linear combination of the principal

components (PC) and eigenvectors of the covariance matrix of $\mathbf{X}$ as follows:

$$X(t_i, j) = \sum_{k=1}^n a_k(t_i) v_k(j), \quad j = \{1, 2, \dots, n\} \quad (1)$$

$$a_k(t_i) = \sum_{j=1}^n X(t_i, j) v_k(j), \quad k = \{1, 2, \dots, n\} \quad (2)$$

The elements of the covariance matrix of $\mathbf{X}$ are defined as a matrix $\mathbf{B}$:

$$B(i, j) = \frac{1}{m-1} \sum_{k=1}^m X(t_k, i) X(t_k, j) \quad (3)$$

where m is the number of epochs. v_k in equations (1) and (2) is the k th eigenvector of $\mathbf{B}$ which can be obtained by spectral decomposition:

$$\mathbf{B} = \mathbf{V} \mathbf{\Lambda} \mathbf{V}^T \quad (4)$$

where $\mathbf{V}$ is an eigenvector matrix with dimension $(n \times n)$ and $\mathbf{\Lambda}$ is a nonzero diagonal matrix containing eigenvalues λ_k (or variances as $\mathbf{B}$ is a covariance matrix) arranged in descending order. Each PC (a_k) corresponds to the k th eigenvalue λ_k and can be determined using equation (2). Finally, the filtered displacement matrix $\hat{\mathbf{X}}$ can be obtained by using the first p dominant PCs or modes computed from equation (1) as follows:

$$\hat{X}(t_i, j) = X(t_i, j) - \sum_{k=1}^p a_k(t_i) v_k(j) \quad j = \{1, 2, \dots, n\} \quad (5)$$

The second term in equation (5) is often called CME. The percent of the variance explained by a particular PC or mode is determined by dividing the corresponding eigenvalues, λ_k , by the sum of the eigenvalues. The significance of any PC can be tested under the null hypothesis that k th modes are not significant from the remaining modes using the F -statistic given by (Smith *et al.*, 2007; Tiampo *et al.*, 2012):

$$F(1, n - k) = \frac{\lambda_k}{\sum_{i=k+1}^n \lambda_i / (n - k)} \quad (6)$$

where λ_k is the eigenvalues (variances) of covariance matrix $\mathbf{B}$ corresponding to the k th PC. The above statistic is the ratio of the two variances, that is, the variance of k th modes divided by variance of remaining modes. The F -statistic is F-distributed with $(1, n-k)$ degrees of freedom. If the F -statistic is greater than the critical value of the F -distribution for some desired false-rejection probability (e.g., 0.1), then the null hypothesis is not correct and the k th mode is dominant.

5. Results

5.1 Surface Deformation

We used stations shown in Figure 5 to calculate the eigenvalues and eigenvectors using spectral decomposition of the covariance matrix $\mathbf{B}$ (equation 4). The percentage of PC eigenvalues is shown in Figure 7 for three displacement components. The first PCs explain 49 %, 42 %, and 55 % while the second PCs explain 26 %, 35 % and 18 % of variance for North, East and Up components. We calculate the F -statistic (equation 6) for each eigenvalue to determine modes that are significantly different from remaining modes. Our analysis shows that the first two modes are significantly different from the remaining modes at the 90% significance level and represent CME in the vertical component. The first two and three modes are significant for North and East components, respectively. These modes represent common signals (e.g., hydrological loading in the vertical component) at the GPS stations. It should be noted that regional filtering also reduces the amplitudes of common noise, i.e. both the white and colored noise components (*Mao et al., 1999; Williams et al., 2004; Hackl et al., 2011; Hackl et al., 2013*).

Figure 8 shows the vertical component of TEST-1 and two of the regional stations (ANG5 and COH1) before and after filtering. Stations ANG5 and COH1 are located 32 km and 33 km from TEST-1, respectively, and show 51% and 50% correlation with TEST-1 in the vertical component. The filtered ANG5 and COH1 time series scatters around zero, consistent with random noise. For example, RMS of time series decreases from 6.0 mm and 10.2 mm to 3.0 and 1.5 mm for stations ANG5 and COH1 respectively. In contrast, the filtered TEST-1 data exhibit a clear uplift signal during the CO₂ injection period, and also show horizontal motion (to the southeast) that are quite different from other stations in the network (Figure 10), presumably reflecting local deformation associated with increased reservoir pressure. While the total uplift over the initial five-month period is small (8.3 mm) it is clearly resolved with our filtering approach and is significantly different from zero at the 95% confidence level.

A least-squares line fit to the north, east and vertical components of the filtered position time series from the beginning of observations (October 11, 2011) to the time of maximum recorded reservoir pressure (March 1, 2012) yields the surface displacements listed in Table 1 and shown in Figure 9. All three sites within the EOR field have motions distinct from the reference frame sites (Figure 10) showing uplift and southeast motion during this period of initial reservoir pressurization. Table 1 also lists the RMS misfits of the linear fit to the displacement time series, presumably reflecting residual noise and un-modeled processes in the filtered position time series. These residuals are quite small: 1.3 mm or less for the horizontal components, and 2.9 mm or less for the vertical component.

We seek to use the behavior of this EOR field as a proxy for the behavior of a reservoir

used for long-term storage of CO₂, and demonstrate successful MVA techniques based on surface deformation. One difficulty with this approach is that the expected long-term surface deformation for the two types of fields is quite different. For CO₂ storage, we expect a long period of injection, during which surface deformation occurs in response to reservoir pressure increases and/or reservoir expansion. In contrast, with EOR, an initial period of injection is generally followed by production. At some point, injection and production more or less balance in the EOR field, at least averaged over long periods. After this point, we do not expect to see significant surface deformation in the EOR field (Figure 8).

In our test field, reservoir pressure rises during the initial period of initial CO₂ injection, through most of 2011 and early 2012 (Figure 3). Shortly after production begins (early 2012) reservoir pressure drops slightly for several months and then stabilizes, presumably because oil production and CO₂ injection are in approximate balance, at least in terms of net pressure effects. After this time, we do not expect to see significant deformation.

We therefore focus on deformation data from the beginning of the time series up to the time of maximum reservoir pressure. This gives a time series that is approximately 5 months long, from October 2011 to March 2012. Deformation data during this period should reflect the location, geometry and growth of the reservoir during the initial pressurization phase, and is most representative of the behavior of a reservoir being pressurized for long-term CO₂ storage.

The utility of the regional filter is illustrated in Figure 10. Figure 10a shows horizontal

displacement vectors for the 24 CORS stations relative to NA12, i.e., from unfiltered time series, for the time span from October 11, 2011 (beginning of our GPS data) to March 1, 2012. Many of the horizontal vectors exhibit significant common mode displacement (large, cm-level motion to the northeast) which may relate to regional hydrologic loading. Figure 10b shows the corresponding filtered displacement, with common mode motion removed. Most stations now show small (less than 1 mm), randomly oriented displacements. In contrast, the three TEST stations in the filtered data show larger (up to 4 mm) southeast displacements, presumably reflecting local deformation associated with the EOR field, and implying a pressure source located northwest of the stations.

The relatively large uplift in TEST-1 (8.2 mm) compared to the other two stations implies that the center of the pressurized source is closer to TEST-1 than the other two stations (TEST-2 and TEST-3 experienced ~ 60% and 75% smaller uplift compared to TEST-1). Horizontal motion is largest in TEST-2. The spatial pattern of these displacements implies a pressure source centered close to TEST-1, with a boundary near TEST-2. This is quantified in the next section.

5.2 Model Description

We model this deformation assuming an infinitely thin horizontal circular disc pressure source (often called a “penny-shaped crack” model; hereafter penny model) in an elastic half space. The penny model was developed by *Fialko et al.* (2001a) to describe deformation associated with a sill-like magmatic intrusion, and has been validated with numerical simulations (*Fialko et al.*, 2001b). Several aspects of the volcano deformation problem are analogous to the CO₂ storage problem, and we exploit that similarity here.

The assumptions and formulation of the penny model are summarized in Figure 11 and Table 2. We treat the pressurized reservoir as a permeable infinitely thin horizontal circular disc embedded in surrounding impermeable, deformable elastic material. The reservoir and surrounding rocks are assumed homogeneous, with the same, uniform elastic properties. The size (radius R) and depth (H) of the reservoir, its pressure increment (P) and the elastic properties of the surrounding rocks (Young's modulus E and Poisson's ratio ν) control the surface deformation. The pressure distribution inside the pressure source is assumed uniform. The model assumes purely elastic behavior, implying that uplift occurs instantaneously from increased reservoir pressure, and is linearly related to pressure. The model therefore does not reflect poro-elastic effects, properties of the injected fluids or hydrological parameters such as porosity and permeability of the reservoir or surrounding media.

For this model, the vertical displacement U_z and horizontal displacement U_r at the surface are described by:

$$U_z = 4 \frac{(1-\nu)(1+\nu)}{E} \Delta P * R \int_0^1 \left[S_0^0 + \frac{H}{R} S_0^1 \right] \varphi(t) dt + \int_0^1 \left[\frac{S_0^0}{t} - C_0^1 \right] \psi(t) dt \quad (7)$$

$$U_r = 4 \frac{(1-\nu)(1+\nu)}{E} \Delta P * R \int_0^1 \left[\frac{S_1^{-1} - (\frac{H}{R}) S_1^0}{t} - C_0^1 + \frac{H}{R} C_1^1 \right] \psi(t) dt - \frac{H}{R} \int_0^1 S_1^1 \varphi(t) dt \quad (8)$$

where $\psi(t)$ and $\varphi(t)$ are Fredholm integral equations of the second kind:

$$\varphi(t) = -\frac{2}{\pi} + \frac{2}{\pi} \int_0^1 [T_1(r, t) \varphi(t) + T_3(r, t) \psi(t)] dr \quad (9)$$

$$\psi(t) = \frac{2}{\pi} \int_0^1 [T_2(r, t) \psi(t) + T_4(r, t) \varphi(t)] dr \quad (10)$$

Variables S , C and kernels T are functions of H/R , r and t and have closed-form expressions (Fialko *et al.*, 2001a). The variable r is the horizontal distance from the center of penny model, readily related to the GPS coordinates, and t is the interval of integration. Equations (9) and (10) can be solved numerically using iterative techniques (Delves and Mohamed, 1985).

5.3 Model Solution

We calculate the surface deformation associated with the penny model using the time series of reservoir pressure measured at the well shown in Figure 1. The unknown parameters estimated in our model are the horizontal position (x,y coordinates) of the center of the penny model, its radius (R), the Young's modulus (E) and Poisson's ratio (ν) of the elastic half space. Fixed (known) parameters include the depth (H) of crack, set to 1600 m, the average depth of the Upper Frio at this location based on industry seismic data (Figure 1 and Figure 14), and the pressure increment, as measured by the down-hole meter. Preliminary modeling suggested minimum sensitivity to Poisson's ratio, a common result in many Earth deformation problems (e.g., Bevis *et al.*, 2005). We therefore set the value of Poisson's ratio to 0.25, a value often used to simulate rock deformation or seismic wave propagation. Table 2 summarizes the fixed and adjustable parameters used in our analysis.

A grid search was used to estimate the parameters that best fit the horizontal and vertical motions at the GPS stations. Grid ranges are -3,000 – 2,300 m in the x coordinate of horizontal position, -2,700 – 2,400 m in the y coordinate of horizontal position (both referred to a local coordinate system), 100-1400 m for radius, and 5-155 GPa for Young's modulus, with search increments 50 m, 100 m and 5 GPa, respectively.

Goodness of fit is assessed using the standard chi-square (χ^2) statistic:

$$\chi^2 = \sum_{i=1}^N \frac{(O_i - C_i)^2}{\sigma_i^2} \quad (5)$$

where O_i is an observation (data), C_i is the corresponding calculated (model) value, and σ_i is the data uncertainty. In its normalized form χ^2_{df} , χ^2 is divided by the degrees of freedom, $df=N-u$, where N is the number of observations, equal to 9 (3 GPS stations, each with three components) and u is the number of adjustable parameters, in this case 4. For large data sets characterized by normally distributed, Gaussian uncertainties, values of χ^2_{df} close to 1 indicate a good fit of data to model and suggest that uncertainty estimates are reasonable. Our data set is quite small and it is not clear that uncertainties are normally distributed, hence this generalization is a rough guide only. Figure 12 displays distribution of χ^2 for various ranges of parameter values, showing trade-offs among the various estimated parameters. For example, larger values of Young's modulus require a larger radius for the pressure source. The best fit model (Table 3) has $\chi^2=7.1$ corresponding to $\chi^2_{df} = 1.4$. Figure 13 shows observed and calculated displacements at the three sites for the best-fit model.

6. Discussion

The center location of the circular reservoir in our model is well constrained. The best fit center value is located 250 m and 900 m northwest from TEST-1 and TEST-2 respectively, and 1950 m north from TEST-3. This center is close to the centroid of the multiple CO₂ injector wells (Figures 1 and 12a). One implication of this observation is that there was limited migration of the CO₂ plume from the injection points during this period. Also, pressure rapidly equilibrated among the various injection wells (at least relative to the

resolution of our data) such that a simple, single pressure source adequately fits the data. This is consistent with the high porosity and permeability of the Frio sandstone units.

The source radius is also well constrained, with a best fitting estimate of 800 m and a standard error of +300/-100 m. The asymmetric uncertainty range mainly reflects trade-offs with Young's modulus. The best fitting estimate of source position and radius places the source and its boundaries within the northern fault block where injection occurred, implying minimal fluid migration and containment within this block (Figures 1, 12, 13, 14).

The lower limit of acceptable values for Young's modulus is well defined, while the upper limit is poorly defined, resulting in an asymmetric uncertainty distribution: 55 GPa (best estimate) with a standard error of +80/-20 GPa. The best estimate and lower limit are typical for sedimentary rocks at relatively shallow crustal levels (e.g., *Ruiz Penã*, 1998), while the upper limit is unrealistically high. To our knowledge, there are currently no publicly available data for the reservoir and caprock properties in our study area for comparison with our results. In a similar geomechanical analysis in Cranfield, Mississippi (*Kim and Hosseini*, 2014) bottom-hole pressure and temperature monitoring data were available for calibration. Young's modulus of the confining layer was estimated at 30 GPa, close to our minimum estimate.

Figure 12f shows the trade-off between penny model radius and Young's modulus. For example, increasing Young's modulus from 30 GPa to 130 GPa would lead to a 30% increase in radius (stiffer elastic material results in a larger radius estimate). However, since we know that higher values of Young's modulus are physically implausible, the larger

radius values are similarly unlikely. Since source location, source radius, and Young's modulus for the half space are the main physical parameters controlling surface displacement (in addition to the pressure increment, known here), independent constraints on Young's modulus would be useful in an operational system where GPS was used to estimate reservoir pressure.

Our GPS stations were installed after the beginning of CO₂ injection, and it is interesting to speculate on the maximum signal that might have been observed if data could have been acquired earlier. We predict the horizontal and vertical displacements during the entire CO₂ injection period using best fit parameter values in Table 3 and observed pressure data (Figure 15). After 16 months of CO₂ injection (from beginning of CO₂ injection to the time of maximum recorded pressure) predicted vertical displacements are as large as 24 mm (at TEST-1), while predicted horizontal displacements are as large as 6 mm (at TEST-2). There are respectively 8 times and 5 times higher than the estimated noise level for these components.

Once surface displacements are calibrated against measured reservoir pressure changes (as available here) it is possible to use the observed surface displacement to predict subsequent pressure changes at depth, for independent comparison to the bore-hole measurements. Figure 16 shows a preliminary attempt for the first year of GPS data. This calculation assumes that the source has not moved during this period.

The limited available data are not sufficient to simultaneously estimate reservoir pressure and test for plume migration, both important MVA activities for future Carbon Capture, Utilization and Storage (CCUS). However, we have demonstrated that a sparse network of relatively simple GPS units has the sensitivity to measure surface deformation associated

with CO₂ injection at rates likely to be reached in operational CCUS sites. In an operational system, additional (10-20?) GPS stations would presumably be available. With a larger GPS network and constraints on the geometry and constitutive properties of the reservoir and caprock (e.g., from seismic, stratigraphic or downhole data) a more sophisticated rheological and deformation model would be warranted (*Vasco et al.*, 2000; *Rutqvist* 2011; *Rutqvist*, 2012). This would allow surface deformation data to better assess plume migration and pressure changes within the reservoir (*Newman et al.*, 2002; *Newman et al.*, 2006; *Kim and Hosseini*, 2014).

7. Conclusions

The GPS system outlined here has demonstrated sensitivity to observe surface demonstration associated with CO₂ injection at depth. We used a principal component analysis to reduce noise associated with seasonal hydrologic effects, achieving post-filter precision of better than 2 mm and 3 mm in horizontal and vertical component respectively. If GPS observations can begin one to two years prior to injection, background deformation associated with other processes, e.g., ground water hydrology can be better resolved.

A model assuming uniform pressurization of an infinitely thin horizontal disc-shaped pressure source in an elastic half-space fits the surface deformation data quite well. The model predicts a location of the pressurized source consistent with injection locations, and suggests minimal horizontal migration of the CO₂ fluid during the test period. Our results suggest that a sparse network of dual frequency GPS receivers can be used to augment sub-surface data for MVA activities associated with Carbon Capture, Utilization and Storage, deriving independent constraints on pressure changes in the reservoir at depth as well as

CO₂ plume migration. Future work should include a larger number of stations in order to better describe plume shape and dimensions.

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Figure 1. Map of the Enhanced Oil Recovery (EOR) site in southern Texas used to test the GPS surface deformation technique. Locations of a well with pressure gauge and CO₂ injectors are shown with red and green circles, respectively. Red triangles indicate location of GPS sites (TEST-1, TEST-2 and TEST-3). The surface projection of major north-northeast striking fault (double black lines) divides the field into west and east parts. Minor east-northeast striking faults separate blocks A, B and C. Contour lines (grey lines) are depth of the top of Upper Frio formation in meters.

Figure 2. Continuous GPS station TEST-3 at the EOR test site in south Texas. The station includes choke ring antenna and radome (on pole in foreground), solar panels, and a white steel box holding the GPS receiver, battery, and power controller. A seismic vault is visible in the background, prior to burial.

Figure 3. Time series of bore-hole pressure measured in northern fault block during the CO₂ injection period. Pressure reached a maximum value 16 months after the beginning of CO₂ injection, shortly after the start of oil production. GPS monitoring began approximately 3 months before oil production, and 5 months before peak reservoir pressure

was reached. Inset shows the full time series of bore-hole pressure versus oil production expressed in Barrels of Oil Per Day.

Figure 4. Relative changes in total terrestrial water storage (TWS) estimated from the GRACE satellite gravity mission, and TEST-1 GPS vertical time series. The similarity between the time series implies that the ground surface is strongly affected by regional hydrological signals.

Figure 5. Map of regional stations used in our analysis. Black stations are excluded from the definition of the regional filter because their vertical displacement time series includes uncorrelated signal and noise and have site-specific motions (i.e., they are affected by local deformations). Red stations are highly correlated (Figure 6) and are used to define the filter for removing common mode effects at the TEST sites (underlined).

Figure 6. Histogram showing GPS stations with correlation greater than 0.4. Stations that are correlated with 6 or more other stations (ADKS, ANG5, COH1, TXAG, TXBC, TXED, TXRS and TXWH) were selected for definition of the regional filter.

Figure 7. Percentage of PC eigenvalues for the three coordinate components.

Figure 8. Upper panel: Unfiltered vertical displacement time series at TEST-1. **Middle panel:** Unfiltered vertical displacement time series at ANG5 and COH1, 32 km and 33 km from TEST-1, respectively. **Bottom panel:** Filtered vertical displacement time series at TEST-1, ANG5 and COH1. For the period from the beginning of GPS data collection to 2012.17 (March 1, 2012) ANG5 and COH1 time series show no significant displacement, scattering about zero (blue line) by several mm, whereas TEST-1 exhibits significant uplift, up to about 8 mm.

Figure 9. Filtered time series (North, East and Vertical) of daily position estimates (small black circles) for TEST stations from beginning of data collection to March 1, 2012. Best fit line used to estimate total displacement during this time period is shown in red (Table 1). RMS scatter of points about this best fit line (Table 1) is one estimate of precision, and is 2.9 mm or less for the vertical component, and 1.3 mm or less for the horizontal components. Note the large vertical displacement at TEST-1 (closer to injection wells) which decreases with distance from the injection wells (see Figure 1).

Figure 10. Horizontal displacement vectors of CORS GPS stations and TEST stations. Vectors represent displacement for the time span from beginning of GPS observations (October 10, 2011) to the time of maximum recorded reservoir pressure (March, 1, 2012). For clarity, the location of the three TEST stations is represented by a single triangle. **(a) (top):** unfiltered time series, referenced to NA12 reference frame. **(b) (bottom):** filtered time series.

Figure 11. Cartoon of horizontal crack or “penny” model, with the “penny” defined by radius R and depth H in an elastic half-space. The half space is defined by rheological parameters E (Young’s modulus) and ν (Poisson’s ratio). The vertical line labeled H is the axis of symmetry, passing through the center of the disc.

Figure 12. Contoured values of chi-square misfit between the GPS data and calculated values for the penny model assuming four adjustable parameters. Two parameters were held at their best fit values to calculate misfit for the two indicated parameters. $\chi^2 = 8$ represents approximate 68% confidence level. The region where the best fit solution is located with a confidence better than 68% is indicated by grey shading. Location of injection wells in Figure 12a shown with small green circles. Location of GPS stations in

Figure 12a shown with red triangles. All figures have same contour interval except for Figure 12f. Note that all values are well constrained except for Young's Modulus.

Figure 13. Predicted (red) and observed (black) GPS displacements between October 11, 2011 (beginning of GPS data) to March 1, 2012 (time of maximum recorded pressure) for horizontal (13a) and vertical (13b) components. The location of injection wells (small green circles), faults (small squares) and surface projection of best-fit penny model (large gray circle) are also shown. Blue triangles are locations of TEST GPS stations.

Figure 14. Map of depth of Upper Frio formation as inferred from seismic data. Dark blue indicates no data. Discontinuities represent normal faults (compare to Figure 1). Also shown is the location and size of a thin horizontal disc-shaped pressure source that best fits the GPS data (radius = 800 m shown by arrow). Note that this source does not cross the fault between blocks A and B, implying that the fault represents an impermeable barrier to CO₂ fluid during the time period represented by the model (October 11, 2011 to March 1, 2012).

Figure 15. Predicted vertical and radial displacements (red) assuming best fit parameter values in Table 3 and observed pressure data, compared to observed displacements (black) at the three GPS stations (a) TEST-1, (b) TEST-2 and (c) TEST-3.

Figure 16. Predicted pressure (black line) for the first year of GPS observations, based on the vertical displacement data at TEST-1 and the penny model described by the best fit parameter values in Table 3. Measured borehole pressure (red line) is shown for comparison. Note increasing divergence of measured and predicted values after 2012.6, which may indicate changes in source geometry (probably due to oil production) after that time.

Tables

Table 1. GPS displacements and RMS misfits of the linear fit to the displacement time series (Figure 9).

Station	Displacement (mm)			RMS (mm)		
Component	<u>N</u>	<u>E</u>	<u>V</u>	N	E	V
TEST-1	-0.7	+1.5	+8.2	1.2	1.0	2.8
TEST-2	-2.8	+2.2	+6.0	1.3	0.9	2.9
TEST-3	-1.5	-0.0	+3.0	0.9	0.7	2.0

Table2. Adjustable and fixed parameters in the penny model.

Parameter	Symbol	Value	Unit
Horizontal position	x,y	adjustable	meter
Depth	H	1600	meter
Radius	R	adjustable	meter
Young's modulus	E	adjustable	GPa
Poisson's ratio	ν	0.25	-
Reservoir pressure change	ΔP	known, varies with time	psi

Table3. Best-fit values and uncertainties (one standard error) for adjustable parameters based on minimum value for χ^2 (misfit of data versus model, weighted by measurement error).

Parameter	Value
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x	-250 ± 100 m
y	40 ± 100 m
Radius R	$800 + 300/-100$ m
Young's modulus E	$55 + 80/-20$ GPa

Figures

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Number of stations with correlation greater than 0.4

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16