Application of Radar Interferometry to Detect Subsidence and Uplift at the Heber Geothermal Field, Southern California

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ABSTRACT

Interferometric synthetic aperture radar (InSAR) is applied to data from the Envisat satellite, collected in the period 2003-2010, to detect surface deformation at the Heber geothermal field in Imperial Valley of southern California. The particular technique applied, SqueeSAR™ developed at TRE, makes use of permanent and distributed scatterers. This makes it possible to observe deformation in agricultural areas, where conventional InSAR does not work, so our results are the first of this kind for Heber. Observations are obtained first in the line-of-sight (LOS) to the satellite from two orbital geometries, descending and ascending, and are subsequently used to calculate horizontal movements in the west-east direction, as well as vertical displacements. Maps of annual deformation rates derived from the satellite data (2003-2010) show two adjacent areas of subsidence and uplift at Heber, confirming observations from annual ground-based leveling surveys. As to the horizontal movements in these areas, they are westward in the uplift area and eastward in the subsidence area. Maximum LOS rates away from the satellite (indicative of subsidence) reach –46 mm/year, while maximum LOS rates toward the satellite (indicative of uplift) reach +22 mm/year. However, the uplift is only taking place after 2005, prior to which the leveling data show mostly subsidence traced back to the beginning of leveling data availability from 1994. These changing trends of surface deformation in the 2003-1010 uplift area can be readily traced to changes in injection volumes. Examples of rates along profiles and mean deformation time series within small polygons of interest are also shown. The results demonstrate the utility of InSAR for geothermal operations management, planning, and environmental impact mitigation.

1. Study Area

The Imperial Valley extends for about 80 km in southern California, from the southern shore of the Salton Sea toward the U.S. – Mexico border (Figure 1). Together with the Coachella Valley...
to the north, it is part of the Salton Trough, which is a spreading center associated with the relative movement of the Pacific and North American Plates. Thus it is characterized by active tectonics, with both subsidence and substantial horizontal movements taking place on a regional scale. Local tectonic sources of deformation are represented by networks of strike-slip and normal faults, many of which do not have surface expression, especially in the agricultural areas.

In addition to the gradual deformation due to regional and local tectonics, the Salton Trough experiences abrupt surface ruptures due to large earthquakes and associated aseismic slip. Seismic swarms, such as those in 1981, 1989, 2005, 2009, and 2012 have been related to the high heat flow in the region (Ben-Zion and Lyakhovsky, 2006). Aseismic creep has been detected on many occasions in Imperial Valley, usually triggered by larger earthquakes in the region and the wider vicinity (e.g., Rymer et al., 2002), but sometimes occurring independently. Of particular interest in the study period (2003-2010) are a M7.2 event, which occurred south of the U.S. – Mexico border in April 2010, and an aseismic event of equivalent magnitude Mw – 4.7, which occurred in October 2006. Both events triggered slip on some faults in Imperial Valley (Wei et al., 2009, 2011). We have previously observed these effects as well, along with the expression of three faults (San Andres, Superstition Hills, and Imperial) in the surface deformation field (Eneva et al., 2013).

The high heat flow in the Salton Trough is associated with a number of geothermal resources. We have previously shown surface deformation maps for the Salton Sea geothermal field (Eneva et al., 2009, 2012, 2013; Eneva and Adams, 2010) and Heber, North Brawley, and East Mesa geothermal fields (Eneva et al., 2013). Here we focus on more details of the surface deformation observed at Heber. This field was first developed in the early 1980’s by the Chevron Geothermal Company. Although the initial output was lower than expected, the operation of the field has been successful since mid-1993 (Sones and Krieger, 2000), when a modular binary power plant was added to an earlier double unit (James et al., 1999). However, DInSAR does not work in agricultural areas like Imperial Valley. For such areas, a recent innovation, PSInSAR™ (Ferretti et al., 2000, 2007) is needed. It makes use of so-called “permanent scatterers” (PS) to produce detailed deformation time series and deformation rates derived from those time series. PS are buildings, fences, lamp posts, transmission towers, rock outcrops, points aligned along roads and canals, etc., which serve as reflectors of the radar waves. We have previously applied the PSInSAR technique for the Salton Sea geothermal field, using two-year data from a Canadian satellite, Radarsat (Eneva et al., 2009; Eneva and Adams, 2010).

The latest improvement of PSInSAR, called SqueeSAR™ (Ferretti et al., 2011), adds to the PS so-called “distributed scatterers” (DS). These are homogeneous areas emitting signals with smaller signal-to-noise ratios than the PS, but still significantly above the background. These include rangelands, pastures, and bare earth characteristic of relatively arid environments. This technique is particularly well suited to study rural areas. We have successfully applied SqueeSAR™ for the San Emidio geothermal field in northwestern Nevada (Eneva et al., 2011) and to the Salton Sea geothermal field (Eneva et al., 2012, 2013) using data from the European Envisat satellite collected over an 8-year period (2003-2010).

Displacement measurements with SqueeSAR are done relative to a reference point, considered to be stable. This is similar to choosing a reference (datum) point when performing leveling surveys. Thus only relatively local movements are measured with SqueeSAR, rather than regional ones. At Heber we compare the satellite observations with measurements from leveling surveys, so we use as a reference point the same datum (benchmark A-33) used for those surveys.

The deformation is first measured in the line-of-sight (LOS) to the satellite. The LOS movements are negative when their direction is away from the satellite and positive toward the satellite. We use two sets of scenes, where the satellite moves north to south (descending) and south to north (ascending). The resulting two sets of LOS movements can be decomposed into vertical and horizontal components.

3. Data

3.1 Satellite data

Two sets of radar scenes from the European Envisat satellite are used in this analysis. The data were obtained from the European Space Agency (ESA). One data set consists of 45 descending images from track 356, covering the period February 7, 2003 – September 3, 2010. The other one consists of 33 ascending images from track 306, covering the period December 16, 2003 – August 21, 2010. The viewing direction from the satellite is right-looking, perpendicular to the heading direction of satellite movement, so it is west-northwest (WNW) for the descending scenes and east-northeast (ENE) for the ascending scenes. The PS and DS

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determined from these two geometries are not identical, and it is common for one of the orbital geometries to be more favorable for a given area, yielding more PS and DS. At Heber this is the ascending geometry. The look (incidence) angles toward the ground, (i.e., measured from the vertical to the ground), are 20° to 22°, i.e. rather steep. The sensitivity of the movements detected in the line-of-sight (LOS) is measured with values between 0 and 1, with larger values indicating greater sensitivity. These are calculated from products of the sines and cosines of the look and heading angles. Because of the steep look angle, the LOS movements are most sensitive to the vertical surface deformation, with sensitivity ~0.93. The sensitivity to the west-east horizontal component of surface deformation is about three times smaller, ~0.34-0.37. This means that if the east component is significantly lower than the triple amount of the vertical movement, the LOS displacement is rather representative of the vertical component of deformation. The sensitivity to the south-north horizontal component is negligible (~0.07-0.08). Therefore, InSAR cannot provide information on the north horizontal displacements.

3.2 Other Data

The surface deformation measured by SqueesAR is compared with leveling data (i.e., vertical measurements) at the Heber geothermal field, provided by the Imperial County Department of Public Works (ICDPW). Our current leveling data set for Heber consists of the locations and the annual surveys for 132 benchmarks, for the period 1994-2011. The reference point for these measurements is benchmark A-33 shown in Figure 2.

We also use relocated earthquake epicenters for the period January 1981 – June 2011 (Hauksson et al., 2012), which are superimposed on deformation maps and time series. We also look at cross-sections in depth along profiles, either along or across linear features suggested by the earthquake epicenters (Eneva et al., 2012, 2013).

Furthermore, we look at the locations of production and injection wells, as well as the monthly volumes of produced and injected fluid for individual wells, or the total from all wells within polygons of interest. These data were obtained from the Division of Oil, Gas and Geothermal Resources (http://www.conservation.ca.gov/dog/geothermal/).

Finally, there are some reports for the existence of right strike-slip and normal faults (James et al., 1987; Allison, 1990) at Heber, shown in Fig. 2. Their locations are approximate at this time, because the sketches in the cited papers do not show geographic coordinates. James et al. (1987) also show temperature maps and cross-sections, indicating that the maximum of the temperature anomaly (380°F) at 6000 ft is located just west of the normal fault, while Allison (1990) reports on the location of the maximum temperature gradient (58°F/100 ft) further northwest.

4. Results

Our results are shown as maps of the annual deformation rates in mm/year, plots of deformation time series, and plots of deformation rates along profiles of interest. The deformation rates are color-coded with “warm” colors (red and yellow) indicating negative movements and “cold” colors (blue) indicating positive movements. When LOS deformation is shown, negative and positive displacements mean movements away from and toward the satellite, respectively. For decomposed vertical movements, negative values indicate subsidence and positive values show uplift. For decomposed east movements, negative values indicate westward movements and positive values show eastward movements. Since the look angle is steep, the LOS movements are highly sensitive to the vertical displacements, so often LOS movements away from the satellite are indicative of subsidence, and toward the satellite – of uplift.

Figure 3 shows the 2003-2010 ascending annual deformation rates in the line-of-sight (LOS) direction to the satellite, superimposed on an optical satellite image. Urban areas have the largest numbers of PS and DS, as seen at El Centro and Calexico. Otherwise PS and DS often align along roads and canals, while the agricultural fields remain mostly devoid of them. We observe that an area of negative LOS movements, i.e. away from the satellite, is seen in the middle of the Heber NGRA, while an area of positive movements, i.e. towards the satellite, is located to the northwest in the KGRA and outside it. These areas are actually associated with subsidence and uplift, respectively, and this is how we refer to them further in the text. The subsidence area appears to be associated with the local right strike-slip and normal faults (James et al., 1987; Allison, 1990) shown in Fig. 2.
Figure 4 shows examples of ascending LOS time series at two individual PS locations, one in the subsidence area (deformation decreasing with time) and one in the uplift area (deformation increasing with time). The slopes of the straight lines fitted to the individual time series represent the annual deformation rates, which are color-coded in Fig. 3.

The ascending satellite geometry is more favorable for the Heber area, so there are more PS and DS points compared with the descending geometry. Similar to Fig. 3, we also examine maps of the descending deformation rates and averaged ascending and descending rates for 200-m pixels (not shown here). Whenever PS and DS from both the ascending and descending geometries are observed within a given 200-m pixel, their mean LOS rates are used to decompose into vertical and horizontal east components.

As seen in Fig. 3, there are areas rather devoid of PS and DS points, so the next step is to interpolate through these areas. Figure 5 shows a linear interpolation. Negative values (yellow-red) indicate movements away from the satellite for LOS, subsidence for the vertical decomposition and westward movement for the horizontal decomposition. Positive values (blue) show LOS movements toward the satellite, uplift for the vertical decomposition, and eastward movement for the horizontal component. The advantage of this type of deformation maps is that they show a reasonable spatially continuous model of the deformation, and the subsidence and uplift areas are clearer compared with Fig. 3. The “east” deformation map shows westward movements in the uplift area and eastward movements in the subsidence area. However, the maximum westward and eastward movements are not centered where the maximum uplift and subsidence are, and are shifted to the northwest.

Table 1 shows the maximum and minimum (i.e., maximum negative) rates of the four types of estimated movements. Note that these are observed at different points for the ascending, descending, vertical, and east rates. The vertical and east horizontal decompositions can be only done within pixels where there are both ascending and descending PS and DS. Since there are no descending PS and DS near the location of the minimum ascending value (–45.9 mm/year) in the center of the subsidence area, the vertical and east components could not be estimated there. Instead, the minimum descending value is observed on the periphery of the subsidence area, and this explains why it is significantly smaller (–22.8
mm/year) than the minimum ascending value in the middle. Consequently, the minimum vertical rate could be only estimated at the periphery of the subsidence area as well, where there are both ascending and descending PS and DS. Inside the subsidence area, the vertical component is likely larger, approaching the ascending observation there, and was likely underestimated by the interpolation.

Table 1. Observed maximum and minimum annual rates (mm/year) at Heber.

<table>
<thead>
<tr>
<th></th>
<th>Ascending</th>
<th>Descending</th>
<th>Vertical</th>
<th>East</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>+22.3</td>
<td>+17.6</td>
<td>+18.2</td>
<td>+22.4</td>
</tr>
<tr>
<td>Minimum</td>
<td>-45.9</td>
<td>-22.8</td>
<td>-27.2</td>
<td>-27.4</td>
</tr>
</tbody>
</table>

Figure 6 shows a zoom-out of the interpolated ascending LOS deformation map (from the upper left corner of Fig. 5), with superimposed locations of the leveling benchmarks, production and injection wells, and relocated M \( \geq 0 \) earthquake epicenters (Hauksson et al., 2012) as recorded by the Southern California Earthquake Network. The seismicity is abundant along the Imperial fault to the northeast and along seismic lineaments, not associated with known faults, which appear to continue from the Superstition Hills Fault (see Fig. 1 for the fault trace). By comparison, only few epicenters are seen within the Heber KGRA, however the local Heber seismic network has likely recorded more events; we have no access to these data at present.

Figure 7 shows four profiles superimposed on the ascending LOS deformation map from Fig. 5. They traverse the subsidence and uplift areas. The corresponding deformation rate profiles are shown in Figure 8. Each plot in this figure shows the four types of rates (ascending, descending, vertical, and east horizontal), together with the leveling rates for the period 2005-2010. The reason these calculations start in 2005 is that in the uplift area there was a subsidence before that, so if the whole period of the satellite data is used (2003-2010), the rates reflecting the uplift would be contaminated by the earlier subsidence, and therefore underestimated. Note that the leveling rates (green triangles in Fig. 8) are directly comparable only with the vertical decomposed rates (pink lines in Fig. 8). We can see that for the most part there
is good agreement between the leveling and satellite vertical rates (i.e., the green triangles are on, or close to the pink curves). The largest discrepancy is seen for one benchmark along profile 3. The reason is that this benchmark is located near the maximum observed subsidence, where there are only ascending PS. Since the presence of both ascending and descending PS is needed to calculate the vertical component, the vertical movement near this benchmark can be only interpolated from the flanks of the subsidence area. Because the interpolation is linear, the vertical movement here (pink line) is likely underestimated.

Another way to look at the results is to calculate the mean time series within small polygons of interest. Figure 9 shows two polygons, A and B, from the uplift and subsidence areas, respectively. The corresponding mean deformation time series from SqueeSAR are shown in Figure 10, along with the individual leveling time series for the benchmarks falling within the polygons. The leveling time series are shown for the whole period, for which leveling data are available, i.e., since 1994. It is clear that in the subsidence area outlined from the satellite data (i.e., for the period 2003-2010), the benchmarks have been indicating subsidence since 1994, whose rate got accelerated after 2005. In the uplift area, the benchmark time series also indicate subsidence for a while, but after 2005 the vertical movements turn into uplift. Note that the horizontal components from the satellite results (2003-2010) show eastward (positive) movements in the subsidence area and westward (negative) movements in the uplift area. In this rendition of the deformation results, one compares the slopes (measuring the rates) of the leveling time series (green curves) with the slopes of the vertical time series (pink curves). There is overall good correspondence between the leveling and satellite vertical measurements. Note that the leveling time series are from individual locations throughout the polygons, whereas the satellite results are averaged over the whole polygons.

Table 2 shows mean rates for the two polygons, A and B, from Fig. 9. Mean ascending and descending LOS rates are generally not the same for a given polygon, but the differences are exaggerated here, because of lack of descending PS points where the largest movements are observed (only “witnessed” by the ascending data). The uplift rates are calculated after 2005, because this is when the uplift starts. Comparing the mean values of the satellite derived
vertical rates and the leveling rates for these two polygons, we can see that they are within only about 2 mm/year from each other.

Figure 11 shows the production and injection wells at Heber. In Figure 12 we compare the time series of the monthly fluid volumes with the leveling time series at the benchmarks in the vicinity of the wells. For this purpose, four polygons are outlined, A to D. Polygon A, near the border between the uplift and subsidence areas, includes only injection wells. Polygon B, in the western part of the subsidence area, includes only production wells. Polygons C and D include both production and injection wells.

Fig. 12 reveals the connection between the characteristics of the leveling benchmark time series and the production/injection volumes. The turn-around from subsidence to uplift, indicated by the leveling benchmarks in Polygon A, occurs when the injection levels are ramped up over a period of about 5 to 6 years. The injection volume levels out in mid-2010, which leads to resumed subsidence, but this is after the 2003-2010 period of the satellite data, so this effect cannot be observed in our SqueeSAR results. In Polygon B, production is increased at the same time when injection is increased in Polygon A to the west. This initially leads to flattening of the benchmark time series, but subsidence resumes after 2008 with changes in the ratio between the injected and produced fluid volumes. Polygons C and D contain both injection and production wells. After 2008 subsidence accelerates with increased production in Polygon C, even though injection is also increased. In polygon D, where production is steadily larger than injection, increased subsidence occurs after 2005, when the injection volume is decreased by about 25%.

The maximum uplift occurs to the west and northwest from the subsidence area, at a distance of 4 to 5 km from its center, and

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**Table 2.** Mean rates at polygons A and B from Fig. 9.

<table>
<thead>
<tr>
<th>Area</th>
<th>Asc</th>
<th>Desc</th>
<th>Vert</th>
<th>East</th>
<th>Mean Lev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsidence 2003-2010</td>
<td>38.7±0.2</td>
<td>-19.3±0.3</td>
<td>-27.5±0.3</td>
<td>+13.8±0.8</td>
<td>-25.4±4.7</td>
</tr>
<tr>
<td>Uplift 2005-2010</td>
<td>+19.3±0.4</td>
<td>+6.2±0.2</td>
<td>+14.5±0.2</td>
<td>-19.6±0.5</td>
<td>+16.4±0.9</td>
</tr>
</tbody>
</table>

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about 2 km from the westernmost injection wells (Polygon A in Fig. 11). There is more total injection in Polygons C and D, but there is also production there, whereas injection and production in Polygons A and B are spatially separated. Although the wells are directional (James et al., 1987), in the absence of additional information, the structural control leading to uplift at such a distance from injection, is not clear.

5. Conclusions

The InSAR technique used in this work, SqueeSAR, as applied to satellite data, is very effective in detecting surface deformation in agricultural areas, such as that of the Heber geothermal field in southern California. We present surface deformation maps, profiles of annual deformation rates, and mean deformation time series in polygons of interest, with all of these compared to observations from annual ground-based leveling surveys. For the period of satellite data used, 2003-2010, two distinct areas of uplift and subsidence are observed at Heber, but leveling data back to 1994 show that the uplift area was previously subsiding, up to about 2005. This changing trend can be directly connected to changes in levels of injection. In this capacity, we demonstrate that satellite observations of surface deformation can be effectively used for assessment of the conditions in geothermal fields, planning, and if needed, impact mitigation.

6. Acknowledgments

Support from the Geothermal Grants and Loans Program of the California Energy Commission (CEC), Grant GEO-10-001, is gratefully acknowledged. The Imperial County Department of Public Works (ICDPW) is thanked for providing digital data for the leveling surveys at the Heber geothermal field. We also thank Alex Schriener from CalEnergy for assuring match share to the CEC grant, helping with the interpretation of the InSAR results, and directing us to relevant information. The Envisat satellite data were obtained from the European Space Agency (ESA) as part of an approved Category-I research data proposal. Data for the production and injection wells were obtained from http://www.conservation.ca.gov/dog/geothermal/.

Figure 11. Polygons, for which benchmark time series and monthly volumes of produced and injected fluid are shown in Fig. 12 next. Benchmarks are shown with empty triangles, production wells with black circles, and injection wells with black squares. Small crosses mark M ≥ 0 earthquake epicenters.

Figure 12. Time series of leveling at benchmarks and of monthly fluid volume produced and injected within the four polygons marked in Fig. 11. Bold lines show time series of total monthly fluid volume for all wells within a polygon. Dashed lines show time series at individual wells. Injection is shown with red lines, and production with blue lines. Leveling time series at individual benchmarks within the polygons are shown with green. Circles show earthquake occurrence times.
7. References


