Application of InSAR to Subsidence Monitoring in the Geothermal Fields of Imperial Valley, California

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ABSTRACT

This is a preliminary report on a new project that will be initiated in the summer of 2006. We will be applying interferometric synthetic aperture radar (InSAR) to the monitoring of surface subsidence that may result from the increase of geothermal production over the next decade in the Imperial Valley of southern California. Compared with time-consuming and expensive land-based methods for detecting and mapping surface deformation, InSAR is a cost-effective technique that can assure semi-continuous monitoring of large areas. The SAR data are collected through remote sensing from spaceborne and airborne platforms. In this project we will collaborate with participants from Sandia National Laboratories, General Atomics Reconnaissance Systems, and San Diego State University. We will also collaborate closely with the geothermal industry operating the geothermal fields in Imperial Valley. We expect that our InSAR results will demonstrate economic viability, ease of application, and efficient feedback to the geothermal operators in their monitoring and mitigation efforts.

Background

The currently active geothermal fields in the Imperial Valley are Salton Sea (350 MW) operated by CalEnergy, Inc., and Heber (85 MW) and East Mesa (93 MW) operated by ORMAT Nevada, Inc. (Figure 1). Thus the present installed capacity in the Imperial Valley exceeds 500 MW. It is anticipated to increase over the next decade four- to six-fold, with an additional 2,000 to 3,000 MW. Increase in geothermal production is bound to have a larger environmental impact than that observed to date, yet it must remain compatible with the agricultural industry uses of the valley floor and the delicate balance involved in continuing the salt leaching technology.

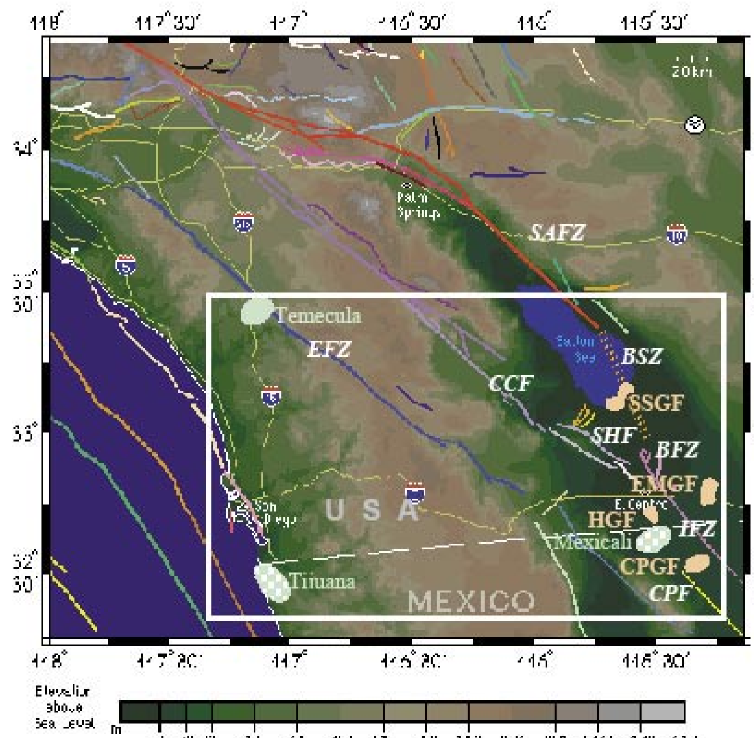

Figure 1. Map of the southernmost part of California. Adapted from the SCEC map "Faults in California/Southern Region" (http://www.data.scec.org/faults/faultmap.html). Geothermal fields and their names are marked in light orange: SSGF – Salton Sea; HGF – Heber; EMGF – East Mesa; and CPGF – Cerro Prieto. Areas of subsidence from underground water withdrawal and their names are marked in light green - filled pattern for known areas (Temecula), checkered pattern for suspected areas (Tijuana and Mexicali). Fault names are marked in white: SAFZ – San Andreas Fault Zone; IFZ – Imperial Fault Zone; CPF – Cerro Prieto Fault; EFZ – Elsinore Fault Zone; CCF – Coyote Creek Fault; SHF – Superstition Hills Fault; BFZ – Brawley Fault Zone; and BSZ – Brawley Seismic Zone.

Interferometric synthetic aperture radar (InSAR) is capable of capturing sub-centimeter surface deformation with mm-precision, with a spatial resolution of 20-30 m from spaceborne platforms, and down to tens of cm from airborne platforms. InSAR has been successfully used to identify and measure land subsidence from a variety of causes, including geothermal extraction. Yet it appears that no attempts have been made to put the technique into a routine practice. In view of the rapidly developing capabilities of SAR interferometry, our project seeks to remedy this stagnation by demonstrating that InSAR is a cost-effective tool for routine monitoring of surface deformation over large areas. In this capacity, it can supply the feedback necessary for the planning of mitigation strategies. We note that either detecting subsidence associated with geothermal activities, or asserting its absence, are very important in this endeavor.

Subsidence Due to Geothermal Field Exploitation

Abundant field evidence shows that geothermal reservoir deformation can propagate to the surface and cause vertical and horizontal displacements that have important implications both for the local environment and the continued successful exploitation of the fields. Because of environmental concerns, such as subsidence and ground water pollution, the spent fluids are usually injected back into the geothermal reservoirs. However, operational factors dictate that only a fraction of the extracted fluid is available for injection, ranging from a low of 20% for steam reservoirs to a high of 80% for hot water reservoirs. For this reason, in most cases there is a net fluid withdrawal from operating geothermal fields, generally resulting in a fluid pressure drop. In addition, injection of spent fluid is accompanied by a temperature drop in at least part of the reservoir. Thus changes in reservoir fluid content, reservoir fluid pressure, and formation temperature are the three main factors causing a redistribution of the stress and strain fields in the geothermal reservoir and the surrounding formations. One of the possible consequences of this redistribution is surface subsidence.

Subsidence has been observed in geothermal fields all over the world using GPS and leveling measurements, e.g. in Italy (Dini and Rossi, 1990), New Zealand (Lawless, et al., 2003), and right across the border from the Imperial Valley, at Cerro Prieto in Mexico (Glowacka, et al., 2003). In California, subsidence has been reported for The Geysers (Mossop and Segall, 1997) and Mammoth (Sorey and Farrar, 1998).

Although high subsidence rates are encountered in some fields (e.g., 45 cm/yr at Wairakei, New Zealand), geothermally induced subsidence typically has annual rates in the centimeter range. Even modest subsidence can have far reaching consequences, especially if the geothermal operations take place near agricultural fields, as in the Imperial Valley. This potential problem was recognized as early as in the 1970s (e.g., Crow and Kasameyer, 1978), even though only small-scale geothermal test activities (<20 MW) were taking place at that time. Indeed, agriculture in the Imperial Valley depends upon a complex system of irrigation canals and drains, constructed on the flat valley floor, which slopes gently to the north. This complex system of underground tiles could be damaged even by slight subsidence.

Spaceborne SAR, InSAR, and Differential InSAR

In ideal conditions, spaceborne InSAR is capable of capturing sub-centimeter surface deformation with mm-precision. In addition, the strong points of any radar include day-and-night and all-weather capabilities, none of which are possible for optical remote sensing systems. Unlike the point geodetic measurements using traditional, ground-based methods, radar observations from a flying platform can provide semi-continuous spatial coverage, and the possibility of frequent monitoring (e.g., every 35 days with the European satellites).

Here is a brief review of synthetic aperture radar (SAR), platforms with SAR instruments on board, interferometric SAR (InSAR) and differential InSAR. "Aperture" relates to the size of the radar antenna on a platform. The platform is generally a satellite or an airplane, although the same techniques have been applied also on the ground. The aperture would have to be physically rather large in order to achieve acceptable measurement resolution. Instead, radar data are processed in such a way that advantage is taken of the motion of the platform that carries the radar instrument. Hence, a large aperture is "synthesized"; for example, the physical size of the antenna on the European satellites ERS is 10 m, but the synthesized antenna is equivalent to a 4-km aperture.

Satellite missions with SAR instruments on board include ERS-1/2 and ENVISAT in Europe, RADARSAT-1/2 in Canada, and JERS-1 and ALOS in Japan. Side-looking spaceborne synthetic aperture radar maps a continuous swath as the satellite moves along its orbit track. A SAR scene is of linear size ~75 to 100 km. Both the amplitude and phase of the radar echoes are measured, as they come from independent patches on the ground, a few to tens of meters in size. The size of these pixels and their combination (so-called "multilooking") determines the spatial resolution of ~25 m. The future RADARSAT-2 will even offer a 3-m spatial resolution.

Several letters are commonly used in remote sensing to indicate different wavelengths. In connection to SAR, the most popular wave bands are P (wavelength ~1 m), L (~1/4 m), C (~5-6 cm), X (~3 cm), and Ku (~2 cm). The longer the wavelength, the more likely it is to penetrate vegetation, but the vertical resolution of the displacement measurements generally decreases with wavelength. ERS, ENVISAT and RADARSAT all use the C-band (5.66-cm wavelength, ~5 GHz radar frequency). This wavelength does not penetrate vegetation efficiently, because it is comparable with the predominant size of tree leaves. JERS-1 and ALOS use L-band (wavelengths 23.5cm, radar frequency ~1.3 GHz) that penetrates vegetation better than the C-band. Thus the C-band is more prone to temporal decorrelation (i.e., incoherent changes over time) than the L-band and works best for relatively arid regions, uncomplicated topography, and urban areas.

If SAR data are collected at two different times, the two images can be compared to create an interferogram (hence, InSAR), in which topography and surface displacement (if any) show up as phase differences in the form of fringe patterns. Comparing two interferograms makes it further possible to exclude topography and estimate only surface deformation, which is the subject of differential InSAR to be used in our project. Thus, InSAR is generally used to measure topography and differential InSAR is used to measure surface displacements, although the term "InSAR" is often used generically in both cases. The InSAR and differential InSAR techniques have been discussed in many publications (e.g., Bürgmann et al., 2000; Rosen et al., 2000; Zebker et al., 1994). The important point for our intended application is that surface displacement occurring between two passes translates into a phase difference that can be measured by differential InSAR. The simplified equation expressing this relationship is $d\varphi/\Delta\rho = 4\pi/\lambda$, where $d\varphi$ is the phase change, $\Delta\rho$ is the displacement measured along the line connecting the ground and the satellite (i.e., line of sight, LOS), and λ is the microwave length used by the SAR instrument. This relationship shows, somewhat counter intuitively, that the amount of surface change captured by InSAR does not depend on the altitude of the platform. This and other details of the technique, omitted here, lead to the unprecedented power of InSAR to detect rather small surface deformations. InSAR is much more sensitive to such changes than to the topography. For example, for the ERS satellites, 1-m of topography results in a phase signature of ~4.3°, while a 1-m surface displacement results in a 3000 times larger effect on the phase. Thus while InSAR can be used to determine topography to an accuracy of meters (from satellites) or tens of centimeters (from airplanes), displacements can be theoretically determined at the sub-centimeter level with millimeter precision.

We note that although differential InSAR is capable of capturing small deformations in ideal conditions (e.g., dry and low-vegetated areas for C-, X, and Ku-bands), the measurements can be adversely affected by various errors due to atmospheric propagation effects, satellite orbit errors, and temporal decorrelation. Thus comparison with ground-based measurements, such as leveling and GPS, plays an important role in validating the InSAR observations.

Airborne InSAR

The airborne SAR instruments date back to the 50's, starting with strictly military applications. Commercialization of the traditionally military airborne SAR has been slow, due to lack of understanding of its possible benefits, and high costs associated with building the SAR instruments. Airborne differential InSAR used to be considered unsuitable for detection of surface deformation, because due to atmospheric winds airplane trajectories could not be determined as accurately as satellite orbits. However, there are several reasons to expect that at present airborne differential InSAR is quite applicable to subsidence detection, even though it has remained largely untapped in this respect. It cannot improve on the already very high precision of detection of vertical displacements from satellites, but can provide much better spatial resolution. The key technology developments in the last decade that make this possible are as follows: (1) greatly improved navigation systems that enable airborne platforms to fly the same course multiple times; (2) adaptive algorithms that allow estimation of any registration and stretching corrections necessary to achieve the high correlation required for coherent exploitation of image pairs; and (3) readily available high-quality SAR imagery and the ability to control the collection of the appropriate image pairs. Thus it is now feasible to use airborne differential InSAR for detection of surface displacements and we intend to demonstrate it as part of this project.

Details on airborne SAR are given by Jakowatz et al. (1996) from Sandia National Laboratories. There exist a number of airborne SAR systems, too numerous to list here. An example of recent advances is the Lynx system resulting from collaboration between *Sandia National Lab* and *General Atomics* (Ku-band, 2 cm wavelength), providing 10-cm 30-cm spatial resolutions at distances of up to 25 km and 55 km, respectively. This fine resolution makes it possible to detect very small surface penetrations, such as footprints in a soft terrain (Burroughs, 1999). In fact, most of the interest of the military for airborne SAR has been wrapped around its capability to identify target movement with high accuracy.

A recent NASA-funded project at the Jet Propulsion Laboratory intends to put L-band SAR on a UAV (unmanned aerial vehicle) platform to support the long term interest to accurately measure surface deformation (http://esto.nasa.gov/conferences/estc2004/papers/b1p2.pdf). The capabilities developed in that project will be unparalleled so far for a civilian system. The instrument will be mounted on a UAV by the fall of 2006 and may become available for data collection on request by 2008. These rapid advances will eventually lead to decreased costs of collection of airborne SAR data suitable for differential InSAR, and hence for detection of crustal deformation for commercial purposes.

Examples of Subsidence Detection in Geothermal Fields Using Spaceborne InSAR

Numerous examples of applications of InSAR to surface deformation due to non-geothermal causes have accumulated over the last decade, such as caused by earthquakes, water pumping, and mining. Regardless of the cause, these are all examples indicating that InSAR is a viable tool for detection of surface deformation in general, of which subsidence over geothermal fields is just one particular example.

There have been several applications of differential radar interferometry to geothermal fields, demonstrating the feasibility of this type of monitoring. Carnec and Fabriol (1999) and Hanssen (2001) used ERS SAR in the Cerro Prieto Geothermal Field just south of the Imperial Valley fields. They identified annual subsidence rates of up to 16 cm. Massonnet et al. (1997) used two ERS SAR scenes to show 7.5 cm of subsidence over two years in the East Mesa geothermal field in Imperial Valley. Coso, in eastern California, provides another prominent example of a geothermal field where subsidence was observed with InSAR (Fialko and Simons, 2000; Wicks et al., 2001). Up to ~3.5 cm/yr subsidence was detected in interferograms covering the period between 1992 and 1997. Another InSAR result is from the Euganean geothermal field in Italy (Strozzi et al., 1999), where ERS SAR scenes between 1992 and 1996 were used to detect a subsidence rate as low as 0.4 cm/yr.

All radar interferometry applications listed above used ERS C-band SAR data. Two applications of L-band SAR data from JERS-1 are also relevant to the proposed work, even though they do not concern geothermal fields. One detected annual subsidence of up to 10 cm/yr in Jakarta, Indonesia, due to water extraction (Hirose et al., 2001), and the other identified uplift of up to 19 cm after steam injection and subsidence of 17 cm following production, both between two consecutive passes of the satellite (44 days for JERS-1), in the vegetated area of the Cold Lake oil field, Albert, Canada (Stancliffe and van der Kooij, 2001). This indicates that both archived JERS-1 SAR data and future data from the PALSAR instrument on the recently launched ALOS will be very useful over the vegetated and agricultural areas in the region of interest to the present proposal.

Project Plan

We will focus on the three operational geothermal fields in Imperial Valley - Salton Sea, Heber, and East Mesa - with attention to other possible causes of subsidence, such as non-geothermal water withdrawal and tectonic causes; see Figure 1 for active faults and sites of water pumping, in addition to the geothermal sites. A primary goal of the project is to bring InSAR into common practice for monitoring subsidence that may result from exploitation of geothermal fields. This technique can provide cost-effective semi-continuous large-scale spatial coverage that cannot be achieved by other means. InSAR is important with its capability to detect subsidence everywhere in a geothermal field, and not just where GPS or leveling instruments are placed.

As part of this project we will stay in close contact with the geothermal industry in the Imperial Valley (ORMAT Nevada, Inc. and CalEnergy, Inc.) and concerned government regulatory agencies (Imperial County Planning Department and the Department of Conservation/Division of Oil, Gas, and Geothermal Resources (DOGGR). Both ORMAT Nevada, Inc. and CalEnergy Inc. have agreed to provide historic and current proprietary records of ground-based subsidence measurements (generally from leveling), and times and locations of fluid extraction and re-injection. In view of the intended increase of geothermal production in the Imperial Valley, our project has the potential to alert geothermal operators to locations of unintended amounts of subsidence and thus aid them in decision-making on future extraction and injection. Our work can be also very useful to assert absence of subsidence, which is the ultimate goal of mitigating the environmental impact of the geothermal operations.

The spaceborne data in this project will come from the Canadian RADASAT-1, and former (ERS-1 and ERS-2) and current (ENVISAT) European satellites, all with C-band SAR instruments on board. We will order the European SAR data from Eurimage (http://www.eurimage.com) and/or the European Space Agency-ESA (http://earth.esa.int). The RADARSAT-1 data will be ordered through the Alaskan SAR Facility (http://www.asf.alaska.edu/), which is the mediatory for the U.S., and/or from the Canadian Data Processing Facility (http://rsi.ca/products/sensor/radarsat/rs1_price_us.asp). In addition, L-band data from the newly launched ALOS will be ordered from the Japan Aerospace Exploration Agency (JAXA), https://www.eoc.jaxa.jp/iss/en/index.html. Finally, if the Canadian RARSAT-2 (C-band) gets launched during the period of project performance, we will attempt to use its data as well.

The airborne SAR data in this project will be collected in the Ku-band (~2cm wavelength) by General Atomics. The data collection will be carried out at three different times at least six months apart, over a site of size 2 km x 2 km to 5 km x 5 km, with spatial resolution of 1 m. These data will be processed at Sandia National Lab.

Some areas of interest are relatively dry and non-vegetated (e.g., parts of East Mesa) and thus most suitable for the intended project. However, agricultural lands are ubiquitous in Imperial Valley and may present decorrelation problems in the C-band (spaceborne) and the Ku-band (airborne). This can result in masking surface displacements, or reducing the accuracy with which they are determined. The magnitude of this problem will become clearer after the data analysis starts. There are several mitigating strategies that can be implemented in this respect: (1) use of existing permanent scatterers in the area, such as paved roads and buildings, which remain the same even with changing vegetation cover; (2) placement of so-called corner reflectors (e.g., metal sheets and/or boxes with gravel) in strategic locations in order to provide additional permanent scatterers amidst vegetation; (3) stacking interferograms from scenes collected frequently enough to decrease temporal decorrelation. In addition, we will use L-band data from the Japanese satellite ALOS, which are expected to be much less sensitive to vegetation.

Summary

In conclusion, we believe that this project will help the geothermal industry in California to:

- conduct cost-effective monitoring of the environmental impact of geothermal extraction (in terms of surface subsidence);
- assure compliance with applicable laws, regulations, and ordinances;
- identify and implement measures to mitigate the adverse impacts of production (e.g., make decisions to adjust rates and sites of extraction);
- mitigate secondary adverse effects (e.g., effect of subsidence on agriculture);
- maintain good public relations by assuring environmentally friendly operations; and
- reduce costs associated with mitigation efforts.

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References

Bürgmann, R., P. A. Rosen, and E. J. Fielding, Synthetic aperture radar interferometry to measure Earth's surface topography and its deformation, *Ann. Rev. Earth Planet. Sci.* 28, 169-209, 2000.

Burroughs, C., Sandia, General Atomics unveil new fine resolution synthetic aperture radar system, EurekAlert, Public Release date: 30 August, 1999.

Carnec, C., and H. Fabriol, Monitoring and modeling land subsidence at the Cerro Prieto geothermal field, Baja California, Mexico, using SAR interferometry, *J. Res. Lett.* 26, 1211-1214, 1999.

Crow, N.B., and P.W. Kasameyer, 1978, Monitoring natural subsidence and seismicity in the Imperial Valley as a basis for evaluating potential impacts of geothermal production: Geothermal Resources Council, Transactions, v.2, p. 125-128.

Dini, I., and A. Rossi, 1990, Monitoring ground elevation changes in the Larderello Geothermal region, Tuscany, Italy: Geothermal Resources Council Transactions, v. 14, p. 1109-1114.

Fialko, Y., and M. Simmons, Deformation and seismicity in the Coso geothermal area, Inyo County, California: Observations and modeling using satellite radar interferometry, *J. Geophys. Res.* 105, 21781-21793, 2000.

Glowacka, E., O. Sarytchikhina, and J. Contreras, 2003, Subsidence in the Cerro Prieto Geothermal Field: Relation between tectonic and anthropogenic components: Geothermal Resources Council Transactions, v. 27, p. 473-475.

Hanssen, R.F., *Radar Interferometry: Data Interpretation and Error Analysis*, Kluwer Acad. Publ., London, 2001.

Hirose, K., Y. Maruyama, D. Murdohardono, A. Effendi, and H.Z. Abidin, Land subsidence detection using JERS-1 SAR interferometry, in *Proc. 22nd Asian Conf. Rem. Sens., 5-9 November, Singapore*, 2001.

Jakowatz, C.V. Jr., D.E. Wahl, P.H. Eichel, D.C. Ghiglia, and P.A. Thompson, Spotlight-Mode Synthetic Aperture Radar: A Signal Processing Approach, Kluwer Academic Publishers, Boston, pp. 429, 1996.

Lawless, J., W. Okada, S. Terzaghi, G. Ussher, P. White, and C. Gilbert, 2003, Two dimensional subsidence modeling at Wairakei-Tauhara, New Zealand: Geothermal Resources Council Transactions, v. 27, p. 761-764.

Massonnet, D. and K.L. Feigl, Radar interferometry and its applications to changes in the Earth's surface, *Rev. Geophys.* 36, 441-500, 1998.

Mossop, A., and P. Segall, Subsidence at The Geysers geothermal field, N. California from a comparison of GPS and leveling surveys, *Geophys. Res. Lett.* 24, 1839-1842, 1997.

Rosen, P.A., S. Hensley, I.R. Joughin, F. Li, S.N. Madsen, E. Rodrigez, and R.M. Goldstein, Synthetic aperture radar interferometry, in *Proc. IEEE* 88, 333-382, 2000.

Sorey, M.L., and C.D. Farrar, 1998, Changes in Surficial features associated with geothermal development in Long Valley Caldera, California 1985-1997: Geothermal Resources Council Transactions, v. 22, p. 61-63.

Stancliffe, R.P.W., and M.W.A. van der Kooij, The use of satellite-based radar interferometry to monitor production activity at the Cold Lake heavy oil field, Alberta, Canada, *AAPG Bull.* 85, May 2001.

Strozzi, T., L. Tosi, L. Carbognin, U. Wegmüller, and A. Galgaro, Monitoring land subsidence in the Euganean geothermal basin with differential SAR interferometry, in *Proc. FRINGE'99, Liege, Belgium, 10 -12 November*, 1999.