Subsidence Monitoring in Imperial Valley, California, Using Satellite Radar Interferometry

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ABSTRACT

We are in the process of applying interferometric synthetic aperture radar (InSAR) techniques to the monitoring of surface subsidence associated with geothermal production in the Imperial Valley of southern California. Subsidence may increase over the next decade as a result of enhanced geothermal production in the region. InSAR is a cost-effective technique for detecting and mapping surface deformation that allows semi-continuous monitoring of large areas, thus potentially overshadowing in the future the time-consuming, area-limited, and expensive land-based methods. There are several types of data that will be used in this project, of which we have started with existing data from the ERS satellites (1992-2000) collected over the Salton Sea geothermal field. Since traditional InSAR is limited in vegetated areas, a permanent scatterers technique (PSInSAR) is being used that is likely more suitable in agricultural areas. We collaborate closely with the geothermal operators who provide proprietary leveling data

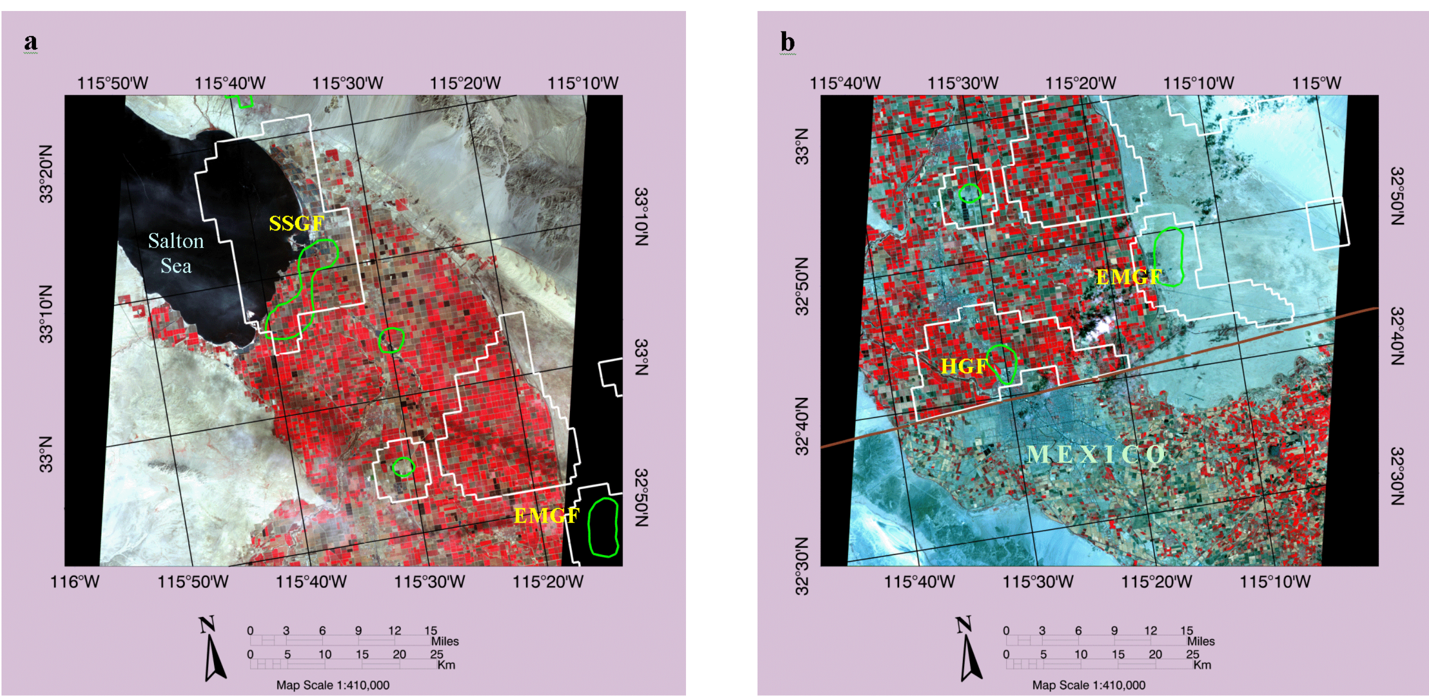

Figure 1. Two satellite images showing study area (ASTER VNIR Level 1B). Red indicates vegetation (RGB representation: R is centered at 0.807 mm, G at 0.661 mm, and B at 0.556, i.e. ASTER bands 3, 2, and 1, respectively). The three geothermal fields are marked as follows: SSGF (Salton Sea), EMGF (East Mesa), and HGF (He-ber). Green outlines mark production areas. White outlines mark known geothermal resources areas. (a) Northern part of study area. (b) Southern part of study area. Brown line marks national border. Note different agricultural pattern in the U.S. compared with Mexico.

for comparison. We expect that our InSAR results will demonstrate economic viability, ease of application, and efficient feedback to the geothermal industry in their monitoring and mitigation efforts.

Background

This project focuses on the three operational geothermal fields in Imperial Valley - Salton Sea, Heber, and East Mesa (Figure 1) - with attention to tectonic causes of subsidence in addition to geothermal extraction. The present installed capacity in the Imperial Valley exceeds 500 MW - Salton Sea (350 MW) operated by Cal Energy, Inc., and Heber (85 MW) and East Mesa (93 MW) operated by Ormat Nevada, Inc. An increase of additional 2,000 to 3,000 MW is anticipated over the next decade, which may have a larger environmental impact than that observed to date, yet must remain compatible with the extensive agricultural use of the Imperial Valley.

Field evidence, such as GPS and leveling measurements, shows that geothermal production can cause surface displacements. Reported examples include areas right across the border from the Imperial Valley, at Cerro Prieto in Mexico (Glowacka, et al., 2003); elsewhere in California, such as The Geysers (Mossop and Segall, 1997) and Mammoth Lakes (Sorey and Farrar, 1998); Italy, New Zealand, etc. Geothermally induced subsidence typically has annual rates in the centimeter range or lower, although high subsidence rates are encountered in some fields (e.g., 45 cm/yr at Wairakei, New Zealand). Subsidence information and appropriate response to it can be very valuable for the continued exploitation of the geothermal fields while minimizing possible adverse environmental effects. The information on subsidence can also help the geothermal operators in evaluating reservoir properties and extent.

Interferometric synthetic aperture radar (InSAR) is capable of capturing sub-centimeter surface deformation with mm-precision over large areas, with a spatial resolution of 20-30 m from spaceborne platforms. Unlike the point geodetic measurements using traditional, relatively expensive ground-based methods, satellite radar interferometry can provide semi-continuous spatial coverage and the possibility of frequent monitoring (e.g., every 35 days). When 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 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 interferometry (DInSAR). Thus, InSAR is generally used to measure topography and DInSAR is used to measure surface displacements, although the term "InSAR" is often used generically in both cases. The InSAR and DInSAR techniques have been discussed in many publications (e.g., Bürgmann et al., 2000; Massonnet and Feigl, 1998; Zebker et al., 1994). A newer technique using so-called "permanent scatterers" in the radar scenes (PSInSAR) makes it possible to extract time series of surface deformation at numerous points of the scenes (Ferretti and al., 2000; Hooper et al., 2007).

Several applications of DInSAR to geothermal fields have been reported, demonstrating the feasibility of this type of monitoring. Examples include the Cerro Prieto geothermal field in Mexico (e.g., Hanssen, 2001), the Coso Geothermal Project in eastern California (e.g., Fialko and Simons, 2000; Wicks et al., 2001), and the Euganean geothermal field in Italy (Strozzi et al., 1999). Also, Massonnet and Feigl (1998) used conventional DInSAR to show up to 7.5 cm subsidence over two years in the East Mesa geothermal field in Imperial Valley.

Past and current satellite missions with SAR instruments on board include the European ERS-1/2 and ENVISAT, and the Canadian RADARSAT-1/2, all of which use a wavelength of 5.66 cm (so-called C-band). This wavelength does not penetrate vegetation efficiently. Thus the conventional DInSAR technique is optimal in less vegetated, dry and urban areas. However, the PSInSAR technique tackles this problem by extracting surface deformation information from numerous points scattered throughout vegetated areas.

In this project we will use all of the above types of SAR data, applying both the DInSAR and PSInSAR techniques. Past and future data collected over all three geothermal fields in Imperial Valley will be analyzed and compared with proprietary leveling data provided by the geothermal operators. Here we report initial results from applying the PSInSAR method to archived ERS SAR data (1992-2000) collected over an area including the Salton Sea geothermal field.

This project seeks to demonstrate that InSAR is a cost-effective tool for routine monitoring of surface deformation over large areas. InSAR is unique with its capability to detect subsidence everywhere in and around a geothermal field, and not just where GPS or leveling instruments are placed. The technique has the potential to inform the geothermal operators about the locations of subsidence and thus aid them in decision-making on future extraction and injection. In this context, both detecting subsidence associated with geothermal production or confirming its absence, are important.

Preliminary Results

We started with the existing 1992-2000 SAR data collected by the European ERS satellites over an area including the Salton Sea geothermal field. Since this field is in the midst of numerous agricultural fields, where the conventional DInSAR technique may be of limited value, the PSInSAR technique was applied to a series of 20 ERS SAR images. Two software packages developed at Stanford University are being used to extract time series of surface deformation at a number of points that appear as permanent scatterers in the SAR scenes. The first one is the StaMPS software (Hooper et al., 2007) and the second one, allowing for more permanent scatterers to be extracted, is an improvement incorporating a maximum likelihood method. The average annual deformation rates extracted from the time series of the second method are shown in Figure 2. These rates are relative to a point assumed to not have moved during the study period. The same reference point is also used by the geothermal operators in the annual leveling measurements at Salton Sea. Figure 3 shows a time series of the individual interferograms used for the rates in Figure 2.

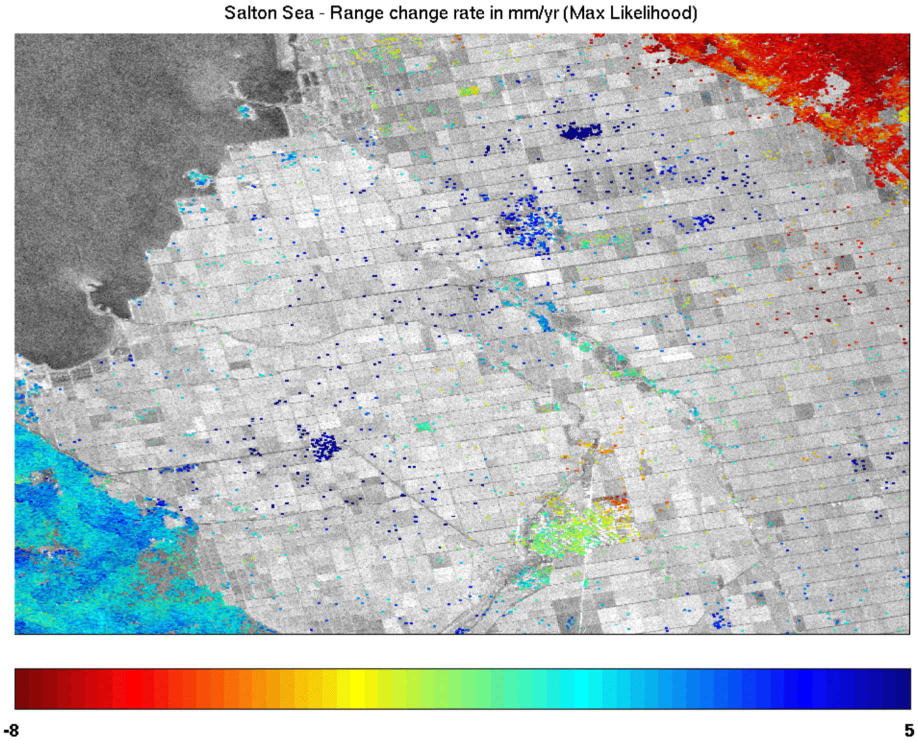

Figure 2. Surface deformation rates (mm/yr) extracted from 1992-2000 ERS SAR data over the Salton Sea geothermal field. Colored points are permanent scatterers. Negative values imply direction of movement towards the satellite, provided that the arbitrary reference point has not moved. Should it in fact be subsiding, the re-maining permanent scatterers might be also subsiding but at a lower rate.

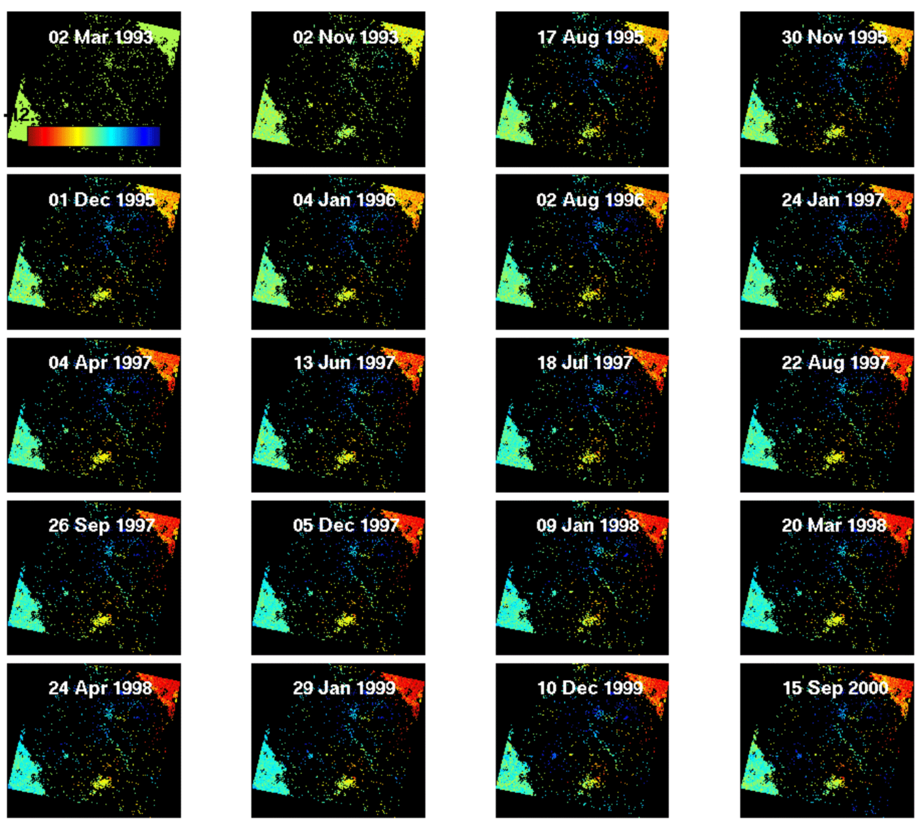

Figure 3. Time series of individual interferograms used to extract the rates shown in Figure 2.

Future Plans

Continued work on this project will include comparisons with the existing information on regional tectonic subsidence and the proprietary leveling data at Salton Sea provided by CalEnergy, Inc. In addition, we just obtained 37 SAR scenes and are in the process of acquiring about 50 more scenes from the ERS successor, the ENVISAT satellite. These data have been collected since 2003 and continue to be acquired, so that they will be very useful for the evaluation of recent and future subsidence rates. We will also use data from the Canadian RADARSAT satellite. This type of analysis will be done for the other geothermal fields in Imperial Valley as well. Although a considerable amount of analysis remains to be carried out, we can already attest to the significant promise of InSAR as a tool for subsidence monitoring.

Conclusions

This is a work in progress - at time of writing the project is only in its third month. We present preliminary results from the analysis of older ERS data (1992-2000) collected over the Salton Sea geothermal field, applying the PSInSAR technique. We were able to identify deformation rates at a number of points throughout the area. These results will be further tied to proprietary leveling data. ERS data over the two other fields (Heber and East Mesa) and the surrounding region will be analyzed in near future. In addition, we are in the process of acquiring SAR data from the ENVISAT and RADRASAT satellites, as well as making arrangements for frequent coverage of the whole area over the next two years.

Although this project is at an early stage, all indications point to the significant potential of InSAR to help the geothermal industry in California in conducting cost-effective monitoring of the subsidence associated with geothermal extraction. InSAR can assure coverage at a higher density of locations over a much larger region than leveling surveys, at a comparable or lower cost. This type of monitoring can significantly help to assure compliance with various regulations and to maintain good public relations by conducting environmentally friendly operations.

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