Advanced InSAR Techniques for Geothermal Exploration and Production

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ABSTRACT

InSAR is a remote sensing tool that has applications in both geothermal exploration and in the management of producing fields. The technique has developed rapidly in recent years and the most evolved algorithms, now capable of providing precise ground movement measurements with unprecedented spatial density over large areas, allow, among other things, the monitoring of the effects of fluid injection and extraction on surface deformation and the detection of active faults.

Multi-interferogram approaches have been used at several geothermal sites in the US and abroad. Two examples are presented here with the aim of illustrating how these techniques are being used for different stages of geothermal exploration and management. In both cases, multiple advanced InSAR techniques were used to quantify surface expression patterns, with a focus on the SqueeSAR™ approach, the latest breakthrough in InSAR technology.

The first case study examines the Salton Sea area (California), where multi-interferogram InSAR provided an overview of surface deformation at a producing geothermal reservoir. Surface deformation in this area was complex, and the added detail provided insight into the interplay of tectonics and production activities. The second example involves the use of InSAR within a suite of tools for exploration of the San Emidio geothermal field in Nevada, as part of a DOE funded initiative. This project aimed to develop geophysical techniques to identify and map large aperture fractures for the placement of new production/exploration wells.

Additional InSAR studies have also been carried out at several areas in Nevada, including the Brady and Desert Peak fields and in California at the Geysers field. These studies, along with ongoing developments in radar satellite technology and in the field of InSAR, show considerable promise for the future monitoring of geothermal production facilities.

Introduction

Geothermal energy is a rapidly growing source of power within the United States, which has the highest installed capacity for geothermal energy production in the world (13 GWth) and generates more than 3,150 MW of electricity on an annual basis (REN21, 2010). Changes in underground water levels, pressure and temperature caused by production activities can lead to surface subsidence occurring over areas of geothermal energy production. As a result, monitoring is required in order to assess the surface-level impacts of production activities. The use of conventional ground-based techniques (such as GPS or levelling) makes it difficult to obtain a complete picture of movement occurring across entire geothermal fields. In contrast, InSAR provide an overview of surface movement related to extraction and injection activities over large areas, and can also be used to assess the stability, and therefore safety, of above ground infrastructure in multiple-use areas.

InSAR is a remote sensing approach that is used to monitor surface deformation occurring over large areas. Advanced InSAR techniques process a large number of satellite radar images (multi-interferogram approaches) to determine the displacement of radar targets over time. These targets can be naturally occurring features such as rock outcrops, or man-made objects such as buildings and wellheads. The processing of a long series of radar images allows the motion history of a radar target to be observed (including non-linearities), and increases measurement precision to mm level. SqueeSAR™, one of the most recent breakthroughs in InSAR, presents the further unique feature of capturing signals from spatially distributed targets covering several pixels, which has the effect of significantly increasing the density of measurement points in non-urban areas (Ferretti et al., 2011). This has benefits for geothermal applications, which are often located in agricultural, desert or other remote areas. Furthermore, it has the advantage of not requiring installation of instrumentation on the ground making it ideal for the monitoring of remote, inaccessible or restricted-access sites.

Multiple sets of radar datasets were acquired over the San Emidio geothermal field in Nevada and the Salton Sea geothermal field in California. Using advanced InSAR techniques, surface movement over the time periods analyzed was measured with millimetre accuracy at both sites. Distinct spatial and temporal patterns of subsidence and uplift, including true vertical and horizontal movement were obtained at both fields. This approach was particularly successful at the San Emidio site, due to the extremely high spatial density of measurement points identified.

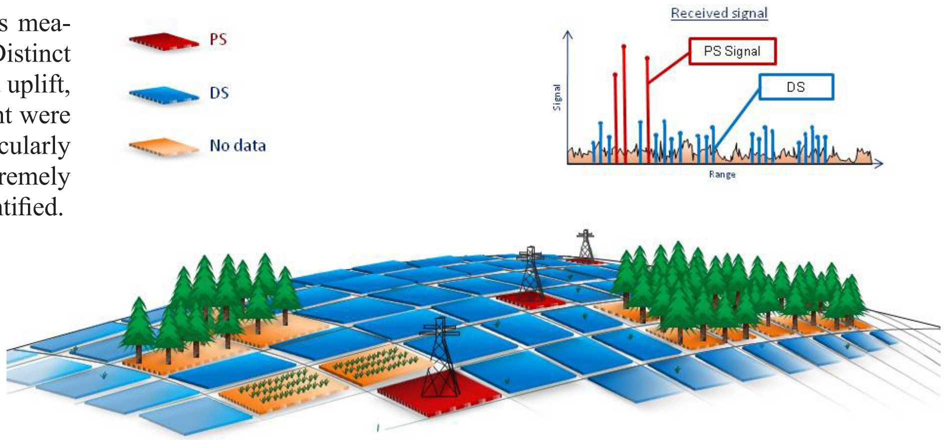

Figure 1. Illustration of the identification of Permanent Scatterers (PS) and Distributed Scatterers (DS) with the SqueeSAR™ algorithm.

Methods

Radar Interferometry

Radar satellites use a form of active remote sensing known as Synthetic Aperture Radar (SAR) to capture ground surface information over large areas. By actively emitting microwave frequencies and recording the reflected signal, SAR systems capture highly precise information on the location of features on the ground. As radar satellites provide their own illumination of the Earth's surface, they can operate continuously throughout the day and night, and in nearly all weather conditions. The signal transmitted by the SAR system is of a specific wavelength, meaning the signal echoed (reflected) from a single point on the ground and recorded by the radar satellite contains many returning radar pulses, including the fraction of the current wave cycle (phase) and the strength of the signal (amplitude). When features on the ground move, the distance between the sensor and the ground changes, which produces a corresponding change in measured signal phase. These changes in the measured phase value occurring between repeat pass image acquisitions is used to quantify ground movement.

Interferometric Synthetic Aperture Radar (InSAR), is the measurement of signal phase change over time. Differences in the signal phase values recorded between successive radar images are represented in an interferogram, which is also used to detect movement on the Earth's surface. However, there are several contributing factors that also impact phase shift including topography and atmospheric interference, which limits the accuracy of measured ground movement to centimetre scales.

PSInSAR™ and SqueeSAR™

PSInSAR™ identifies individual pixels with strong signal returns (referred to as Permanent Scatterers) in order to measure surface movement occurring over time (Ferretti et al., 2000, 2007). Natural radar targets of the Permanent Scatterer (PS) type often correspond to relatively small objects such as buildings, above-ground pipelines, or rock outcrops. The more advanced SqueeSAR™ approach not only identifies PS from radar datasets, but larger areas that also demonstrate a homogeneous signal response (referred to as Distributed Scatterers) (Figure 1). Distributed Scatterers (DS) are features extending over larger areas such as fallow fields or bare earth. By identifying both PS and DS measurement points, the SqueeSAR™ technique can usually identify a significantly higher density and greater spatial distribution of identified radar targets than traditional Permanent Scatterer (PSInSAR™ and other PSI) type methods, particularly in rural areas (Ferretti et al., 2011).

In order to measure ground movement with millimetre precision, both the PSInSAR™ and the SqueeSAR™ algorithms analyze multiple interferograms created from stacks of radar images (15 or more) (Ferretti et al., 2007). First, all of the images within a data stack are focused and precisely aligned, or co-registered, to one another. A series of statistical analyses on the phase and amplitude characteristics of the backscattered radar signals are then used to identify scatterers (individual pixels in a PSInSAR™ analysis; individual pixels and clusters of pixels in a SqueeSAR™ analysis). Scatterers are defined as PS and DS candidates when they are detected in all, or most, of a set of SAR images. These candidates are then used to estimate and remove the contribution of atmospheric effects and orbital errors to the radar signal phase. A master image is then selected from each dataset to serve as the base image for the generation of a series of differential interferograms. The signal phase and amplitude values of each PS and DS candidate within these interferograms are then analyzed to select only the most consistent (stable) and coherent measurement points as true PS and DS points.

Movement Decomposition

The displacements measured by the satellites are one-dimensional (1D). The satellite "sees" an object on the ground either moving towards it or away from it. This is called a line-of-sight (LOS) measurement. The collection and processing of multiple LOS datasets acquired from different viewing angles (ascending and descending orbits) allows surface movement measured by a satellite to be combined and decomposed into different vectors of movement. Decomposition is achieved first by re-sampling and then averaging all measurement points identified in both the ascending and descending dataset into two regular grids. The two grids are then superimposed and the displacement rates from homologous cells are represented as vectors. The vectors are then analyzed with standard vector geometry to determine the specific geometric relationships for the detection and quantification of vertical and east-west horizontal movement.

Salton Sea Geothermal Field, California

Site Description

The Salton Sea geothermal field, located on the southern shores of the Salton Sea, consists of a network of production wells that provide water from superheated reservoirs below the Earth's sur-

Figure 2. The Salton Sea geothermal field located in California.

face to ten geothermal plants in the area. With an installed capacity of 350 MW, this site is the largest producer of geothermal energy in the Imperial Valley. The area of interest (AOI) covers approximately 35 miles squared and is shown in Figure 2. Although fluid extraction occurs deep underground, surface movement has been observed at this site prior to the onset of this analysis.

Most of the area is covered by agricultural fields, which can be challenging for InSAR analysis, as these areas are often regularly worked (causing variations in the amplitude and phase signature used to identify stable measurement points). Additional limitations for interferommetry in this area include areas of dense vegetation and water, which also cause the radar signal to decorrelate.

Radar Data and Analysis

Two sets of radar images acquired from the RADARSAT-1 satellite over the Salton Sea area of interest (AOI) were used in this study. An ascending dataset included 18 scenes acquired in S1 beam mode on Track 52, covering the time period from 20 May 2006 to 22 March 2008. The second dataset consisted of 21 images acquired from a descending orbit in S6 beam mode on Track 116, captured between 24 May 2006 and 26 March 2008. Both sets of radar imagery were analyzed with the PSInSAR™ algorithm to measure line-of-sight displacement, enabling the reconstruction of surface motion occurring over a 2-year period of geothermal operation. PSInSAR™ results were decomposed into true vertical and east-west horizontal movement. The SqueeSAR™ approach was applied to the descending dataset only, due to the higher number of images within this data stack.

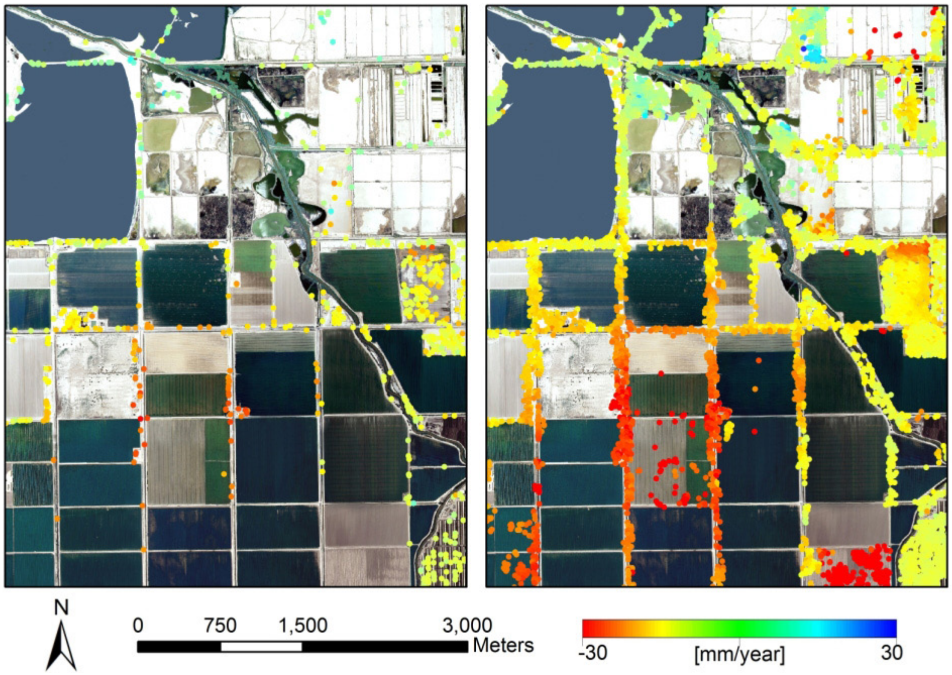

Figure 3. PSInSAR™ (left) and SqueeSAR™ (right) LOS displacement results identified from the Radarsat-1 descending dataset for a subsection of the Salton Sea geothermal field. Total displacement measured over the entire time period analyzed (2006 to 2008) ranged from -62 mm (representing movement away from the satellite) to 28 mm (movement towards the satellite).

Results

Over 3,000 and 4,400 unique PS points representing line-of-sight movement were identified from a PSInSAR™ analysis of Radarsat-1 ascending and descending data over the Salton Sea AOI. Resulting in spatial densities of 87 and 125 PS per square mile, the majority of the measurement points identified were located in areas with little to no vegetation, along roads and over the geothermal plants. In contrast, the SqueeSAR™ analysis of the descending dataset identified nearly 24,000 PS and DS points, marking a 550% increase from the results of the PSInSAR™ analysis. In addition to the PS identified from man-made structures and other point targets, numerous DS were identified from fallow fields and ditches, contributing to a density of 672 PS and DS per square mile. PSInSAR™ and SqueeSAR™ results for a portion of the AOI are shown in Figure 3.

Decomposition results indicate that this region is experiencing significant vertical subsidence and horizontal movement (Figure 4); however, previous studies found that the movement observed was mainly related to ongoing regional subsidence

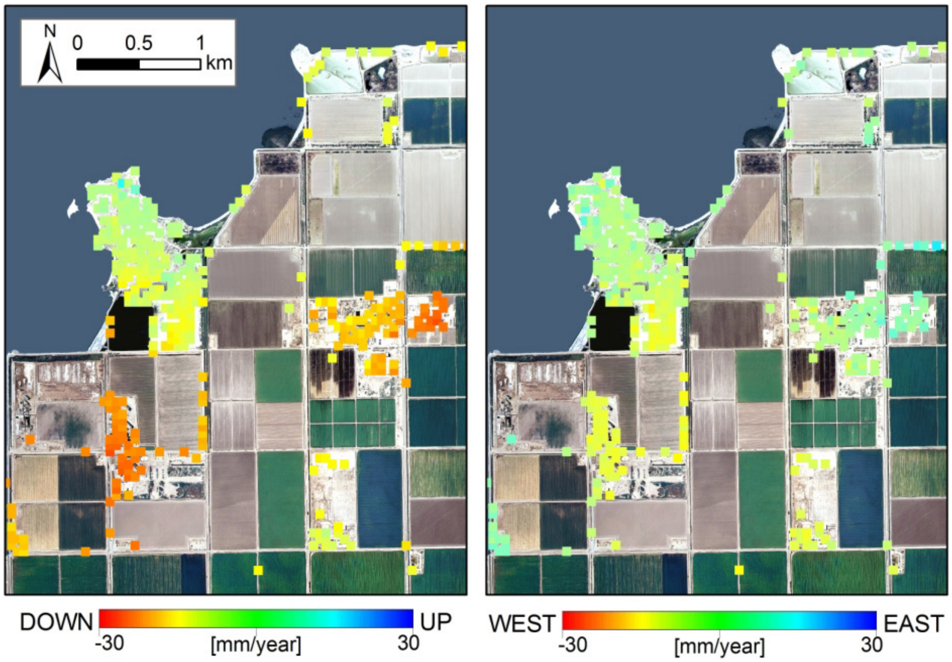

Figure 4. Vertical (left) and east-west horizontal (right) results shown for a subsection of the Salton Sea geothermal field produced by combing the ascending and descending Radarsat-1 image stacks.

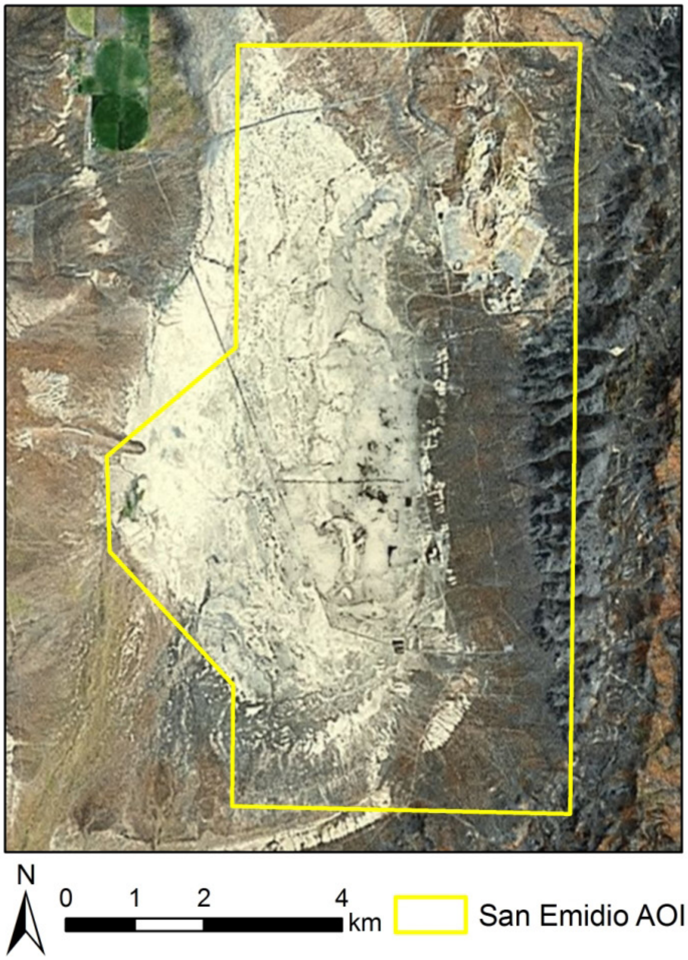

Figure 5. The San Emidio geothermal field located in Nevada.

and local tectonic activity as opposed to geothermal energy production (Eneva et al., 2009; Eneva and Adams, 2010). By pairing InSAR results with ancillary data, complex relationships between surface motion, underlying tectonics and production activities at the Salton Sea geothermal field could be revealed. Based on the high precision of the SqueeSAR™ results, the close agreement with ground-based measurement techniques (leveling data), and the ability of this technique to provide an overview of surface movement dynamics over time, this technique was recommended for future deformation monitoring over geothermal fields (Eneva et al., 2009).

San Emidio Geothermal Field, Nevada

Study Area

The San Emidio geothermal field is located in northern Washoe County, Nevada. Overseen by U.S. Geothermal Nevada, a recent project funded by the DOE was implemented to measure ground deformation occurring over the San Emidio site in order to assist in the planning of improvements to existing facilities. Up to six additional geothermal resource wells (in addition to the four production wells already at the site) have been proposed for the area. The area of interest (AOI) analyzed was 23.1 square miles in size (Figure 5). The relative lack of vegetation and arid climate make this an ideal setting for the application of InSAR. The topography of the area is relatively flat, with the exception of the eastern edge and northeastern corner of the AOI, where the terrain becomes rougher.

Radar Data and Analysis

Three archive radar datasets from the ERS and ENVISAT satellites were used to analyze movement at the San Emidio geothermal field. The first dataset comprised 36 descending orbit images collected between 3 May 1992 and 10 January 2001, from Track 27 of the ERS satellite. The second dataset consisted of 45 ascending orbit images from Track 120 of the ENVISAT satellite, while the third dataset included 52 images acquired from Track 27 in a descending orbit, also from the ENVISAT satellite. The ENVISAT ascending and descending radar datasets covered the time period from 29 October 2003 to 9 June 2010. All three datasets were analyzed with the SqueeSAR™ algorithm to determine line-of-sight displacements, and reconstruct historic movement occurring over the San Emidio site. The ascending and descending ENVISAT datasets were also decomposed to extract true vertical and east-west horizontal movement.

Results

The SqueeSAR™ processing of the three radar datasets produced radar target densities ranging from nearly 7,200 to more than 9,100 PS and DS per square mile, representing an increment of one or two orders of magnitude compared to what would have been possible to obtain with PSInSAR™. The desert environment of the San Emidio area is ideal for demonstrating the advantages of the SqueeSAR™ approach, as the arid environment and absence of vegetation meant radar targets could be identified with a near uniform distribution over the entire AOI, despite the lack of man-made structures.

Decomposition results (Figure 6) indicate that significant vertical displacement occurred at several locations throughout the period of analysis, and provide a means by which to identify surface response to production activities. Total vertical displacement measured over the time period analyzed (2003 to 2010) ranged from -138 mm (subsidence) to 28 mm (uplift). Average total subsidence observed within the subsidence bowls was approximately 60mm. While displacement was observed in close proximity to production wells, the areas experiencing the highest rates of vertical movement (western portion of the AOI) were most likely caused by surface response to decreased precipitation levels (Eneva et al., 2011). Of particular interest at the San Emidio site, are the seasonal fluctuations of ground movement, which can be observed in measurement points identified in areas of movement (Figure 7).

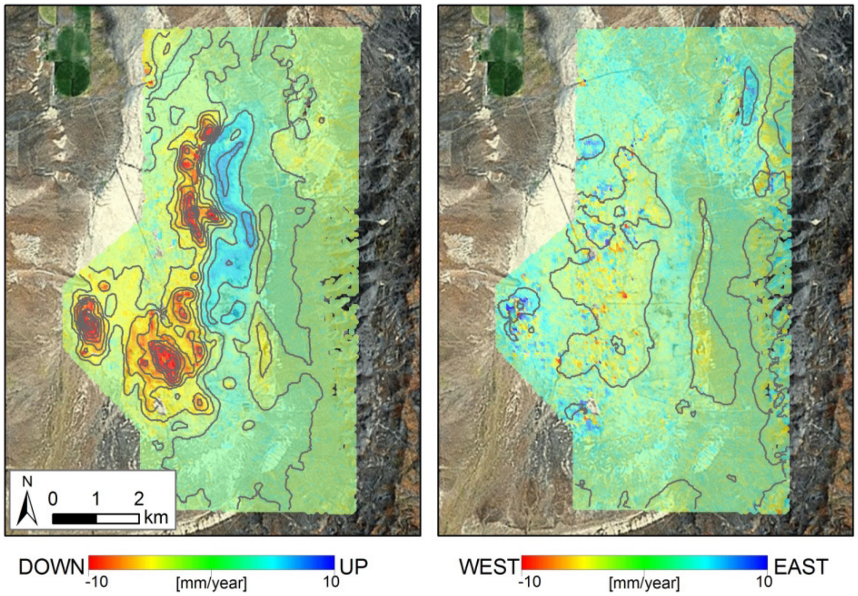

Figure 6. Decomposed vertical (left) and east-west horizontal (right) movement over the San Emidio geothermal field. Contour intervals of 2 mm are shown on both images.

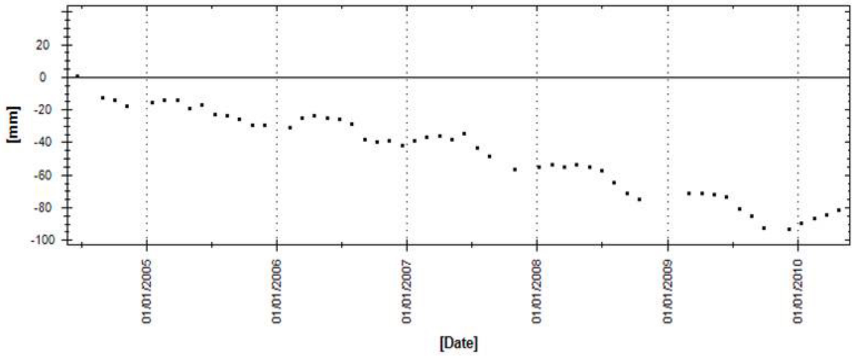

Figure 7. A typical time series showing cyclical displacement occuring in an area of subsidence. The rate of measured LOS displacement of this point is -14.38 ± 0.49 mm/year.

A significant advantage of the SqueeSAR™ approach is the potential to derive information on below-ground activity. For instance, clusters of measurement points that show sharp changes in displacement rates may indicate the presence of sub-surface structural controls on geothermal fluid movement (such as the distinct boundary between the areas showing uplift (blue) and subsidence (red) in the middle of the left panel in (Figure 6). Future work will use this data to assist in the planning of additional production and exploration well placement by providing indicators of reservoir boundary locations and below-ground connectivity, which can be useful for identifying potential untapped reservoirs.

Conclusions

The results achieved at the Salton Sea and San Emidio geothermal sites provide an indication of the potential of this technique for contributing to the exploration and management of producing fields. By mapping surface movement and using results to make inferences on the temporal evolution of sub-surface structures, advanced InSAR approaches were shown to assist in several aspects of geothermal production. Similar InSAR analyses have been carried out at the Brady, Desert Peak and Geysers geothermal fields, also located in Nevada and California. As the field of InSAR continues to grow, so too do the applications of this technique within the geothermal sector.

The recent launch of newer generation radar satellites (with X-band frequencies) offer improved surface deformation monitoring due to the fine resolution of the radar data and the shorter repeat times between acquisitions. Due to the small cell (pixel) size of X-band imagery (3 by 3 m), the ground surface can be mapped in much greater detail than is possible with C-band radar satellites (including the ERS, Envisat, and Radarsat-1 datasets analyzed at the Salton Sea and San Emidio fields). Furthermore, by acquiring repeat-pass images with a higher frequency (intervals as short as 8 days with the Cosmo SkyMed constellation of X-band satellites), the temporal evolution of surface deformation can be measured with greater detail and accuracy.

The potential of advanced InSAR techniques for geothermal field monitoring are only beginning to be realized. With geothermal energy production continuing to expand in countries throughout the world, the continued development of exploration and management approaches is needed to keep pace with demand. Advanced InSAR techniques are becoming increasingly prominent as a monitoring tool due to their comparative ease of implementation (no ground-based instrumentation is required), the high density of surface information extracted (often magnitudes higher than traditional ground-based techniques) and the millimetre scale precision of measurements. Surface deformation results obtained from PSInSAR™ and SqueeSAR™ analyses have also demonstrated correlation with known faults, levelling techniques, gravity (Bouguer anomalies), temperature, and seismic velocities. InSAR has the potential to provide a more important role in future geothermal applications.

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References

Eneva, M., and D. Adams, 2010. "Modeling of surface deformation from satellite radar interferometry in the Salton Sea geothermal field, California." Geothermal Resources Council *Transactions*, v. 34, p. 527-534.

Eneva, M., G. Falorni, D. Adams, J. Allievi, and F. Novali, 2009. "Application of satellite interferommetry to the detection of surface deformation in the Salton Sea geothermal field, California." Geothermal Resources Council *Transactions*, v. 33, p. 315-319.

Eneva, M., G. Falorni, W. Teplow, J. Morgan, G. Rhodes, and D. Adams, 2011. "Surface deformation at the San Emidio geothermal field, Nevada, from satellite radar interferometry." Geothermal Resources Council *Transactions*.

Ferretti, A., A. Fumagalli, F. Novali, C. Prati, F. Rocca, and A. Rucci, 2011. "A new algorithm for processing interferometric data-stacks: SqueeSAR™." *IEEE Transactions on Geoscience and Remote Sensing*, v. 99, p. 1-11.

Ferretti, A., C. Prati, and F. Rocca, 2000. "Non-linear Subsidence Rate Estimation Using Permanent Scatterers in Differential SAR Interferometry." *IEEE Transactions on Geoscience and Remote Sensing*, v. 38, p. 2202-2212.

Ferretti, A., G. Savio, R. Barzaghi, A. Borghi, S. Musazzi, F. Novali, C. Prati, and F. Rocca, 2007. "Submillimeter accuracy of InSAR time series: Experimental validation." *IEEE Transactions on Geoscience and Remote Sensing*, v. 45, p. 1142-1153.

REN21, 2010. "Renewables 2010 Global Status Report." Paris: REN21 Secretariat.