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New Potential of InSAR for Geothermal Systems

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ABSTRACT

Monitoring crustal deformation using interferometric synthetic aperture radar (InSAR) has frequently been applied to geothermal systems but extensive use has been hampered by costly and intermittent data. New data streams from the current Sentinel-1 A/B and upcoming NISAR satellites should provide low-cost and easily accessible data with short repeat times. These new datasets, combined with open-source software designed to process time series of interferograms, will allow routine time series processing of InSAR data over geothermal regions in the Western U.S. and worldwide. This should enable observations of temporal change in deformation with sampling at less than one-month intervals. Here we explore what signals might be resolvable, how they might be combined with other datasets, and what new information might be inferred about the geothermal systems. One example of open-source InSAR package is the GMTSAR package, which uses the Generic Mapping Tools (GMT) for back-end data analysis. It is maintained by a cross-institutional group of developers and includes the capability to process Sentinel 1 A/B data. Currently, the software is used by hundreds of scientists and engineers around the world. Yearly short courses for new users have been conducted and extensive documentation is available. We present examples of several geothermal areas examined with time series data and outline typical signals, provide examples of modeling, and address the likely resolution (spatial and temporal). Geothermal areas with little or no discernable signal are also presented to demonstrate current limits of the technique.

1. INTRODUCTION

Interferometric synthetic aperture radar (InSAR) has been used for almost 20 years to image surface deformation associated with geothermal production. One of the first clear examples was the East Mesa field in Imperial Valley, California (e.g. Massonnet et al., 1997). A number of studies have been conducted and useful constraints on geothermal extent and reservoir conditions inferred. In general, widespread adoption has been hampered by a number of factors including cost of data, the specialized knowledge and processing required to produce reliable imaging of surface deformation, and high noise due to atmospheric variations.

Recent new satellites and improved processing capabilities remedy these issues to a large extent. In particular, the advent of SAR satellite constellations, which consist of identical sensors in repeating orbits provide greater spatial coverage and reduced revisit time, which enables better data flow (Milillo et al., 2016). The Sentinel-1 satellite constellation consists of two C-band (~5 cm) imaging radar satellites, Sentinel-1A and Sentinel-1B. The exact repeat cycle is 12 days for each satellite, with 6 days possible using both satellites. The imaging mode varies, but over land the interferometric wide swath is commonly operational and has a resolution of 5 by 20 m. The data is freely available and can be downloaded within days of acquisition. Sentinel-1A was launched in April 2014 and Sentinel-1B in April 2016. The planned NISAR (NASA-ISRO Synthetic Aperture Radar) is anticipated to launch in 2020 and will be equipped with both an L-band (24 cm) and S-band (12-cm) radars. The expected repeat orbit is 12 days at a resolution of 5-10 meters.

The advantage of dense coverage with rapid repeat times is that it permits the construction of time series of interferograms over a specific site. In turn, time series analysis such as small baseline subset (SBAS) (Berardino et al., 2002) or persistent scatterer (PS) techniques (Feretti et al., 2001) allow precise measurements of surface deformation over time. These techniques are especially effective on signals that slowly evolve over time, such as deformation observed in geothermal areas. Impulsive short duration signals, as might be produced by earthquakes, are less well imaged using these methods but can still be improved.

2. NEW DATA AND PROCESSING

InSAR estimates relative changes in ground surface by calculating phase differences between radar images at different times. These measurements are with respect to the line-of-sight to the satellite. As the radar does not image vertically, the line-of-sight is at angle to the ground. The direction depends on the radar orientation and whether the satellite is ascending or descending orbit. Errors may be due to loss of phase coherence between adjacent pixels (decorrelation), often caused by vegetation growth or water, changes in atmospheric water vapor content or in the ionosphere, both of which can cause spurious phase changes, or artifacts in processing due to orbit errors or inadequate DEM corrections. The effect of the errors depends on the radar wavelength, which is typically either 3 cm (X-band), 5 cm (C-band) or 21 cm (L-band). Longer wavelengths tend to show slower decorrelation over time and are more effective in vegetated terrains but differ in resolution.

In general, generation and interpretation of interferograms has required specialists' knowledge, first to understand and acquire the appropriate data from a plethora of satellites with different modes, formats, and orbits, and second, to process and interpret the data. Significant computer resources are also needed to accommodate the terabytes of data, intermediate products, and multiple interferograms.

Even a short time series analysis can generate 100's or 1000's of interferograms. This presents a significant barrier but, with the advent of large datasets, considerable effort is being made to streamline the processing.

2.1 Processing

A wide variety of processing software is available, from open-source to commercial. For recent satellites, focused data is available, which reduces the amount of processing needed for a specific pair. However, the advent of large amounts of data for a single area has increased the amount of disk space required. In general, processing is becoming more automated and several groups are experimenting with automated processing such as the Advanced Rapid Imaging and Analysis (ARIA) Project (https://aria.jpl.nasa.gov/data), on-demand web-based InSAR processing (Galve et al., 2017) and cloud-based processing (Arko et al., 2016). The NISAR data is expected to include bulk and on-demand processing. It is likely that high-quality InSAR images will be widely available for almost any geothermal system in the world. Several of these cloud-based platforms use open-source software such as GMTSAR (Sandwell et al., 2011), which is based on the open-source mapping software GMT. It handles all common satellite data including Sentinel TOPS data as well as stacking and timer series.

A key aspect of recent satellites is that the orbits are well constrained, which in turn permits precise co-registration of the data. For Sentinel data this is essential, as it employs a mode named TOPS (terrain observation by progressive scans, which requires precise processing to produce high-quality interferograms. One advantage of precise alignment is that it allows multiple corrections including both geometry and elevation corrections to be applied simultaneously which greatly simplifies the processing stream (Zebker, 2017). As a result of these advances in processing, especially when coupled to web-based delivery and cloud computing, it may not be necessary for user to construct their own interferograms; rather it will be possible to simply download the required images for any geothermal system in the world.

2.2 Application to geothermal fields

A clear example of the possibilities in observing geothermal fields using recent Sentinel (TOPS) data, is the study of Xu et al., (2017), who applied advanced co-registration combined with SBAS time series analysis. It included 42 ascending interferograms and 34 descending interferograms between October 2014 and July 2016. Comparison with known GPS measurements located within the scene showed good agreement indicating that the InSAR estimate were accurate at the sub-cm level and were capable of estimating horizontal tectonic motion as well as subsidence related to the Cerro Prieto geothermal field and to the Heber field to the north (Figure 1).

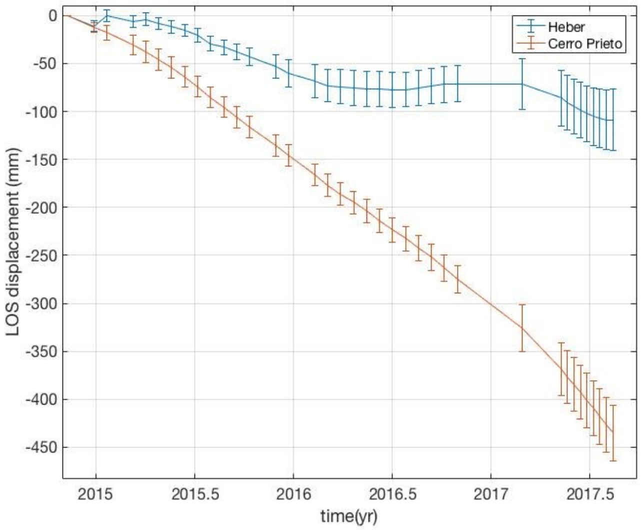

Figure 1: Example time series analysis showing relative displacement of selected locations in Cerro Prieto and Heber geothermal field using Sentinel data. This is an example of what should be possible for almost any geothermal field in the world today and we are currently applying to Blue Mountain and Soda Lake geothermal fields.

Another example using older SAR data but demonstrating the capability to image large areas, was conducted by Semple et al., (2017), who systematically processed data over the Western U.S. using C-band data (ERS-1, ERS-2, and Envisat) from 1992-2001 to map deformation over a wide area. Due to constraints in data availability and computational resources, it was not possible to create a seamless map of deformation and the use of older generation satellites (ERS-1 and ERS-2) with poor orbital control meant that not all possible pairs could be processed nor could streamlined processing based on orbit registration alone applied. Nevertheless, it demonstrates that large area mapping is possible. Ideally, this type of wide area processing would be routinely conducted on the new satellite data which would allow users to directly extract processed data of interest. As part of this work, an in-depth study was made of deformation at the East Mesa site, revealing a clear indication of variations in deformation over time. The subsidence between 1992 and 2000 was attributed to net water loss by Han et al. (2011) although the uplift reported by Semple et al., (2017) in the south end of the field after 2016 does not appear to be completely consistent with the available data on the change in net water volumes (Semple et al., 2017).

Not all geothermal display clear geodetic signals. The Desert Peak field, which is located near to Brady and possesses similar geology, show no obvious subsidence at the surface. This likely due to a combination of depth, lithology, and lack of connecting fault to the near surface. As the threshold for detection decreases and error handling is improved, deformation at more fields will be mapped.

3. IMPLICATIONS FOR GEOTHERMAL

3.1 Production

A variety of methods have been used to interpret the signals (usually subsidence) over geothermal fields, and in turn, infer constraints on the reservoir. One method is to assume an elastic media and model the deformation using a change in volume. Ali et al. (2016) inferred a connection between the shallow subsurface and the deeper reservoir at Brady Hot Springs based on observations of shallow subsidence centered on known faults. Hole et al., (2007) observed complex deformation in New Zealand geothermal fields but were constrained by lack of suitable data. Fialko and Simons (2000) estimated reservoir geometry over time and related micro-seismicity to deformation sources, perhaps due to pore pressure changes or thermal effects. Barbour et al. (2016) matched subsidence over the Salton Sea geothermal field with poro-elastic contraction in the geothermal reservoir.

More sophisticated estimates are based on numerical simulations and reservoir models. Vasco et al., (2013) observed clear variations over short distances from an EGS test at the Geysers fields from a combination of C-band and X-band data. This was interpreted to indicate fractures and a possible north-south flow. Deformation effects from pressure appeared to outweigh effects from thermal contraction. Liu et al., (2017) used a coupled thermo-hydro-mechanical model to model poro-elastic and thermal mechanical effects to model surface deformation. The results indicated that a shallow component of the reservoir must exist that is linked to the deeper, producing reservoir. In addition, indications of a flow barrier within the reservoir were noted.

A key factor is that much previous work, except for Ali et al (2016), Vasco et al., (2013), and Barbour et al., (2016), relied on only a few interferograms to constrain the work and are based on a temporally-aliased image of the reservoir evolution over time. In addition, the use of only a few scenes results in the high likelihood of contamination by atmospheric artifacts with resulting errors in modeling. The imaging capability demonstrated by Xu et al., (2017) when combined with the numerical modeling of Liu et al., (2017) or Vasco et al. (2013) show considerable promise for the future. Enhanced geothermal systems (EGS) fields will likely benefit from additional coverage as well. First, the data will provide constraints on reservoir behavior after injections, and second, the effects of any significant induced seismicity will be imaged.

3.1 Exploration

The capability of modern InSAR to measure subtle horizontal tectonic motion as shown by Xu et al (2017) raises an interesting possibility for geothermal exploration. Geothermal fields are often located near the ends of faults or by step-overs. This is true in the Imperial Valley and in the Basin and Range (Faulds and Hinz, 2015). If high-resolution strain maps for the entire Western U.S. become available, as seems likely, it may be possible to map areas of complex fault behavior and discover areas of geothermal potential. This may be especially useful in the Basin and Range to locate ‘blind’ geothermal areas with no surface expression.

3. CONCLUSIONS

InSAR data availability is on the verge of a revolution and it is expected that high-quality surface deformation maps will be widely available at low cost. This will be useful in monitoring geothermal reservoir, both for understanding the reservoir and assessing impact. The new InSAR maps may also be useful in generating high-resolution strain for exploration.

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