Geodetic measurements for geothermal site monitoring at Soultz-sous-Forêts and Rittershoffen deep geothermal sites

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Keywords: Geothermal monitoring, GNSS, InSAR, Time series, Surface displacement, PSI.

ABSTRACT

We establish a long-term geodetic monitoring around the geothermal sites of Soultz-sous-Forêts and Rittershoffen in the North of Alsace, France. The monitoring strategy is based on two space geodesy methods: Global Navigation Satellite System (GNSS) and Synthetic Aperture Radar Interferometry (InSAR) methods. This study presents the processing strategy and the results of the geodetic monitoring. The accuracy of the GNSS processing strategy is validated by an experimental test of controlled vertical displacement.

This study shows the ability of the geodetic strategy to detect surface displacement at centimeter to millimeter level, depending of the duration of the measurements and of the technique used. Geodetic methods are a suitable tool for acceptability of the geothermal site. 1) It helps to discriminate between the geothermal source of displacement and others sources of surface displacement. 2) The cGNSS has the ability to be an alarm tool in case of incidents and before significant damages occur. E.g. if the power plant of Landau (Germany) had a cGNSS monitoring in 2013, the incident at the power plant (Heimlich et al 2015, 2016) would have been seen before cracks apparition on the power plant. 3) At long time scale, the results can be an input for reservoir modelling and give information about possible fault reactivation, induced seismicity and slow deformations that are not visible by seismometer.

1. INTRODUCTION

The Upper Rhine Graben has a high potential of deep geothermal energy owing to well known geothermal anomalies. In 1987 the geothermal pilot plant of Soultz-sous-Forêts (Genter et al. 2010) was initiated between the villages of Soultz-sous-Forêts and Kutzenhausen, North Alsace, France (Fig. 1).

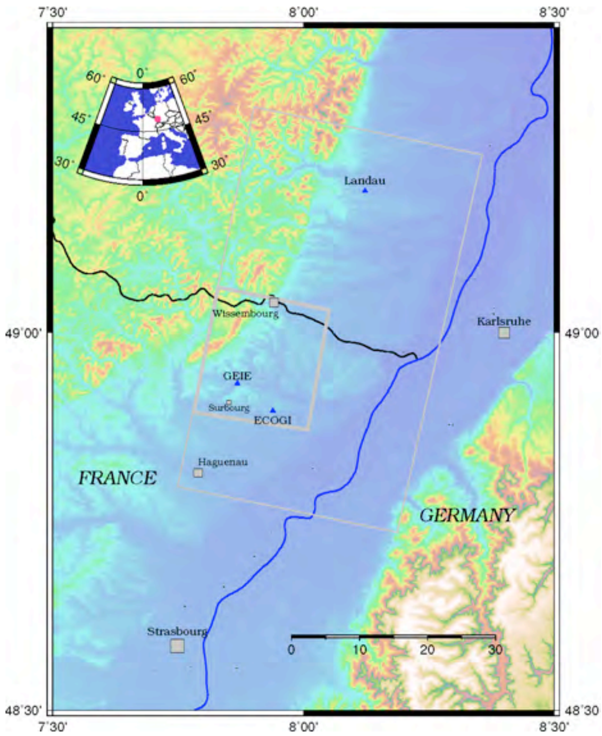

Figure 1: Location of the Soultz geothermal site (GEIE) and Rittershoffen geothermal site (ECOGI). Triangle, geothermal sites; large grey rectangle, area of the study; thin grey rectangle, SAR acquisition track of TerraSAR-X satellite; square, main cities; background, SRTM topography. Scale in kilometres.

This geothermal research site developed an Enhanced Geothermal System (EGS) using doublet, triplet or quadruplet configurations. The wells were drilled between 3,200 m and 5,260 m depth and benefits of natural geothermal water circulations through fractured and altered granites. The Soultz site is going to be converted from a research to a commercial site and will restart in June 2016 after renewal of the production equipments. At 7 km east of Soultz site, is located the new geothermal power plant ECOGI, achieved in 2016. ECOGI produces heat energy for the industrial partner Roquette in Beinheim, located at 15 km from the power plant (Baujard et al. 2015).

The seismicity monitoring is commonly used in geothermal projects, which is not the case for geodetic monitoring. Some previous studies give evidences for aseismic slip at Soultz site where the amplitude was not entirely visible by seismicity monitoring (Cornet 1997). Heimlich et al. (2015) shows uplift around the geothermal power plant of Landau due to geothermal water intrusion in sedimentary layers without seismicity signatures. Such kind of displacement can be visible by geodetic monitoring.

2. MONITORING STRATEGY

2.1 Global Navigation Satellite System (GNSS) network

Figure 2: cGNSS network around Soultz and ECOGI geothermal sites. Blue circles, location of the Soultz geothermal site (GEIE) and Rittershoffen geothermal site (ECOGI); pink lines, baseline (in km) between the 6 cGNSS sites; background, Google earth optic image.

We install a GNSS network in the vicinity of the two geothermal sites. The network is composed by 6 continuous GNSS (cGNSS), 3 of them are located on the geothermal sites, GPK1, GPK2 at the Soultz-sous-Forêts power plant and ECOG at the ECOGI site. The cGNSS acquisitions began in July 2013 with a network of 5 cGNSS, the sixth station (GPK2) complemented it in April 2014. The maximum length is of 9.4 km and the minimum of 400 m (Fig. 2). The cGNSS network is processed with GAMIT/GLOBK (Herring et al. 2015) software using double difference method, which is the more precise method. The software process only the GPS signal of the GNSS.

2.2 GNSS processing strategy

The GNSS method has a high accuracy in horizontal displacement (1 to 3 mm) and a lower accuracy for vertical displacement (5 to 7 mm). Or the expected vertical displacement is very small because of the doublet or triplet configuration and the fact that the whole geothermal water volume is re-injected.

In order to test our processing strategy to retrieve vertical displacement, we do an experimental controlled vertical motion. The experiment consists in moving the GNSS antenna vertically during time and to compare the ground-measured displacement to the GPS measured displacement. The results show that the trend anomaly due to the ground displacement, with a displacement rate of 7.5 mm/year or higher, is observed for a time series over 90 days of measurement. For the experiment with the slower velocity of displacement, the GPS trend (green line) is close to the ground displacement trend (red line) at submillimeter scale for the whole 136 days time period of displacements (Fig. 3). We measured by GPS a displacement of 2.4 mm, this result is close to the ground displacement which is of 3 mm. The velocities are respectively of 6.6 mm/year for the GPS result and 7.5 mm/year for the ground measured displacement.

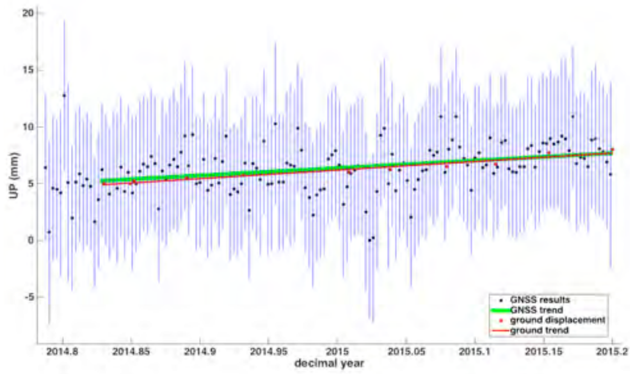

Figure 3: Time series of one controlled GPS experimentation of vertical displacement (mm); black dots, daily GPS results; blue lines, standard deviation; red dots, reported ground in situ vertical displacement of the antenna; red line, trend of the ground in situ vertical displacement; green line, estimation of the GPS trend during the uplift period (136 days).

2.3 SAR data

The Synthetic Aperture Radar (SAR) images are delivered by TerraSAR-X satellite from the German space agency DLR (www.dlr.de). We acquired images from the descending orbit that covers the two French geothermal sites and also Landau geothermal site (Heimlich et al. 2016) since May 2012 at the highest temporal acquisition rate (repeating cycle of 11 days). The images were processed with Stanford Method for Persistent Scatterers (StaMPS) from Hooper et al. (2004; 2007). This method uses the radar phase signal to retrieve the surface displacement in the satellite Line Of Sight (LOS) direction. For this acquisition, the LOS is 21° from the vertical with an azimuth of 192°, then the measurements is mainly sensitive to the vertical component of displacement. The wavelength of the X-band signal is 3.1 cm. The Persistent Scatterers Interferometry (PSI) method consists to identify Persistent Scatterers pixels in interferograms using phase spatial correlations. The inconvenient of PSI method is that pixels can suffer of decorrelation when the displacement exceeds one half phase length between two acquisitions. The signal is also uncorrelated in vegetated areas.

3. RESULTS

3.1 GNSS results

Examples of GPS results are presented as their baseline variations in time (Fig. 3 and 4). The shorter the baseline is, the more accurate is the time series results: we observe less dispersion in the baseline time series GPK1-GPK2 (0.4 km baseline length, Fig. 3) than for the HATN-GPK1 baseline time series (8,8 km baseline length, Fig. 4). For the dataset from July 2013 to May 2016, we do not observe significant displacement related to the geothermal site during our measurements. We observe variations at millimeter scale for the horizontal and total baseline component. For example the baseline between two wells of Soultz site, GPK1 and GPK2 (Fig. 3), presents few oscillations at millimeter range or less and a displacement at 3 mm level. The main displacement (of 3 mm) occurs in January 2016, it can be related to surface storage near the GPK2 antenna (antenna masking effect and elastic load effects). We do not retrieve this displacement in the HATN-GPK1 baseline for example (Fig. 4).

3.2 PSI results

Figure 5 shows the PSI results for the time period between May 2012 and October 2014. The results are mainly located on villages and roads, which are good radar reflectors. The forest south of ECOGI induces uncorrelated signal in InSAR and PSI measurements, so this area is not monitored. The mean velocity of the surroundings areas of the two geothermal sites is between -4 mm/year and 3.6 mm/year. The main displacements are observed in Merkwiller-Pechelbronn and in Surbourg villages. The pattern of displacement suggests a local origin of displacement.

On the Soultz geothermal site, we observe no significant displacement. The site was not in production during this time period. On the ECOGI site, we observe a millimeter subsidence that can be related to the drilling phase by the load of the rig on the launch pad. The subsidence is also observed by GPS and levelling.

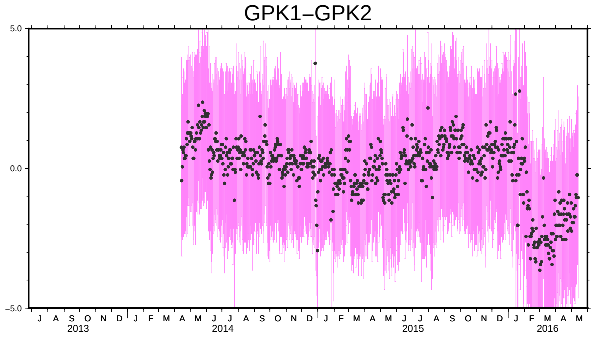

Figure 3: Time series of the baseline variation (mm) between GPK1 and GPK2 at the Soultz site. Black dots, daily GPS results; pink lines, standard deviation. The total baseline length is of 0.4 km.

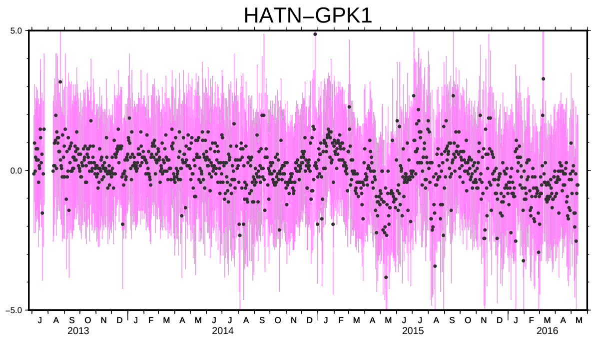

Figure 4: Time series of the baseline variation (mm) between HATN and GPK1. Black dots, daily GPS results; pink lines, standard deviation. The total baseline length is of 8.8 km.

3.3 Levelling

A levelling network has been installed in the surrounding villages in 2014 (Ferhat et al. 2014). But only one repeated survey has been done. The levelling result between GPK1 and GPK2 gives 1 mm of variation in the time interval of 1 year that is consistent with the GPS and PSI results.

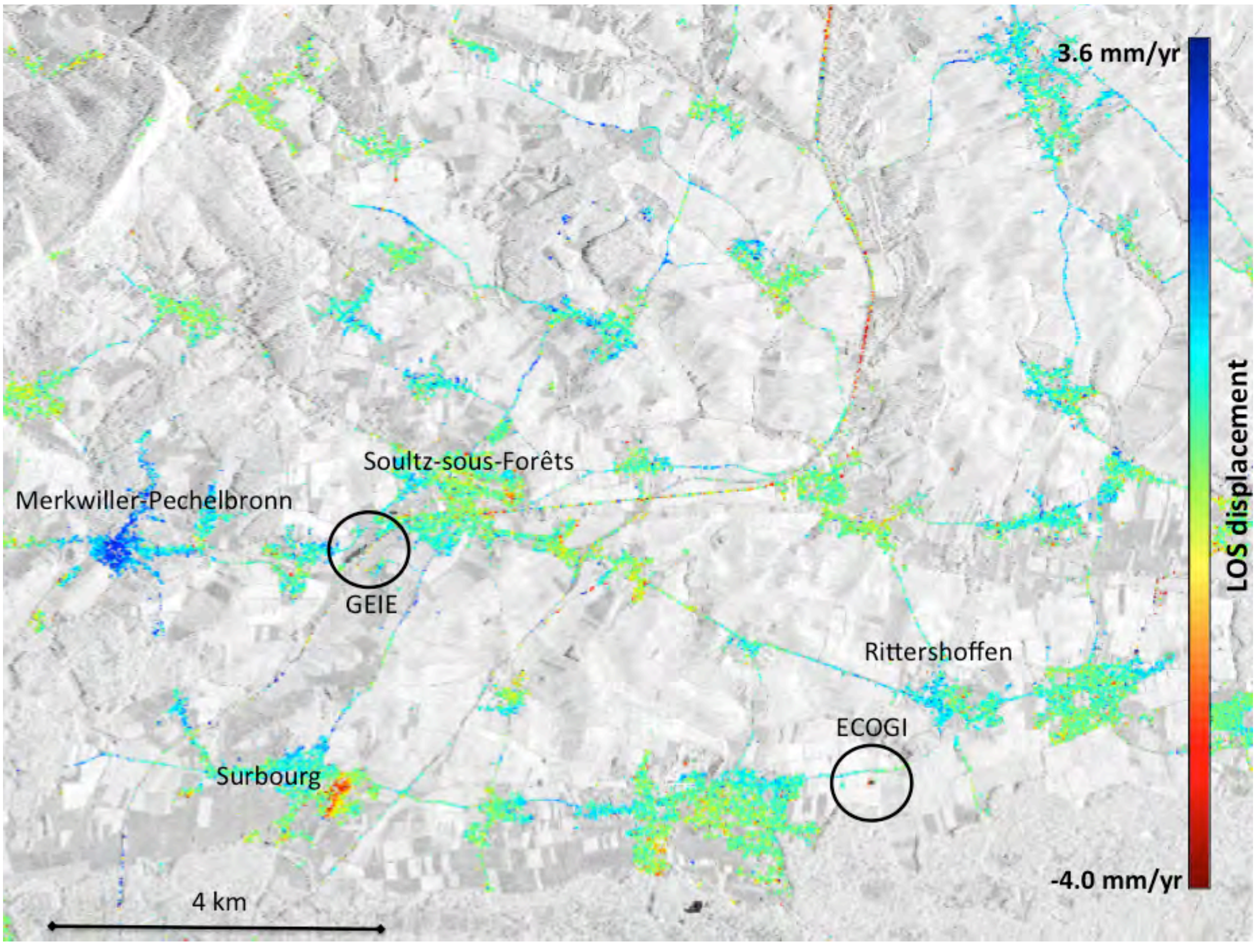

Figure 5: Mean velocity displacement map (mm/yr) between 5 May 2012 and 10 October 2014. The displacement is measured in LOS direction, which is close to vertical from a descending track. The velocity scale ranges from -4.0 mm/yr to +3.6 mm/yr, negative value indicates increasing distance from the satellite. The black circles locate the two power plant location. The main PSI are located on man-made structures (roads, villages)

5. CONCLUSIONS

In this study, we propose a geodetic monitoring of two geothermal sites, Soultz and ECOGI, located in north Alsace, France. We show that the geodetic monitoring is able to detect surface displacements of millimeter to centimeter magnitude, depending of the time series length and of the technique used.

For the GNSS monitoring, the processing strategy is validate by a GNSS experiment and shows the ability to observe vertical displacement at sub-centimeter level for a duration of measurement over 90 days. The short baseline between the GNSS is factor of high accuracy with using double-difference GNSS processing. The GNSS has the advantage to provide continuous measurements in 3D and to be more easily processed than PSI measurements. Once acquired, the GNSS is costing less than the other techniques.

The PSI method is a suitable tool to detect surface displacement at millimeter scale close to the vertical component. The interest of the InSAR measurement is that it provides information with a large spatial extension. It covers the surroundings area and therefore is a suitable tool to discriminate between several possible origins of displacement. The displacement result can be inverted on the basis of different mechanical models (point source, fracture opening, fault slip, etc) to better characterize the origin of displacement (Heimlich et al., 2015; 2016). But the distribution of the PS is depending on the surface reflector.

The levelling provides measurements of the vertical component. It has that advantage to be a terrestrial measurement technique, then to be less affected by troposphere effects, as it is the case for spatial geodetic methods. For this kind of monitoring, high accuracy levelling is needed in order to be able to compare the results of the three techniques at millimetre level. The inconvenient of the levelling compared to the other techniques is that the levelling needs campaign and the measurement acquisition are dependent of the quality of the operators.

The combination of the three methods provides a more complete monitoring tool and also complementary to seismology monitoring.

A geodetic monitoring can provide information about aseismic displacement, that can not be observed by seismic monitoring, e.g. at Merckwiller-Pechelbronn, Surbourg and Landau (Heimlich et al. 2015; 2016). Our geodetic observations before the complete implantation of a geothermal site provides an inventory of displacements sources before the installation of geothermal sites. And therefore helps to discriminate between several sources of displacements. The geodetic monitoring can also be an alarm tool when unexpected displacements occur. If the power plant of Landau had a geodetic monitoring like a cGNSS at the power plant location, the displacement anomaly observed by Heimlich et al. (2015, 2016) would have been observed before damage occurs on the surface. For all these reasons, the geodetic monitoring can also contribute to acceptability of geothermal energy.

With a long term geodetic monitoring, we can also expect constrains on the dynamic behaviour of the surroundings area of the geothermal plant or for the geothermal reservoir at relevant space and time. And then the displacement measurements could be an input for geothermal reservoir modelling and for understanding aging of the geothermal plant.

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Acknowledgements

This work has been conducted under the framework of the LABEX ANR-11-LABX-0050_G-EAU-THERMIE-PROFONDE, and it is supported by funding from the state managed by the French National Research Agency as part of the Investments for the Future program and by the Région Alsace.