Geodetic analysis of surface deformation at the power plant of Landau (Germany) related to the 2013-2014 event

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ABSTRACT

The power plant of Landau is an EGS geothermal site with a doublet configuration. It is located in the South of the city of Landau (Germany). Using Synthetic Aperture Radar (SAR) images from TerraSAR-X satellite, we observe pluri-centimeter surface displacement in the area of the power plant during the production phase. Our results are based on the analysis SAR images processed by Persistent Scatterers (PS) method with StaMPS software (Hooper et al. 2007). We obtain time series and velocity map of the surface displacement over the city of Landau and compare the PS-InSAR results to levelling and GNSS measurements made by the city of Landau.

The analysis of time series shows that an uplift centered on the power plant location started in mid-2013 and continued until the plant shutdown in March 2014. Then a pluri-centimeter subsidence occurs centered at the same location. The vertical displacement at the power plant location is at least 12 cm. In this study, we present the observation and analysis of the surface displacements during the entire 2013-2014 period. We re-process and complete the results published in Heimlich et al. (2015) and go further in the analysis.

We model the surface deformation with the elastic Mogi model (Mogi 1958) and Okada (Okada 1985) usually used in volcanology. Our modelling gives indication about the depth and the variation of volume that causes the deformation. The result is consistent with an injection of geothermal water at around 450 m depth.

This study highlights 1) the ability of geodetic methods to analyze the origin of surface displacements, 2) the utility of geodetic monitoring for control and alarm of damages due to human activities, thus of geothermal projects. Our results give also indications about the geological structures that are differentially affected by the deformation.

1. INTRODUCTION

The city of Landau is located in the northern part of the Upper Rhine Graben. The area of Landau benefits of a deep temperature anomaly, which makes it suitable for geothermal energy production (Baillieux et al. 2013). The geothermal power plant of Landau is located within the city, in the South of the city. Two geothermal well are drilled until around 3 km depth. The production well is deviated to the West and the re-injection well is deviated to the East. Others production sites are located in the surroundings of Landau. Oil production sites take place since 1955 close to the city and on the villages northern of Landau. Another geothermal power plant is located in the village of Insheim South of Landau and underground water is also pumped in the East part of the city. All these producing wells are able to contribute to surface displacement over the city.

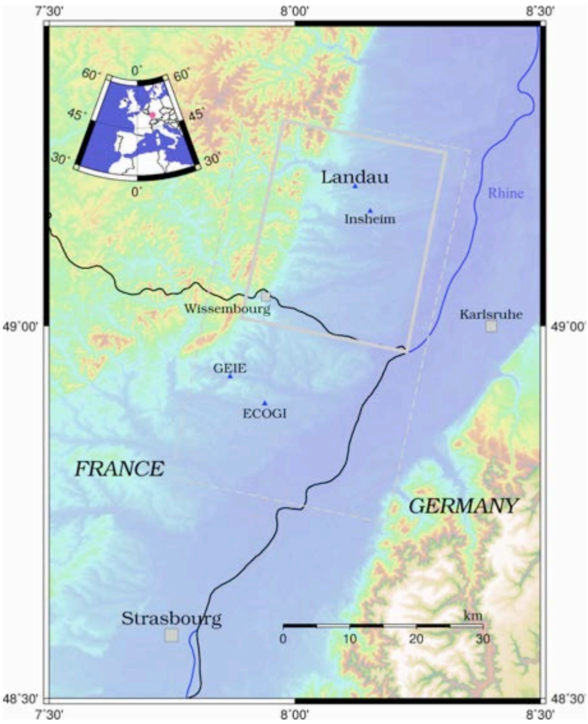

Figure 1: Location of the studied area (grey box). Dashed rectangle, satellite track; triangle, geothermal plant location. Scale in kilometres.

In 2014, cracks appear in the vicinity of the geothermal power plant with pluri-centimeter opening. But urban works were in progress in the same area, so the origin of the cracks was not obvious. Geodetic measurements with levelling and GNSS reveals that the geothermal power plant was the center, then the origin, of the main visible surface displacement. The geothermal power plant was shut down mid-March 2014.

In order to understand the processes that affect the surface, we processed Synthetic Aperture Radar (SAR) images from TerraSAR-X satellite. This work has been possible because since 2012 we establish a geodetic monitoring of geothermal sites in North Alsace, France (Heimlich et al. 2014; 2016) using TerraSAR-X satellite images from the German Space Agency. And our data set covers also the area of Landau. The processing of the SAR images combining with the GNSS and levelling allows to retrieve part of the spatio-temporal evolution of the surface displacement around Landau. We also modeled the results to better constrain the source parameters (depth and volume variations) in order to analyze the origin of displacement.

2. GEODETIC METHODS

We use 60 SAR images equivalent of 2 years of measurements provided by the German spatial agency DLR (www.dlr.de). The images are from the descending path of the satellite. The SAR images are processed with StaMPS software (Hooper et al. 2007) in order to do time series analysis. The first steep consists to do interferograms between couple of images, then, to select permanent scatterers (PS) within the whole set of InSAR data. This method has been previously used for example, for oil reservoir monitoring (Ferretti et al. 2001), volcano monitoring (Hooper et al. 2004). Lubitz et al. (2013) uses also this technic to measure the surface displacement in the city of Staufen (Germany) caused by an incident in shallow geothermal wells.

We compare our PS InSAR (PSI) to levelling and GNSS measurements in the near range of the geothermal power plant.

3. RESULTS

Figure 2 presents the mean velocity map in the LOS direction of the PSI results. The mean of the velocity extends from -5 mm/yr to 15 mm/yr in the two years of measurements. But the maximal values are underestimated because of phase jumps in the vicinity of the power plant. The PSI results are mostly located in the North of the geothermal power plant. It is due to the vegetated area and urban works in the South. In these areas the spatial continuity of PSI is disrupted. The consequence is that the phase cycles can not be definitively resolve, the displacement in this area can not be resolve without others geodetic technics.

We observe a main displacement in the South of the city that is centred on the geothermal power plant location. The displacement is in the satellite direction, so mainly in uplift direction of displacement. Another displacement to the satellite direction happens in the North of Landau located close to oil production fields and over the whole city of Landau in a North-South direction. The border between the affected and non-affected areas is clearly delineated.

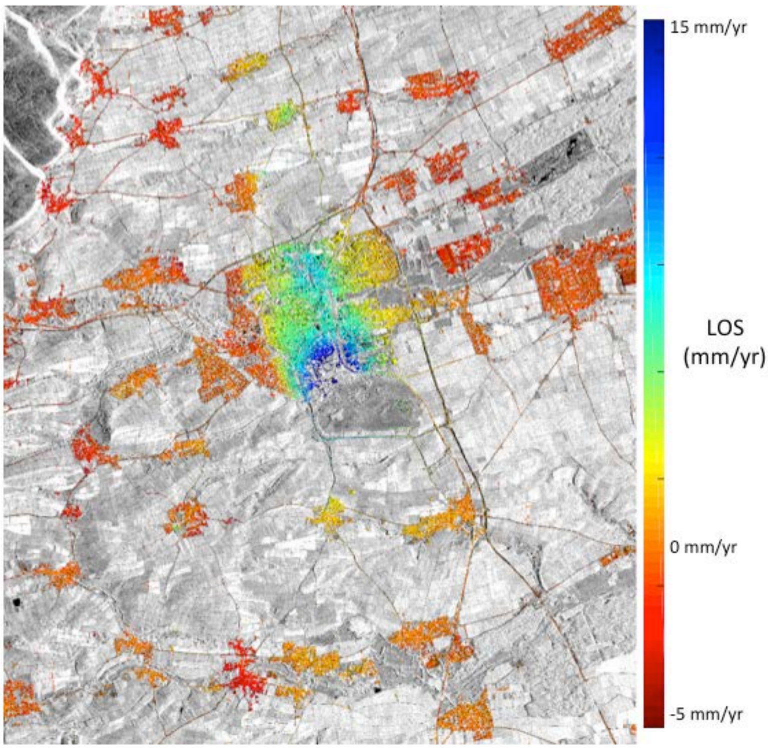

Figure 2: Mean velocity displacement map (mm/yr) in LOS direction between January 2013 and January 2015.

The temporal evolution of the surface displacement can be divided in two main phases separate by the shutting down of the power plant mid-March 2014.

The uplift phase is the first period (Fig. 3). The uplift begin in June-July 2013 and is clearly visible in the PSI on the images between June and September 2013. When we combine the PSI with levelling results, we can assume than the displacement is over 12 cm in this area. The pattern of displacement is quasi-circular and centred on the power plant.

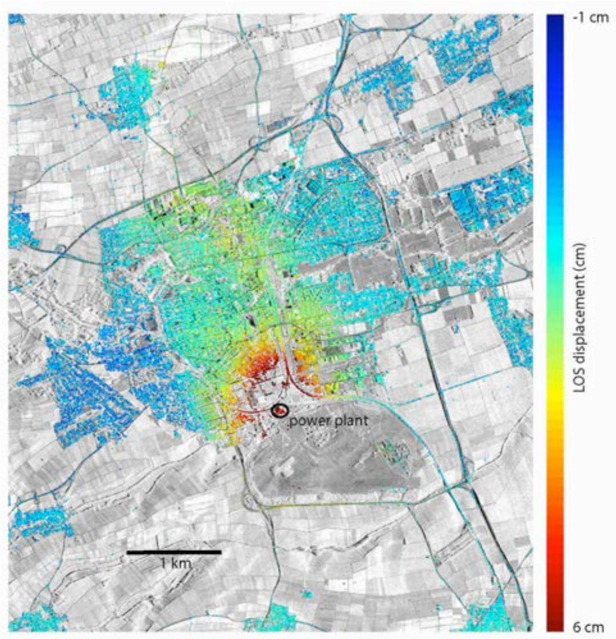

Figure 3: Main uplift displacement between 2013 and 18 March 2014 in the city of Landau. Black circle: location of the geothermal power plant. The maximal uplift value is outside the scale (> 12 cm).

The second main phase is the subsidence phase (Fig. 4), and begins after the shutting down of the power plant. The subsidence displacement has similar pattern than the uplift displacement and is centered on the same location. As for the uplift phase, the PSI in the near range of the power plant are affected by phase jumps that underestimate the whole displacement. The comparison with levelling results allows to correct the phase jump and then to better retrieve the real displacement. The subsiding displacement is over 11 cm close to the power plant location. The lateral extension of the subsidence is lower than for the uplift. We observe also that we did not retrieve the same level at the end of the measurements (January 2015 for PSI end March 2015 for levelling) than before June 2013 (Fig. 5).

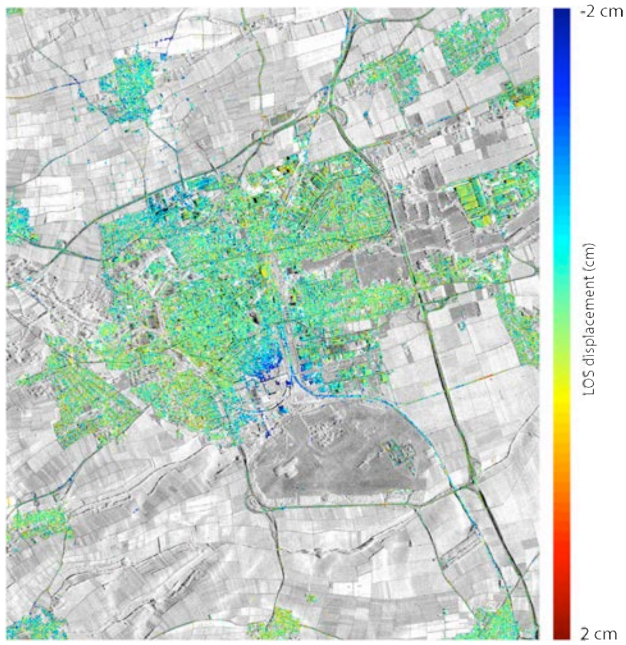

Figure 4: Displacement during the subsidence period in the vicinity of the power plant from 18 March 2014 to January 2015.

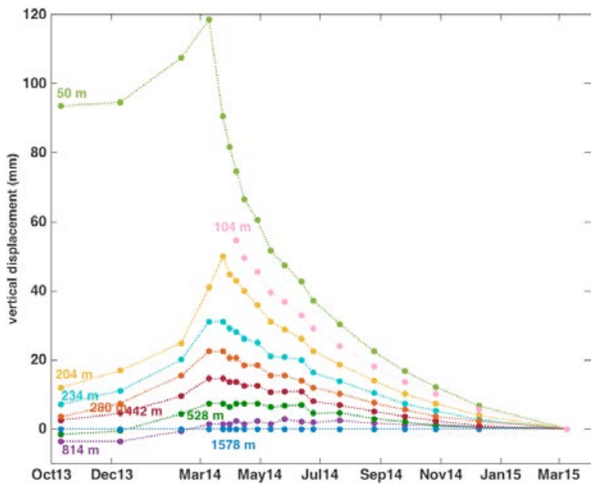

Figure 5: Time series of vertical displacement measured by levelling (mm). The time series are presented relatively to the last acquisition in March 2015 and with indication of the distance of the measurement point from the geothermal power plant. The range is from 50 m (in green) to 1578 m (in blue).

4. ANALYSIS

The fact that the displacement polarity changes with the shutting down of the power plant argues to the fact that the main displacement is elastic. The increasing amplitude of displacement and the circular pattern of displacement indicate that the source of displacement is located on the power plant area. In order to better understand the process involved, we modelled the displacement with elastic model usually use in volcanology. Figure 6 presents a solution with combining Mogi models (Mogi, 1958). The main source is at 500 m depth and minor sources are at 180 m depth. The total variation of volume with this modelling is of 83,000 m^3.

The modelling results agree with the technical log of the well. The re-injection well is not cemented between 479 and 751 m depth (Ministry of Economic Affairs, Climate Protection, Energy and Regional Planning press talk, 9 April 2014). So a leakage in the re-injection well like a defective joint can introduce geothermal water at 479 m depth or deeper.

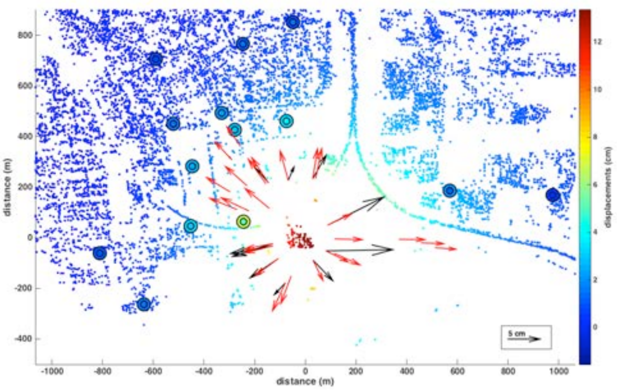

Figure 6: Comparison between geodetic measurements and modelling for the uplift phase with modelling using multiple Mogi models. Dots, modelling PSI displacement; black arrows, GNSS measured horizontal displacement; red arrows, modelled horizontal displacement; little circle, measured vertical displacement by levelling; large circle, modelled vertical displacement.

The spatio-temporal evolution of the subsidence shows that the subsidence first affects an restricted area around the power plant. This observation argues to the fact that the subsidence is related to the shutting down of the power plant. The shut down of the power plant correspond to a pressure change in deepness. The displacement can be modelled as a deficit in water injection in deepness. The same models can be used as for the uplift phase with an inverse polarity. The modelling of the subsidence period using Mogi modelling gives a depth around 250 m that is less deep than for the uplift phase.

4. CONCLUSIONS

In our previous study (Heimlich et al. 2015), we analysed the surface displacement during the uplift phase. The modelling with Mogi and Okada models gives a source deepness at around 500 m for the uplift phase, this study confirm the source deepness for the uplift. The result is in accordance with the re-injection well leakage and the well design. This event highlights the importance of the integrity of the geothermal well.

In this study, we analyse also the subsidence phase. The subsidence phase follows the shutting down of the power plant. For the subsidence phase, the source deepness is lower, at around 250 m and has a lower lateral extension. The comparison between the uplift and subsidence displacement shows that the main contribution of displacement is elastic then reversible. But we observe that we did not retrieve the same surface level 1 year after the shutting down, this observation argues to fact that also another process is also involved.

This study highlights the interest of geodetic tools to geothermal monitoring. 1) The geodetic tolls have the ability to analyze the origin of surface displacements, then it can be used to better understand underground process and to discriminate between several sources of displacement. 2) Geodetic tools (e.g. GNSS) can be control and alarm tools of damages due to human activities, thus of geothermal projects. If a continuous GNSS site had been installed on the Landau power plat, the uplift would have been detected in the first month of the event, widely before visible damages. Our results give also indications about the geological structures that are differentially affected by the deformation.

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