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HYBRID GRAVITY MONITORING OF A GEOTHERMAL RESERVOIR

Hinderer[1], J., Calvo[2], M., Abdelfettah[1,3], Y., Ferhat[1,4], G., Riccardi[5], U., Hector[6], B., Bernard[1], J.-D., Littel, F.[1]

1 Institut de Physique du Globe de Strasbourg UMR 7516 CNRS/Université de Strasbourg, 5 rue Descartes, Strasbourg, France
2 Observatorio Geofísico Central, IGN Madrid, Spain
3 Institut für Nukleare Entsorgung INE, Karlsruher Institut für Technologie (KIT), Germany
4 INSA Strasbourg, France
5 Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse (DiSTAR) Universita "Federico II" di Napoli, Italy
6 LTHE Grenoble, France

Jacques.Hinderer@unistra.fr

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ABSTRACT

Time-lapse gravity is a monitoring tool to investigate underground mass redistributions and hence helps to follow a geothermal reservoir both in its natural state or undergoing man-made stimulations and therefore optimizing its utilisation. We first recall the concept of hybrid gravimetry, which is the optimal way to combine different types of instruments and techniques of measurement. In particular, hybrid gravimetry uses a reference station where gravity is continuously recorded with a relative gravimeter (spring or superconducting) and regularly checked with absolute gravity measurements, as well as repetitions of a micro-gravimetric network of several satellite stations in the vicinity of the reference one.

We investigate the feasibility of the hybrid gravity technique applied to two geothermal reservoirs in northern Alsace, France, namely the Soultz-sous-Forêts site which is the first EGS (Enhanced Geothermal System) demonstration site producing electricity in France and the Rittershoffen site where the ECOGI experiment dedicated to an industrial use for heat application (24 MWth at 160 °C) takes place.

We first show model predictions for the gravity changes both at the surface and as a function of depth using a very simple source linked to a simulated geothermal activity. We show the temporal gravity variations (double differences) that have been observed on the micro-gravimetric network of Soultz in the absence of any geothermal production and infer a detectability threshold for the gravity monitoring that can be achieved by precise observations and appropriate corrections. We finally point out the importance of the precision of the height changes that are needed to correct gravity measurements for the effect of the ground deformation and we present what can be inferred from high precision leveling.

1. INTRODUCTION

Time-lapse gravity is a tool to monitor surface and underground mass redistributions of various origins (ice melting, hydrology, volcanology) and hence finds a potential application to follow a geothermal reservoir both in its natural state or man-made stimulated for production..

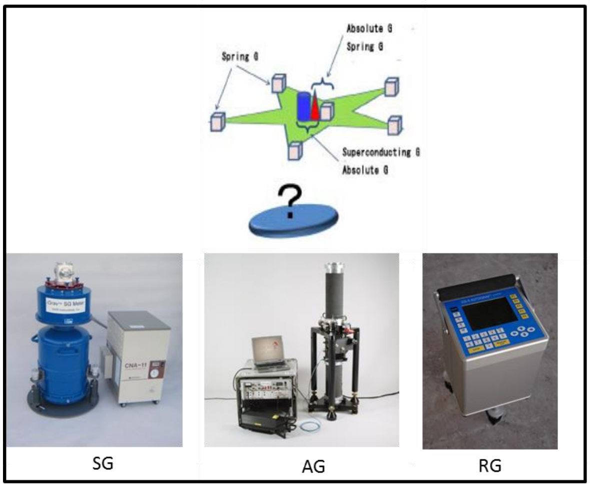

Fig. 1. The concept of hybrid gravimetry with the combination of superconducting gravimeter (SG) absolute gravimeter (AG) and relative spring meter (RG) (adapted from Sugihara et al. 2013).

The term Hybrid Gravimetry (HG) was first introduced by Okubo et al. (2002) in a study dedicated to the gravity monitoring of a Japanese volcano (Mt Fuji) where the design for a gravity network included a portable absolute gravimeter (AG) acting as reference for relative measurements (RG) done with spring meters. Later on Sugihara and Ishido (2008) introduced the concept of Super Hybrid Gravimetry (SHG) for geothermal reservoir monitoring by adding a new generation of superconducting gravimeter (SG) to the hybrid system (AG + RG).

The concept of hybrid gravimetry relies on the optimal way to combine different types of instruments) (Fig. 1) and techniques of measurement (Crossley et al. 2013:

- a permanent gravimeter which allows a precise continuous monitoring of the time-varying gravity at a reference station located on the investigated site; this is usually done with a superconducting gravimeter (SG) rather than a spring meter because of its very small instrumental drift and better precision (Hinderer et al. 2015a);
- a ballistic absolute gravimeter (AG), collocated with the SG, that allows both to control long term gravity changes and to regularly check the stability of the SG calibration;
- a spring relative gravimeter (RG) to repeat observations on a micro-gravimetric network of different stations around the reference station by successive loops in order to gain more insight into the space-time gravity changes in the investigated region.

A field where hybrid gravimetry is promising is related to geothermal activity (Nishijima et al., 2000; Takemura et al., 2000; Sugihara and Ishido, 2008; Sofyan et al., 2011; Oka et al., 2012) which has clearly become important as a possible alternative energy resource for the future. Many experiments have started and more references can be found in Hinderer et al. (2015b). The goal of these studies is the modeling of the geothermal fluid circulation and mass transport which is often occurring at large depths (several hundreds or even thousands of meters). A nice example of hybrid gravimetry in the geothermal context can be found in Oka et al. (2012) on the Takigami geothermal field in Japan producing a 25 MW power. A study involving AG and RG (jointly with GNSS) could identify the spatial distribution of gravity changes on the geothermal site just after the start of the power generation and the modeling led to a 12 MT (megatons) water extraction per year.

2. MODELING OF SURFACE AND UNDERGROUND GRAVITY CHANGES DUE TO GEOTHERMAL ACTIVITY

The first step was to compute surface and underground gravity changes that can be expected from mass redistribution related to the geothermal activity.

As an example for the deeply buried mass source of geothermal origin, we located at a depth of 2 km a mass excess of 0.17 megatons (MT), resulting from a continuous water injection at a rate of 20 l/s during 100 days. This injection rate is comparable to what was indeed used in some hydraulic tests done in 2010 and 2011 in Soultz during periods of several months (Genter et al. 2010, 2013). For the sake of comparison this mass excess is by far smaller than the 1200 MT value quoted in Allis et al. (2001) for the Geysers geothermal reservoir in several years leading to several hundreds of μGal gravity changes. The mass excess was distributed inside a prism of dimension 100 × 100 × 100 m, located and centered at a depth of 2 km (Pohanka 1988). This computation was done using a geological model for our study zone extracted from Baillieux (2012) which is derived from seismic and borehole data and consists in a 6 layer model with dimension ~30 × 20 × 5 km. The geothermal reservoir in this simulated water injection area is located in the granitic basement unit existing below 1500-m depth.

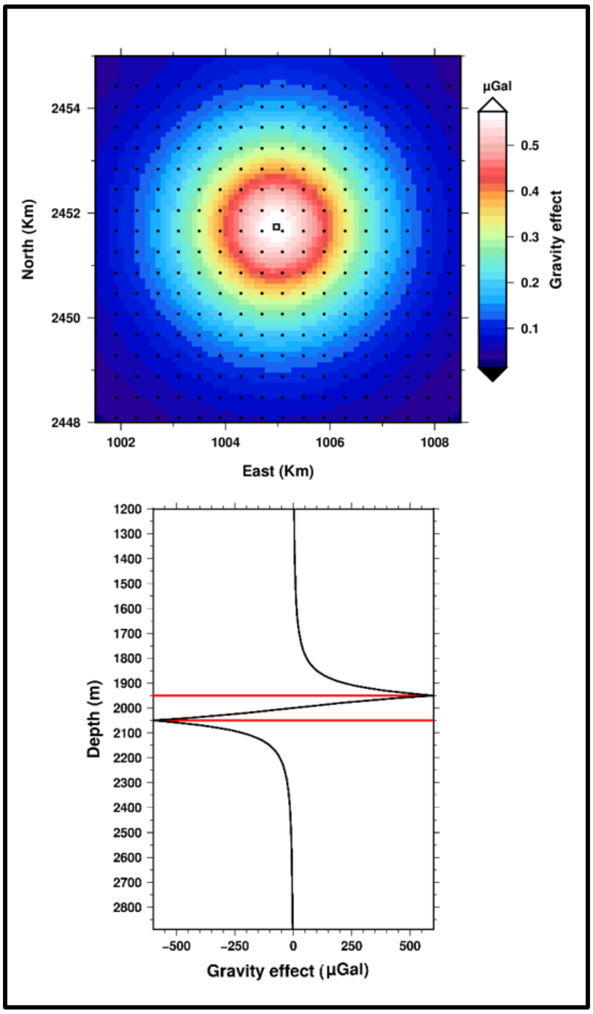

Fig. 2. Modelled surface gravity effect (in μGal) due to a mass perturbation of 0.17 MT located at 2 km depth (top). Modelled borehole gravity effect as a function of the depth due to a mass perturbation of 0.17 MT located at 2 km depth (bottom).

The resulting gravity effects due to Newtonian attraction are shown on Fig. 2. The top part is at the Earth's surface as would be observed by a classical network; the black square represents the projection at the surface of the perturbed deep volume, and the points are the stations where the gravity change has been computed. The bottom part represents the gravity

change as a function of depth when nearing the source (borehole gravimetry); the two horizontal red lines show the top and bottom of the layer (100 m thick) where the source anomaly occurs.
The maximum gravity change is 0.6 µGal (6 nm s^{-2}) right on the vertical of the source. This predicted gravity change is very small (because of the large distance between the source anomaly and the surface) and hence undetectable in micro-gravimetry.

On the contrary the borehole gravity prediction as a function of depth for the same source anomaly shows that the gravity changes become large when one measures near to the anomaly; it is for instance reaching 250 µGal at a distance of 100 m from the source. Such changes of a few tens or hundreds of µGal are easily measurable today with borehole gravity tools (Nind et al. 2007; Seigel et al. 2009).

3. GRAVITY OBSERVATIONS ON THE SOULTZ AND RITTERSHOFFEN SITES IN NORTHERN ALSACE

Our hybrid gravimetric approach on the geothermal fields in northern Alsace (France) uses a reference station GPK1 (see Fig. 3) where gravity is continuously recorded with a relative spring gravimeter (in the absence of a superconducting gravimeter). This reference site is regularly (one to two times a year) checked with absolute gravity measurements, and we repeat with spring meters a micro-gravimetric network of several satellite stations in the vicinity of the reference one. We established in 2013 around the Soultz-sous-Forêts geothermal site a repetition network of 11 relative stations linked in 5 separate loops around GPK1 station (Fig. 3). The survey was routinely done with a RG (Scintrex CG5 microgravimeter) on a weekly basis during summer months in 2013, 2014 and 2015. Initially only two stations were established around the ECOGI site near Rittershoffen but in 2015 the Rittershoffen network was increased to 14 stations (4 being common to the Soultz network). The Strasbourg Gravimetry Observatory where both a superconducting gravimeter (GWR C026) and an absolute gravimeter (Micro-g Solutions FG5#206) are available, is only 50 km away. However we acquired in 2015 a continuous gravity time series at GPK1 with a second Scintrex CG5 to verify the ability to retrieve precise tidal parameters with a spring meter when no superconducting gravimeter is available.

The first results of the hybrid gravimetry experiment applied to the Soultz site can be found in Hinderer et al. (2015b). We reported in this former paper on the stability of the reference point (GPK1) from a series of absolute gravity measurements done with our FG5 AG.

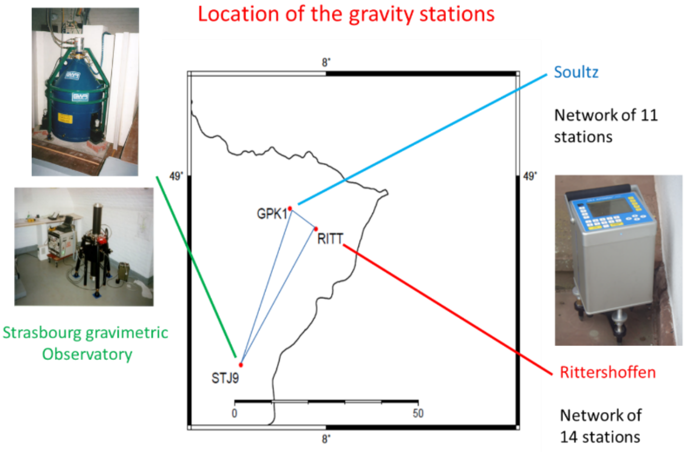

Fig. 3. Location of the Soultz (GPK1) and Rittershoffen (RITT) networks close to Strasbourg in northern France (Alsace Province). STJ9 is the Strasbourg gravimetric Observatory.

We also showed the preliminary temporal gravity variations derived from these repetitions, after removal of the instrumental drift and applying precise tidal corrections.

These gravity changes (Δg) are gravity double differences at time t and space x with respect to the base station x_0 and to a single epoch t_0 defined as follows:

$$\Delta g_{x-x0}^{t-t0} = (g_x - g_{x0})_t - (g_x - g_{x0})_{t0} \qquad [1]$$

To process the data, we developed a software called pyGrav (Hector & Hinderer 2016) written in Python language. This code is very appropriate for all kinds of gravity time-lapse surveys and allows in particular an easy reprocessing of repeated micro-gravity networks. It has a user-friendly interface for handy and fast processing of the raw gravity data at every station of the network.

As shown by Fig. 4, the gravity simple differences (at every station as a function of time) are in the range of several tens of milliGal. They are due for the largest part to elevation changes and can be used to infer the so-called Bouguer corrected free air gradient for the area that amounts to -0.206 milliGal/m.

The gravity double differences on the contrary lead to useful information on the redistribution of masses linked to water storage changes in the vadose zone and/or deeper aquifers (e.g. Hector et al. 2015) or to the geothermal deep-water circulation.

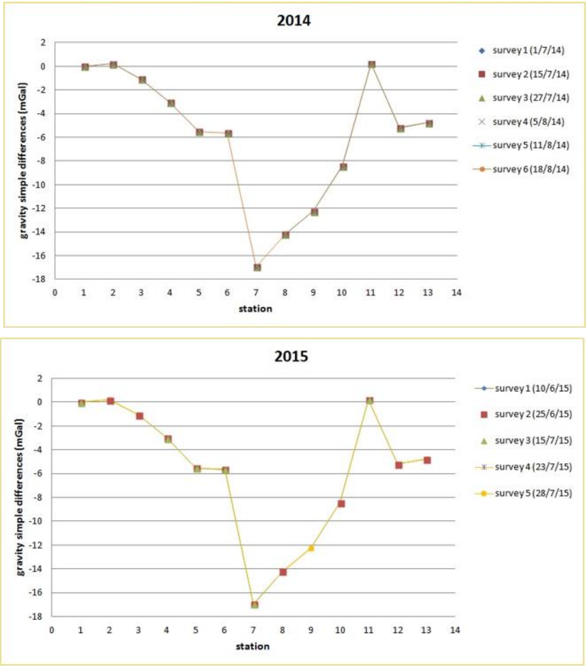

Fig. 4. Gravity simple differences on the 13 stations of the Soultz network for the 2014 and 2015 surveys.

It turns out that the 2014 micro-gravimetric measurements are much better than the 2013 ones mostly because of the use of a more stable RG instrument, reducing the average loop error by almost a factor 10 (Hinderer et al. 2015).

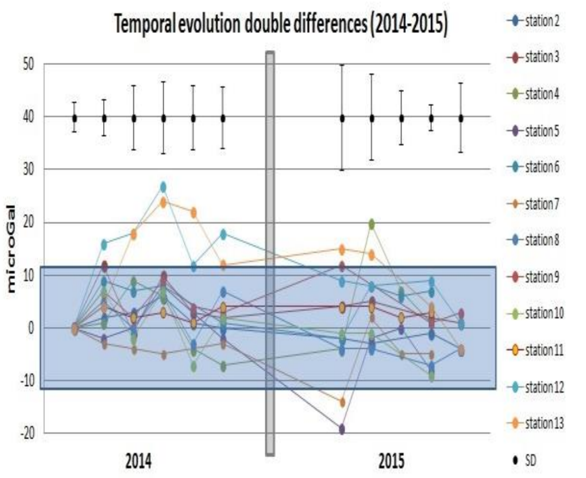

Fig. 5. Gravity double differences of the Soultz network in 2014 and 2015. The error bar for each survey is indicated on the top. The blue rectangle is the average ± 2 σ uncertainty band.

We hence could infer a threshold for detecting any gravity signal of geothermal origin (both natural and man-made) in the frame of our local network of Soultz. The 1 σ uncertainty taking into account all error sources in the measurements and processing was found to be close to 5 µGal for most of the surveys.

It is interesting to note that almost no changes in the gravity double differences can be observed outside the ± 2 σ uncertainty band as shown on Fig. 5. There are only two stations (12 and 13) close to ECOGI (Rittershoffen) that stick out of this band in summer 2014 and this was correlated in time with an injection test on one of the boreholes (GRT1).

4. HEIGHT CHANGES

Gravity changes due to mass redistribution must be corrected for any vertical height changes. Usually corrections are based on the so-called free air gradient (– 0.3086 µGal/mm) or on the Bouguer corrected free air gradient, which amounts to –0.2 µGal/mm assuming a mean crustal density of 2670 kg m^{-3}.

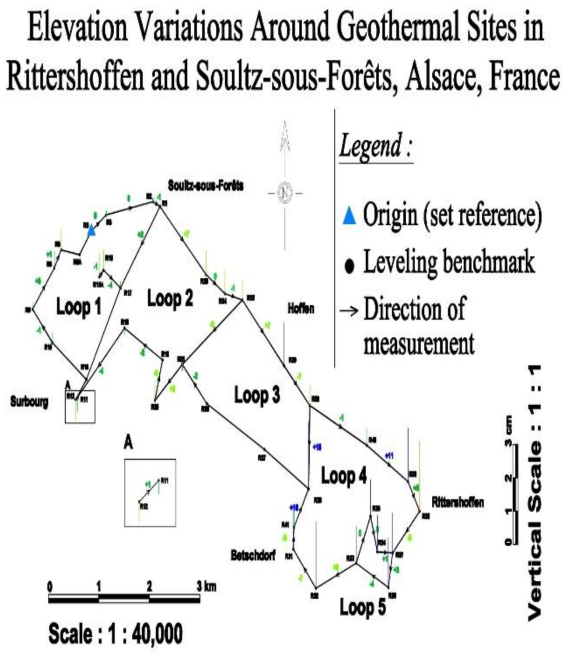

Fig. 6. Elevation error variations between the two epochs of 2014 and 2015. GPK1 (blue triangle) is supposed to be fixed (Ferhat et al. 2016).

This is why a precise control of the station elevations in time is required. During May 2014, a large leveling network (~40 km long) connecting the 13 gravimetric sites was observed in 4 main loops and a small loop around ECOGI site. The loop closures show an equivalent precision of 1.5 mm/km for the main loops and 0.5 mm/km for the small loops (Ferhat et al. 2014). This accuracy is large enough to guarantee a vertical precision better than a few millimeter required for gravimetric variation interpretation. This leveling network has been surveyed in May 2014 and May 2015. Differences in elevation between consecutive benchmarks have been computed and are less than few mm (Ferhat et al. 2015, 2016).

In order to evaluate the effect of the network geometry, we fixed the altitude of the GPK1 benchmark and computed the error transmission for all benchmarks using 2014 and 2015 leveling observations.

Figure 6 shows that vertical errors are a few mm at sites close to GPK1, and reach 1 or 2 cm (equivalent to 3.1 to 6.2 µGal with the free air gradient or 2 to 4 µGal with the Bouguer corrected free air gradient) at the more distant points. Only one leveling benchmark exhibits a value of 2.1 cm (Ferhat et al. 2016).

5. CONCLUSIONS

We have shown that the gravity time changes of the weekly repetitions of the micro-gravimetric network of Soultz in 2014 and 2015 are clearly small and mostly within the ± 2 σ uncertainty level where σ is of the order of 5 µGal in agreement with the fact that no geothermal activity was ongoing in the investigated period. We have then a well-defined reference network in the lack of any geothermal activity and this will help to identify possible gravity changes that might occur when the geothermal plants will be restarted in summer 2016.

The rather large distance of the mass sources in deep geothermal reservoirs (2.5 km for Rittershoffen and 5 km for Soultz) leads to very small surface gravity signals, at least from the purely Newtonian point of view as confirmed by our gravity modeling. When the source-sensor distance decreases like in borehole gravimetry, a significant gravity signal should arise after water injection.

We also showed that the changes in height derived from precise leveling on the network stations are small (most are below one cm) and do not affect significantly gravity.

This feasibility study will be followed soon by a true gravity monitoring after the start of production of the Soultz and Rittershoffen geothermal sites which is planned in 2016.

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