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Continuous Microgravity Monitoring in a Volcanic Geothermal Field: Integrated Observational Approach in Þeistareykir, NE Iceland

Kemâl Erbaş[1], Florian Schäfer[1], Ásgrímur Guðmundson[2], Egill Júlíusson[2], Gylfi Páll Hersir[3], Richard J. Warburton[5], Jean-Daniel Bernard[4], Nolwenn Portier[4], Jacques Hinderer[4], Vincent Drouin[6], Freysteinn Sigmundsson[6], Kristján Ágústsson[3], Benjamin Männel[1], Andreas Güntner[1], Christian Voigt[1], Tilo Schöne[1], Arthur Jolly[7], Hreinn Hjartasson[2], David Naranjo[1,8], Philippe Jousset[1]

[1] Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany; [2] Landsvirkjun, National Power Company of Iceland, Háaleitisbraut 68, 103 Reykjavík, Iceland; [3] Iceland GeoSurvey, Grensásvegur 9, 108 Reykjavík, Iceland; [4] EOST, 5 rue René Descartes, 67080, Strasbourg, France; [5] GWR Instruments, Inc. 5985 Pacific Center Blvd, Suite 202, San Diego, California 92121, USA; [6] Institute of Earth Sciences, University of Iceland, Sæmundargata 2, Reykjavík, Iceland; [7] GNS Science, 1 Fairway Drive, Avalon, Lower Hutt 5010, New Zealand, [8] ETH Zürich, Eidgenössische Technische Hochschule Zürich, Switzerland

kemal.erbas@gfz-potsdam.de

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ABSTRACT

In volcanic and hydrothermal geosystems, monitoring of mass and stress changes provide information for both volcanic hazard assessment and estimation of geothermal resources. The combined continuous recording of the gravity field and ground motion with sufficient accuracy in an active volcano-tectonic setting allows a better understanding of the mass and stress transfer mechanisms that produce short term gravity changes and local seismic activity. The aim is to gain a better understanding of geothermal system processes by addressing short-term mass changes within geothermal reservoirs in relation to external influences such as anthropogenic (reservoir exploitation) and natural forcing (local and regional earthquake activity and earth tides). This contributes to knowing the reservoir properties, structure and long-term behaviour.

Þheistareykir (Northeast Iceland), where the geothermal power production started in autumn 2017 (2x45 MWe) is the site chosen for this unique experiment. The overall goal of the project is to use a network of continuously measuring gravity meters to detect small variations in gravity associated with managing a geothermal field (injection and extraction). The gravity changes are expected to be small: ~5 µgal/6 months (1 µgal=10^{-8} ms^{-2}). Therefore, high performance and up-to-date instrumentation such as superconducting gravity meters (SG), spring gravity meters and broadband seismometers are used. To achieve these goals, in autumn 2017 a network of 5 relative gravity meters (3 iGravs and 2 gPhones) and 14 seismic stations were deployed. Three gravity monitoring sites are in close vicinity to the production and injection area, and one iGrav is set up outside the geothermal field for reference. Presented in this report are the details of the infrastructure and instruments deployed and the first results of more than 18 months of continuous gravity and seismicity monitoring.

1. INTRODUCTION

Microgravity studies have been performed for a long time on volcanoes (e.g., Brown and Rymer, 1991; Jousset et al., 2000) and also geothermal fields (e.g., Hunt, 1995; Hunt, 1984). However, those approaches were limited to surveys typically separated by several months. In order to measure both short and long-term gravity variations associated with the addition or removal of the mass, continuous measurements have been proposed (e.g., Jousset et al., 2000; Carbone et al., 2003). However, in many cases only one continuous gravity station could be set-up, due to the expensive instrumentation required.

In this study, 4 continuous gravity stations and a large number of other instrumentations were deployed for the first time in order to cover the spatial and the temporal changes of gravity on a geothermal field. This microgravity experiment had been started in Indonesia in 2015 as a follow up for the 2009-2014 project activities (Erbaş et al., 2015). It is now carried out in Þeistareykir in North East Iceland due to changes in boundary conditions in Indonesia and the extensive support of Landsvirkjun, the National Energy Company of Iceland, ISOR and the University of Iceland.

For the first time at a geothermal production site, simultaneous monitoring of mass distribution changes using high-performance high-frequency records of microgravity, 3 of the instruments being superconducting gravity meters (GWR Instruments, Inc. iGrav SGs). Since December 2017, a network of 4 gravity stations is continuously operating in the vicinity of the power plant Þeistareykir where production started in autumn 2017. Three of the gravity stations are in the geothermal fields: one at injection area in the West (SCGW), one at the production area in the East (SCGE), and one in between (GPXC), while the reference station (SCGR) is located some 15 km outside the geothermal fields close to Húsavík (Fig. 1). The gravity monitoring stations are supplemented with additional instrumentation (Schöne et al. 2013, Carbone, 2019) to measure all other parameters that may affect the records (deformation, pressure, temperature, hydrological parameters, snow thickness) continuously (Fig. 2). Additional installation of 14 seismic broadband stations (Fig. 3) supports the permanent monitoring (Ágústsson et al., 2020) of seismic activity in this very active region of the Northern Volcanic Zone of Iceland and will give detailed insights to changes of deformation and stress.

2. SETUP

Gravity and seismology network site selection was done in summer 2017. The three priorities for choosing the gravity sites were that they be: near the production and injection areas of the geothermal field, near to a power source (~3.5 kW), and located upon a consolidated rock. Also, the sites had to be accessible for building the concrete pillars and placing the pre-assembled containers used to shelter the gravity meters, computers, and the additional equipment, while taking the environmental aspects of the geothermal site into account. For the reference station, a setting was found where the power could be provided by connection to a ski-station of the Husavik community. This location was far enough away not to be influenced directly by injection or extraction of water or any other geothermal processes under study. Figure 1 shows the final distribution of the gravity stations close to the power plant.

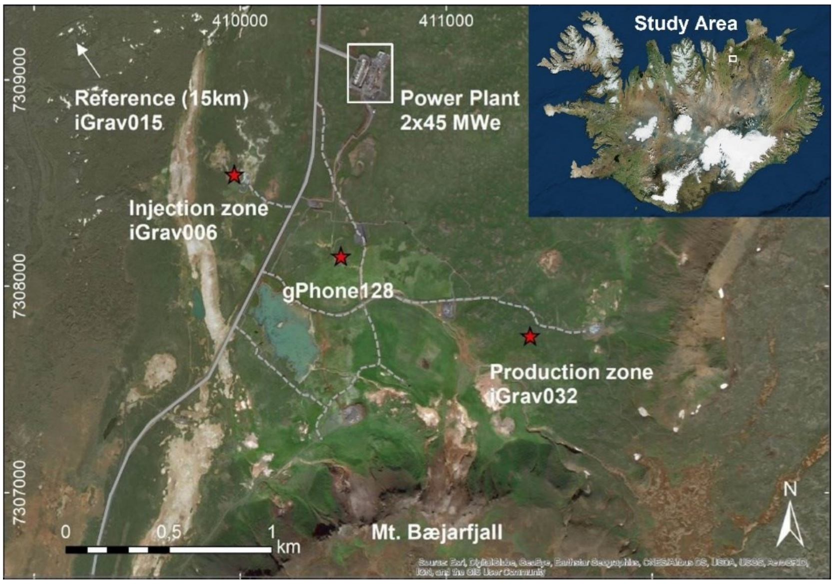

Figure 1: Location of the Þeistareykir geothermal field in northeast Iceland, one iGrav each deployed in the production area in the east (iGrav032) and the injection wells in the west (iGrav006). The centre station is equipped with a spring gravity meter (gPhone128) while the reference station (iGrav015) is some 15 km to the NW, outside the geothermal field. (Source: map.is/os, UTM Zone 28N)

2.1 Gravity network

Figure 2 shows the principle setup of all gravity stations. At each location, two concrete pillars were built after the topsoil was removed from the bedrock (lava sheets). The smaller pillar hosts the continuously measuring relative gravity meter, and the bigger was designed for absolute measurements with an FG5. The pillars are decoupled from the containers which were pre-fabricated in Germany with suitable circular holes in the bottom. Within each container, there are two compartments; one for the instruments installed permanently (Fig. 3, right), and another for instruments installed temporarily for calibration or comparison measurements (Fig. 3, left).

Figure 2: Placing the container for the gravity meters on the concrete pillars at SCGE (left) and the final setup of each gravity station with the hydrometeorological instrumentation installed (e.g., SCGE) (right). (pictures: P. Jousset, K. Erbas)

Although the containers are well isolated and had been equipped with electrical radiators in advance to keep temperatures as constant as possible, the air conditioning operated continuously throughout the year because of the iGrav's air-cooled refrigeration compressors operating inside the container output ~1.3 kW of heat. In retrospective, it would be better to vent the compressor heat outdoors via a heat exchange mechanism. Nonetheless, this setup worked very well. Manual interventions were only rarely needed after the AC ventilation fans were blocked by snow driven during powerful blizzards.

Figure 3: Typical setup of a FG5 absolute gravity meter (left) and an iGrav SG on the pillars in the container. The compressor for the iGrav is placed in the front compartment to minimize vibrational noise from its operation. On each relative gravity meter pillar, there is also a broadband seismometer placed. (pictures: K. Erbas)

Installation of the gravity meters was done at the beginning of December 2017, some two months after the start of the power plant operation. For iGrav015 and iGrav032 we successfully realized a "cold transport" from the Strasbourg gravimetry Observatory (J9) at their 4K operating temperature, while iGrav006 had to be re-cooled from only slightly increased temperature (~8K) after cold transport (Schäfer et al., 2020).

2.2 Seismic network

Based on the experiences with the installation of temporary local seismic networks in volcanic geothermal settings in Indonesia (Muksin et al., 2013; Erbas et al., 2015) and Iceland (Jousset et al., 2018, 2011), a network of 14 seismic stations with high-dynamic broadband sensors (Trillium compact (120s), Nanometrics Inc., Canada) and CUBE3 (DIGOS GmbH, Germany) data recorders (sampling set to 200 Hz) were deployed in September 2017. These are optimally integrated into the existing permanent network of IMO and LV (Fig. 4 and Ágústsson et al., 2020) by using hypothetic event locations and magnitude relations taken from a previous regional seismicity study that coincides with geothermal injection and production areas (Toledo et al., 2018).

Figure 4: Typical setup of a Trillium broadband seismometer at the bottom of a barrel with a CUBE3 recorder (right) and distribution of the seismic network installed in and around the geothermal field (left). The stations of the installed temporary network are shown in green, IMO stations in orange and the stations of the local Landsvirkjun network in blue. For clarity, the permanent stations in and around Krafla are not shown here. (Source: Google Earth, picture: K. Erbas)

3. PRELIMINARY RESULTS

While all gravity stations are remotely accessible in real time and the hydrometeorological data is automatically transferred to servers at GFZ, the seismic data has to be downloaded from the CUBE3 recorder in the field every ~4 months. With the support of the Landsvirkjun staff, it was able to collect the data and change batteries even in the winter. Therefore, able to collect a continuous dataset with very few gaps for more than 1.5 years so far. The general procedures for the preliminary data analysis and the first results of the ongoing monitoring are presented below.

3.1 Gravity data analysis

The gravity data, which is recorded in daily records with 1-second sampling, are combined into monthly intervals and then filtered and decimated to 1-minute intervals. These are combined into a continuous dataset for each gravimeter that still contains all information recorded (air pressure, tilts, temperatures). In a later stage these can be used to apply different filters for the analysis of short, medium or long period signals, but currently we apply all corrections on a 1-minute basis. The tide correction for each station is done using an ETERNA tidal model that was calculated with ANALYZE (ETERNA 3.4, Wenzel, 1996) from the datasets recorded and which is updated as the record lengths increase. The barometric correction is applied using a factor of 3.655 nm/s^2mBar that was also calculated by the ETERNA tidal analysis for the Þeistareykir area. Earthquakes and spikes are currently determined and removed with automatic routines of Tsoft (Van Camp et al., 2005) and, if needed, offsets that occur in the data, due to external events like power cuts or air conditioning failures, are corrected manually. The resulting residual gravity data is then corrected for polar motion using the data of the IERS service: https://hpiers.obspm.fr/iers/eop/eopc04/.

Although SGs are known to have little instrumental drift (Hinderer et al., 2015) we decided to determine the instrumental behaviour of the gravity meters used (iGrav006, iGrav015, iGrav032, gPhone061, gPhone128) prior to the installation in Iceland at the gravimetric observatory J9 in Strasbourg (Schäfer et al., 2020). Also, we prepared all sites such that repeated measurements with an FG5 can be made to determine drift behaviour in Iceland (Fig. 2 and 3). These measurements were carried out in January 2018, June/July 2018 and June 2019. The winter 2018 FG5 values currently are not used because the uncertainties are quite large; measurement conditions had been worse than ever in the EOST FG5 measurements worldwide with noisy inacceptable conditions during the measurements. Due to oscillations in the optical spot to adjust the beams for the interferometric fringes to be measured, the mean value could be wrong by itself, and this was the main reason to decide that winter 2018 FG5 measurements currently are not incorporated into the drift analysis of the first months in Iceland. As an example of a reliable FG5 measurement, Figure 5 shows the data of June 2019 together with the 1-minute data of iGrav032 at the position SCGE within the production zone of the geothermal field. Such mean values are used for drift adjustments.

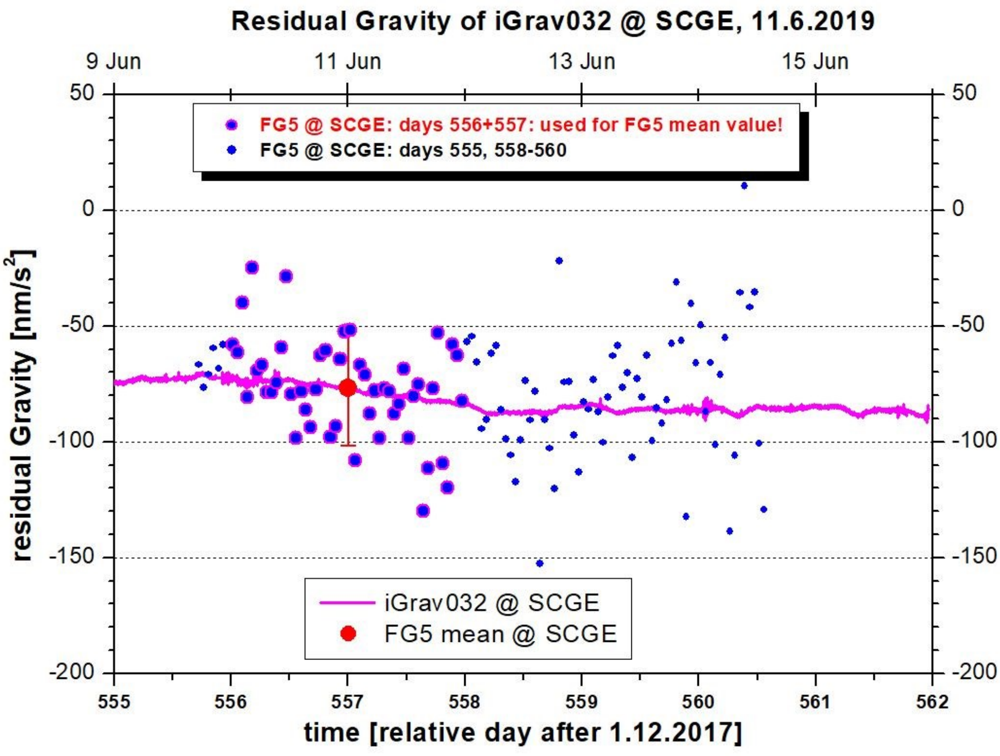

Figure 5: Preliminary compilation of the FG5 (# 206) measurements from June 09 to June 14, 2019, at SCGE together with the 1-minute residual gravity of iGrav032. The absolute values for June 10 and 11 have been used to determine the relative changes to the mean value of 982 282 500.5 ± 1.4 µGal in hourly intervals. The error bars represent a confidence interval of ± 2.5 µGal (± 25 nm/s^2) based on the operator's experience.

3.2 Residual gravity: December 2017 to June 2019

The drift of the gravity instrumentation is of major importance for a differential analysis to detect small variations by mass changes in the underground and locate the sources. Therefore, all instruments were set up together at the gravity observatory J9 near Strasbourg in summer 2017 before the shipment to Iceland (Schäfer, 2020) to determine the individual drifts. Mostly due to delays during transportation, the goal of having the drifts of the iGravs undisturbed after installation in Iceland was only partially met. It was chosen not to repair iGrav032 (with trapped flux) by warming it to room temperature, recooling, and re-initialization it because this would delay the start of gravity monitoring by another month; a higher priority was to start gravity monitoring as close to the beginning of the power plant operation as possible.

For the preliminary analysis shown here, therefore, it was decided to take the summer 2018 and summer 2019 FG5 measurement values at each site as given fixed references to determine a linear approximation for drift in the three iGravs. The FG5 measurements at the reference station (SCGR) in January 2017, fits well with the drift corrected residuals, and also the value at SCGW fits well with the general trend. While the later may be adjusted by a non-linear drift correction, the FG5 value in the production area (SCGE) cannot be explained yet and will be analyzed further.

The drift correction was made as follows: the relative gravity curves were first shifted to agree with the FG5 values in summer 2018; then, the relative gravity curves were tilted to match the corresponding FG5 point in summer 2019. The results are shown in Fig. 6.

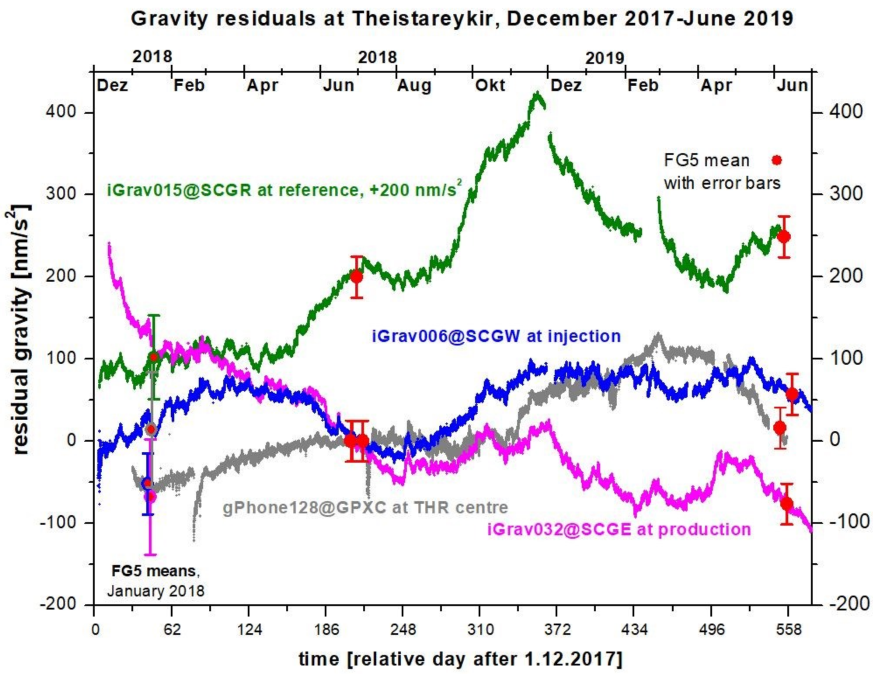

Figure 6: Gravity residuals of the relative gravity meters at Þeistareykir from December 2017 to June 2019 fitted to the FG5 absolute measurements in summer 2018 and summer 2019 by a linear drift approximation.

Most short-period variations correlate very well, and also the seasonal signals observed by iGrav006 and iGrav032 close to the power plant are quite similar. The increasing trend of iGrav006 (~ +57 nm/s^2/year) is visible, as well as the trend of iGrav032 at SCGE, which is decreasing by ~77 nm/s^2 between summer 2018 and summer 2019. These trends are also closely matched by the gravity differences observed by the time-lapse micro-gravity campaigns between summer 2017 and summer 2018 (Portier et al. (2020) that were also repeated in summer 2019. The seasonal variation at the reference site SCGR shows a different pattern, most likely caused by processes in the mountain range nearby. This completely different seasonal behavior ruled out the site SCGR as a useful reference site. In addition, the fact that the measurement series was interrupted in December 2018 (AC failure) and in February 2019 (power supply shortcut) led to the decision to move the instrument to the center position GPXC in between SCGW and SCGE. It has now been installed there since June 12, 2019 next to gPhone128.

3.3 Seismology

Processing is done under Python programming language using numerous capabilities of the Obspy reference library (Beyreuther et al., 2010). After combining the recordings of the temporary network deployed with the permanent IMO and Landsvirkjun stations into a single continuous database, the next task was to determine the parameters for a recursive STA-LTA detection algorithm (Trnkoczy, 2012). This was done by manually identifying seismic events on several days of the database and then adapting the parameters such that all of these are detected. The resulting working parameters for Þeistareykir are a band-pass filter between 4 and 25 Hz; STA and LTA windows of 0.3 s and 10 s, respectively; an activating threshold for the computed STA/LTA ratio function of 5; and a deactivating threshold of 2. Detection is then validated when at least four stations triggering windows coincide. The number of possible events detected with these parameters is in the order of 10000 events per year!

Using the Obspyck software (Megies et al., 2016), the events are manually reviewed, classified and picked when relevant.

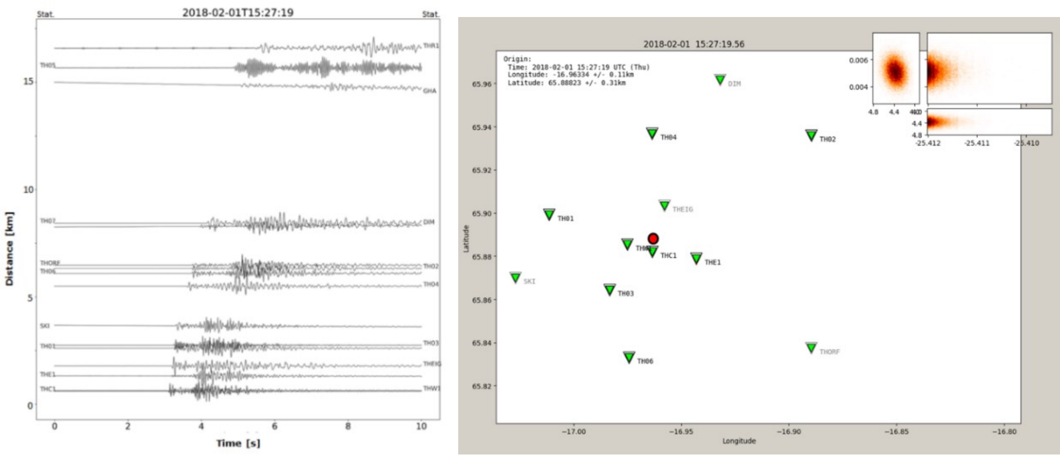

Figure 7: Seismic traces for an event of February 1st, 2018 (left) that had been detected by the automatic detection algorithm. On the right, the resulting preliminary hypocentre localization using NonLinLoc (Lomax et al., 2000) is shown.

After manually picking P- and S- phases, a preliminary event location is performed using an oct-tree search (Lomax et al., 2000) over a 3D volume with velocities corresponding to those of the 1D SIL model (Bjarnasson et al., 1993). Figure 7 illustrates an example of a picked event roughly located in the centre of the geothermal field.

Once enough events are picked (for ~ 2 months) and analysed, additional automatic detection routines were implemented for analysis of the remainder detections.

4. DISCUSSION AND CONCLUSION

With the gravity and passive seismic monitoring that we began in December 2017 shortly after the power plant in Þeistareykir started operation, we are collecting a unique dataset until now. The overall goal of the project is to use a network of gravity meters and seismometers to measure small underground variations associated with managing a geothermal field (injection and extraction).

We have demonstrated that multiple superconducting gravity meters could be moved to NE Iceland and be operated under rough conditions. Despite all the difficulties and technical challenges to monitor and control this high-performance equipment over a period of more than 1.5 years, the gravity dataset alone offers a variety of insights to global (tides), regional (ocean loading) and hydrological processes ranging from the deep subsurface to the soil layers and the atmosphere. Usually, all the effects mentioned above (and many more) have to be corrected before a detailed interpretation can be achieved. Having two iGravs continuously monitoring within a distance of ~1.65 km between SCGW in the West and SCGE in the East, now allows for detailed differential analysis of gravity signal variations between the two sites. Figure 8 (left) shows drift corrected raw gravity at SCGW close to the injection, at SCGE within the production area and their difference for 6 months. The difference of the raw gravity signal is nearly free of diurnal, global, and regional variations versus time, and even the signature of seismic events that are visible in the raw data are nearly eliminated.

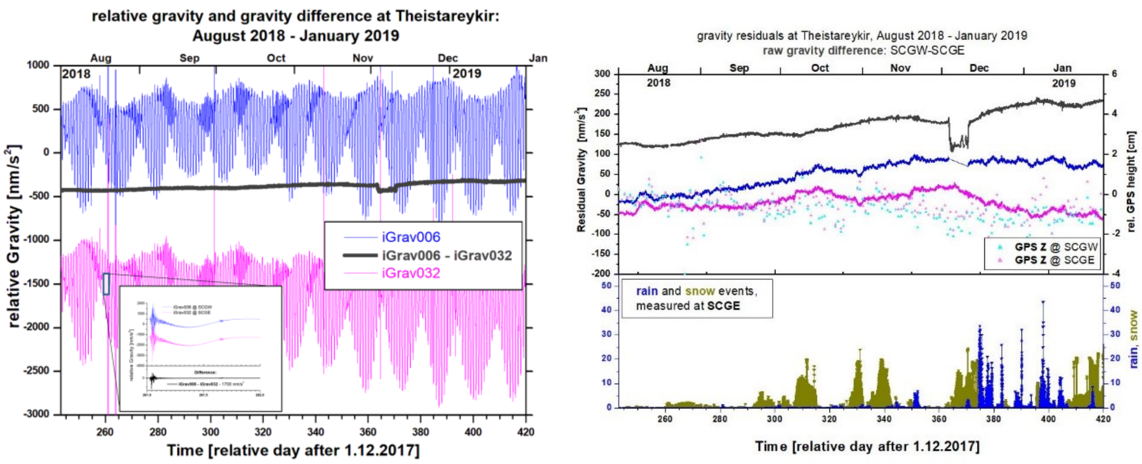

Figure 8: Drift corrected raw gravity at SCGW close to the injection, at SCGE within the production area and their difference for a 6-month period (left) and the difference of the drift corrected raw gravities plotted together with the daily variations (PPP solution) of the vertical displacement that is measured continuously by GNNS receivers and the measured rain and snow data at SCGE (right).

Figure 8 (right) shows the differences of the drift corrected raw gravities from Figure 6 plotted together with the daily variations (PPP solution) of the vertical displacement that is measured continuously by GNNS receivers and the measured rain and snow data at SCGE (right). As shown, the gravity difference is not visibly affected by either rain or snow during this period. In addition, the GPS-Z data show that height change between the two stations cannot account for the positive trend of the gravity difference.

It still has to be shown, how the positive trend of the difference is related to the masses produced (steam/water) in the vicinity of SCGE and "cold" water injection at SCGW. Analysis of operational data (production, injection) has started in summer 2019 and the first preliminary results can be expected by the end of 2019.

Lessons learned in the field from the SG gravity monitoring at Þeistareykir so far:

- Comparative measurements with an absolute gravity meter are a must! However, limitations to AG measurements must be carefully considered in planning a campaign.
- No instrumental drift is best, but even high linear drifts ~ -8 µgal/year for iGrav006 and ~ -60 µgal/year for iGrav032 can be handled if they are linear and confirmed by AG measurements.
- If the iGrav SG instruments are transported over a short distance and very carefully, linear drift rate returns to its previous value quickly (within 2-3 days)
- After power-downs and disturbances of the liquid helium cooling system, short term exponential drifts that decrease with time may occur. This effect will be examined in-depth with the data available now.
- Calibration errors will result in tide signals dominating the differential residual signals. This is not the case here where relative calibrations measured at J9 have remained constant to +/- .01 $nm/s^2/V$
- For differential analysis, the reference station needs to be close enough to the network so that earth tides, ocean loading, atmosphere and background hydrology effects can be removed from different signals. From the measurement results, it can be concluded that the reference location chosen because of power availability near the ski-station of the Husavik was too far to fulfill this requirement.

5. OUTLOOK

Continued monitoring until another absolute gravity campaign takes place is essential to verify the reliability of the gravity analysis in terms of reservoir parameter estimation. The analysis and interpretation of the seismic monitoring will allow for the determination of changes in the subsurface that may affect the injection and production regime. A combined interpretation of the gravity and seismic analysis will help for the understanding of long-term reservoir sustainability.

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