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# Continuous High Resolution Gravity Measurements at a Geothermal Field in Northern Iceland: Setup and Instrumental Performance

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## ABSTRACT

For a better understanding of the sustainability of geothermal resources, we quantify subsurface mass changes caused by production and injection of geothermal fluids. For this purpose, we installed a network of three superconducting gravity meters (iGrav006, iGrav015 and iGrav032) in vicinity to the new geothermal power plant that started operation in October 2017 at Þeistareykir in Northeast Iceland. Prior to the set-up of the monitoring network in Iceland, all gravity meters were setup at the gravimetric observatory J9 in Strasbourg for simultaneous side-by-side measurements. We performed instrumental calibration, comparison of noise levels and tidal analysis. For determination of the iGrav drift behaviour, we compared them to the superconducting gravity meter iOSG023 which has been operating at J9 since February 2016. In Þeistareykir and at a reference site outside the geothermal field, we built four monitoring stations, with decoupled concrete pillars for remote operation of the three iGravs and one gPhone. On a second pillar next to the relative gravity meters, we performed repeated AG measurements (FG5#206) for instrumental calibration and drift correction. At each station additional physical parameters, which influence the local gravity signal, are measured. This includes the continuous monitoring of GPS-positions, rainfall, soil moisture and snow thickness. Here, we present the results of this unique intercomparison of three superconducting gravity meters at Strasbourg and the time series obtained at the geothermal site in Iceland. We compare the calibration stability, the noise levels and the drift behaviour at both sites. Based on our findings, we give a recommendation for the preparation of high-resolution gravity measurements in remote areas.

## 1. INTRODUCTION

The iGrav is a superconducting gravity meter (SG) developed and commercialized by GWR Instruments, Inc. for continuous high-precision gravity observations. iGrav SGs have been used both for campaign-based gravity measurements (Fores et al., 2017; Kennedy et al., 2016; Kennedy et al., 2014), and for long-term observations in remote areas (Carbone et al., 2019; Carbone et al., 2017). Compared to the compact (CT) or observatory superconducting gravity meter (OSG) typically used at permanent SG stations around the world (Voigt et al., 2017), the iGrav has the advantages of lower weight, less power consumption, and much simpler initialization procedures for sphere levitation and centering. Similar to the OSG, the iGrav operates remotely after setup, and it does not depend on a regular refill with liquid Helium. The dewar is initially filled with liquid Helium by using its refrigeration system to liquefy Helium gas supplied by gas cylinders and it is refilled after power failures using the same process (Hinderer et al., 2015). These properties makes it more adapted for remote operation even in harsh or remote environments.

While these technological developments make it easier to transport SGs from one monitoring site to another, the question arises whether specific instrument parameters and characteristics for one set-up can be transferred to the new monitoring location. Among these, the instrument-specific scale factor to convert from the instrument's output voltage to gravity units is essential for accurate monitoring. The flexibility of instrument deployment at different monitoring sites would be much enlarged in case the same scale factor can be applied at each location. Similarly, if known instrumental drift characteristics that superimpose onto the true gravity changes recorded by the gravity meters are transferable to the new monitoring site, the ease of their data interpretation would be much enhanced. This also applies to (high frequency) noise characteristics of the instrument after transport. Schilling and Gitlein (2015) described the variability of these parameters for a gPhone spring gravity meter at different measuring stations in Germany. However, there are no studies so far that report on how the iGrav instrumental parameters may be influenced by transport to a new location. Therefore, the overall aim of this study is to quantify the instrumental parameters and performance before and after transport to remote monitoring sites. We deployed three iGravs (006, 015 and 032) for continuous measurements at the gravimetric observatory J9 in Strasbourg (France) with well-defined and stable site characteristics, before transport for monitoring at a remote geothermal field in the Northeast of Iceland (Erbas et al., 2020). The observatory measurements at J9 were used for instrumental calibration and for comparison of the noise levels. For determination of the iGrav drift behaviour at J9 we used iOSG023 as a reference which has been operating at J9 since February 2016. A similar analysis of scale factor, noise, and drift behaviour were repeated for each instrument after relocation to Iceland. As a reference for drift characterization at the Icelandic remote sites, we performed absolute measurements using an FG5 absolute gravity meter (FG5#206).

## 2. SITES AND SETUP

### 2.1 Co-located gravity measurements at the gravimetric observatory J9 in Strasbourg

For calibration and comparison measurements, the three iGravs were set up at the gravimetric observatory J9 near Strasbourg (Fig. 1). Together with the superconducting gravity meter iOSG023, they were operating between June and October 2017: iGrav006 from 21.09.17 to 23.10.17; iGrav015 from 21.06.17 to 24.10.17; and iGrav032 from 17.06.17 to 29.08.17 and after maintenance break from 28.09.17 to 24.10.17). All instruments were located within 2 to 10 meters to each other, ensuring common influence of all external parameters (meteorological conditions, hydrology, phreatic changes, etc.).

**Figure 1: Measuring setup for iGrav032 and iGrav015 at the underground observatory J9 near Strasbourg, France.**

### 2.2 Remote operation at a geothermal field in Northeast Iceland

After transport to the northeast of Iceland, in December 2017, the gravity meters started operation at the remote monitoring sites in Þeistareykir (Fig. 2). Two iGravs (006 and 032) were set up inside the geothermal field within two kilometres distance to each other. The third iGrav (015) was located 15 kilometres to the northwest, for reference measurements outside the geothermal field, until June 2019. Then it was relocated to the central station between iGravs 006 and 032.

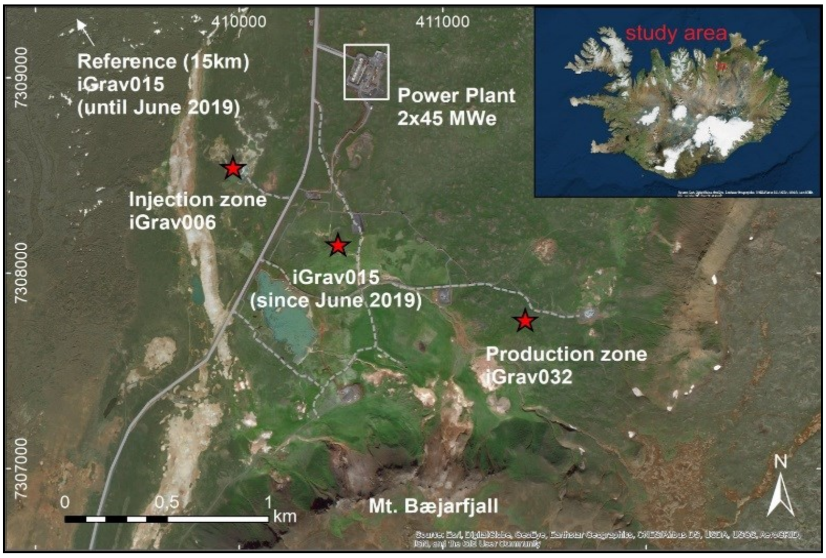


**Figure 2: Location of the geothermal field in the northeast of Iceland, one iGrav each deployed at the production wells in the east (iGrav032) and the injection wells in the west (iGrav006), iGrav015 was moved from reference to central station in June 2019 (maps compiled with ArcGIS 10.5.1).**

All monitoring sites have similar configuration as shown in Figure 3. They consist of an isolated container with two rooms, each housing a circular concrete pillar. Both pillars are decoupled from the container and grounded to the subsurface. The continuous operating gravity meter is set-up on the pillar in the rearward room (Fig. 3b). The pillar in the entrance room is used for performing comparison measurements with an FG5 absolute gravity meter. Each container is equipped with a heater and air conditioning to keep a constant room temperature of approximately 16°C. A remotely operated multi-parameter station (ROMPS) (Schöne et al., 2013) outside the container (Fig. 3a) is monitoring additional hydro-meteorological parameters, which may influence the local gravity signal. This includes barometric pressure, air temperature, precipitation, wind speed, soil moisture and temperature; additionally, snow weight, snow properties and snow height are monitored at one site. At every gravity station, we deployed geodetic GNSS receivers for continuous observations of ground motion. Three cameras at each site allow visual inspections of the surroundings and estimation of snow heights at the container corners.

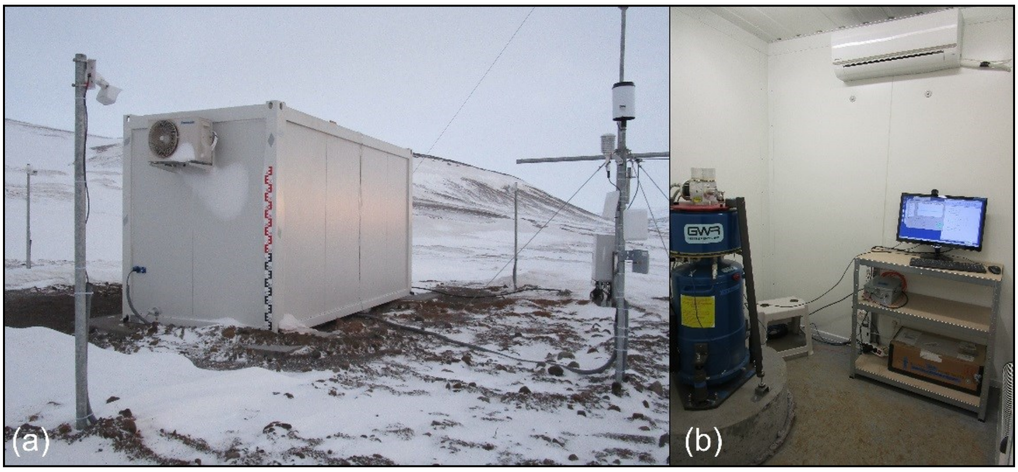


**Figure 3: Reference gravity station 15 km northwest from Þeistareykir (a) showing setup similar at all 4 gravity stations with GNSS and hydro-meteorological parameters measured outside the container; measuring setup inside the container (b) for an iGrav installed on a concrete pillar, decoupled from the surroundings and grounded to the bedrock.**

## 3. STABILITY OF INSTRUMENTAL PROPERTIES

### 3.1 Calibration factors

The raw signal of every SG must be multiplied by a distinct scale factor to convert the recorded output feedback voltage to gravity units. From calibration measurements with iOSG023 at J9, we obtained the relative scale factors: -914.27 ±0.0042 nm/s$^2$/V for iGrav006; -930.18 ±0.0019 nm/s$^2$/V for iGrav015; and -895.84 ±0.0065 nm/s$^2$/V for iGrav032. The relative uncertainties given for each scale factor is better than ±0.01 nm/s$^2$/V; while their absolute uncertainties are limited to ±4 nm/s$^2$/V by the uncertainty of the absolute calibration of iOSG023. In addition, we measured the relative scale factors between pairs of the three iGravs before and after transport to Iceland to check the stability of the calibration coefficients. For Þeistareykir we used 8 days of iGrav data sets from June/July 2019, when iGrav015 was located at the central station at about 660 m distance to iGrav006 and 1000 m distance to iGrav032 (cf. Fig.2). The differences between the scale factors before and after transport are shown to depend upon the distances between the instruments at Þeistareykir. After correction for the different geographical locations and elevations we obtain scale factor stabilities better than 0.01% for all three iGravs.

### 3.2 Noise levels

A combination of instrumental noise and/or geophysical signals (commonly called noise) may limit the precision with which gravity signals of interest can be measured. We expect lower background geophysical signals to be present at quiet, isolated sites like J9 in Strasbourg, compared to tectonically and geothermal active sites like Þeistareykir. In addition, we expect to observe larger gravity signals (load and waves) at the Icelandic remote sites, due to their short distance to the coastline. To compare the noise levels between the different instruments and sites, we performed a frequency analysis, by computing power spectral densities (PSDs) for each gravity record. The PSD calculation follows the standard procedure of noise level comparison for SGs by Banka and Crossley (1999). In this study, we applied the generalized method from Rosat et al. (2004) to calculate the iGrav noise levels at seismic frequencies. We used unfiltered gravity signals in nm/s$^2$ with 1 Hz sampling rate and the New Low Noise Model (NLNM; Peterson, 1993) as a reference signal to estimate the quality of each site and instrument. For the noise level comparison, we choose gravity records from seven “quiet” days at the J9 observatory. From the Þeistareykir gravity records, we choose seven “noisy” winter days and seven “quiet” summer days.

Figure 4 shows the noise levels of iOSG023 and one representative iGrav (015) at J9. The results for both meters are in good agreement to each other, with differences of less than 10 dB. The same plot shows the noise levels of iGrav015 during seven winter and seven summer days at Þeistareykir, with about 40 dB higher noise level in winter. As the gravity stations are located close to the coastline (8 km for the reference station) the increased noise can be attributed primarily to strong winds and accompanying ocean waves during the Icelandic winter. The summer days show low noise levels, differing by less than 10 dB to the values at J9.

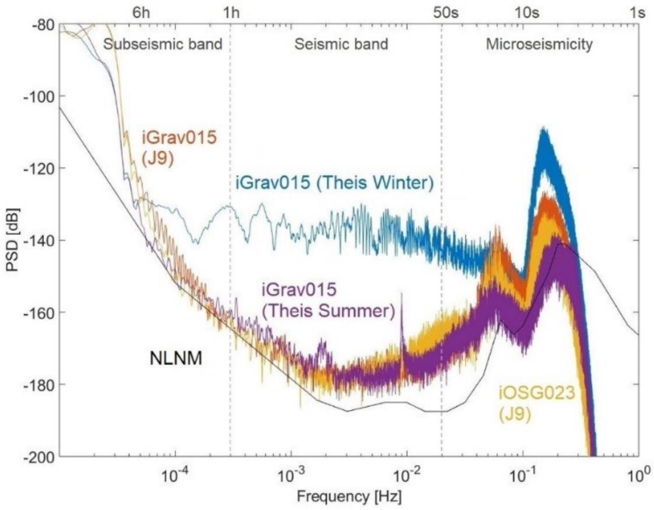


**Figure 4: Power Spectral Densities (PSD) relative to 1 $(m/s^2)^2/Hz$ with a sampling rate of 1 Hz, for iOSG023 and iGrav015 during seven quiet days at J9 (orange and brown), and for iGrav015 during seven noisy (winter, blue) and seven quiet (summer, purple) days at Þeistareykir, New Low Noise Model (NLNM; Peterson, 1993) shown for reference.**

### 3.3 Drift behavior

Every relative gravity meter, including SGs shows a distinctive instrumental drift behaviour superimposing onto the true gravity changes. Drift functions for most SGs are normally toward increasing gravity and have been described as the combination of an exponential component that decays in 4 to 6 months followed by a small linear term that vary from 16 to 49 $nm/s^2$/year for nine SGs operating in Europe (Hinderer et al., 2015; Crossley et all, 2004). The drift function for C021 operating at Membach since 1995 has been shown to be exponential after operating for over 10 years although differences between the linear and exponential drift curves remain small (Van Camp and Francis, 2007).

One goal of this work was to measure the individual drift curves of the three iGravs at J9 and then to transport them to Iceland with full liquid helium dewars, at their 4K operating temperature without disturbing these drift curves. This goal was only partially fulfilled. iGrav006 was cooled at J9 only 3 weeks before shipping and its dewar partially warmed to 8 K after 13 days in transit caused by bad weather during ship transport to Iceland. Therefore, we expected iGrav006 to have a 'normal' drift curve as described above.

In contrast, the drift curves observed at J9 for both iGrav015 and iGrav032 were 'abnormal' and can be described by an exponential decay toward increasing gravity followed by a much larger negative drift. Different approaches were taken to fix the drift in these two iGravs. iGrav032 was shipped back to GWR to replace its getter which was diagnosed as a potential problem. Unfortunately, this was a misdiagnosis – the real problem was most likely caused by shipping iGravs after side coils had been used to trap flux in the sphere, coils and shield. This procedure had been instituted to raise the frequency of the commonly observed orbital sphere resonance (Hinderer eta al., 2015) out of the long-period seismic band. This problem was diagnosed and removed from other iGravs about one-year after the start of the Iceland installations. And in retrospect both iGravs 015 and 032 could have been 'repaired' by warming them to room temperature, recooling them to 4 K, and reinitializing them without using the side coils to trap flux. This possibility was discussed but it would have delayed the start of gravity monitoring in Iceland by another month, so it gave way to the higher priority of starting the gravity monitoring as close to the beginning of the power plant operation as possible.

GWR attempted to 'repair' iGrav015 by heating its sensor inside the vacuum can to 80 K and letting it slowly recool to 4K. In theory, this process should remove all trapped flux from the superconducting components of the sensor. This procedure was done at J9 while the dewar and vacuum can remained at 4 K. Some 20% of the liquid helium was lost in the dewar, but it was refilled to 100% before shipping to Iceland. In later work, GWR found that this high-temperature annealing would generally reduce the magnitude of the negative drift but would not eliminate it completely. This mechanism is not yet fully understood. In any case, iGrav015 operated for 3 months at J9 and it did not show a big change in its drift behavior between J9 and Iceland.

To identify the instrumental drift of the three iGravs we removed the effects of solid earth tides, ocean loading and polar motion, as well as the effect of atmospheric pressure from the calibrated gravity time series. As a standard tool for gravity reduction, we applied tidal modelling (Merriam, 1992; Francis and Mazzega, 1990; Melchior, 1974) to calculate the residual time series for every monitoring site. For J9 we used local tidal parameters and atmospheric admittance factors available from long-term gravity analysis at the observatory. For Þeistareykir we calculated local tidal models for each of the remote monitoring sites. The tidal analysis was performed with the program ANALYZE from the ETERNA 3.4 package (Wenzel, 1996).

Figure 5a shows a comparison of the iGrav015 and iOSG023 residual time series at J9. For further reduction of the remaining gravity effects including local hydrology we subtracted the residual (reference) signal of iOSG023 from the iGrav015 residuals, and subsequently shifted the beginning of both time series to zero in time (Fig. 5b). It is noticeable that the iGrav015 time series is much smoother than in Figure 5a because most of the higher frequency gravity changes are present in both gravity signals (of iOSG023 and iGrav015) and hence disappear in the difference. As a first approach to estimate the long-term drift, we applied linear drift correction for iGrav015 (in Fig. 5b). From the corrected time series (dark green) we clearly observe the expected initial exponential increase for over 30 days after the beginning of observations. The estimated linear drift rate of iGrav015 (dashed line) is -0.316 nm/s$^2$ per day.

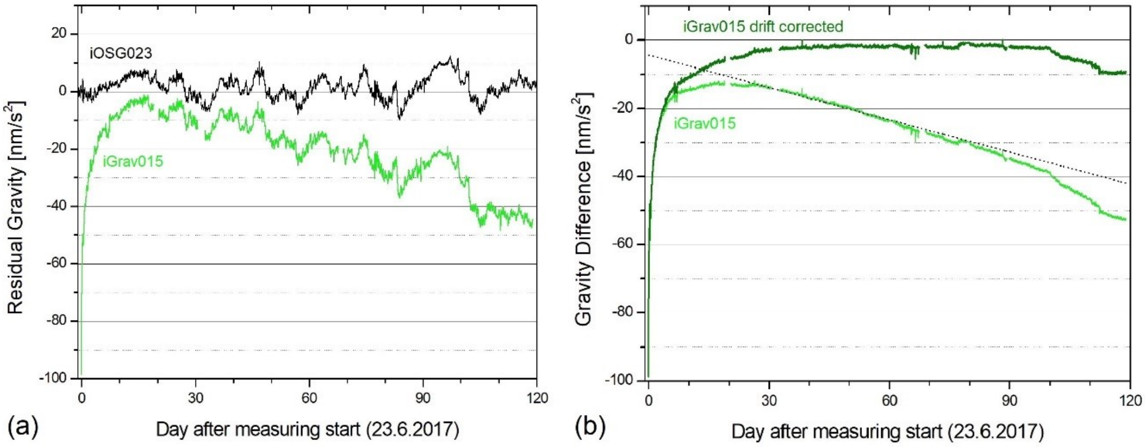


**Figure 5: Gravity time series from J9, (a) showing residuals of iGrav015 and iOSG023; (b) showing gravity differences of iGrav015 to the reference iOSG023 and linear drift correction applied for iGrav015.**

Unlike the setting at J9, the Icelandic remote monitoring sites are located distances of several kilometres to each other (up to 2 km at the geothermal field and 15 km apart for the reference station) and satisfactory reduction of site-dependent gravitational effects (e.g. solid earth tides or ocean loading) cannot be achieved by calculating gravity differences between two instruments as in Figure 5b. For this reason, we performed tidal analysis for each of the remote monitoring sites. The resulting iGrav015 residuals for the first 120 days of observation are shown in bright green in Figure 6 (cf. Fig. 5a). For instrumental drift characterization we used AG measurements (Fores et al., 2017; Hinderer et al., 2015) from two FG5#206 campaigns at Þeistareykir in June/July 2018 and June 2019. The drift corrected residuals for iGrav015 are shown in dark green, with an estimated long-term drift rate (dashed line) of -0.217 nm/s$^2$ per day. The reduction of drift rate compared to Figure 5b (-0.316 nm/s$^2$/d) most likely indicated that the high-temperature annealing of the sensor at J9 was somewhat effective in reducing the magnitude of the drift. It has not been proven that the negative 'abnormal' drift magnitude is linear. Therefore, and alternative explanation is that the negative drift could also have an exponential component and that its magnitude slow decreased in the time elapsed between operation at J9 and installation in Iceland.

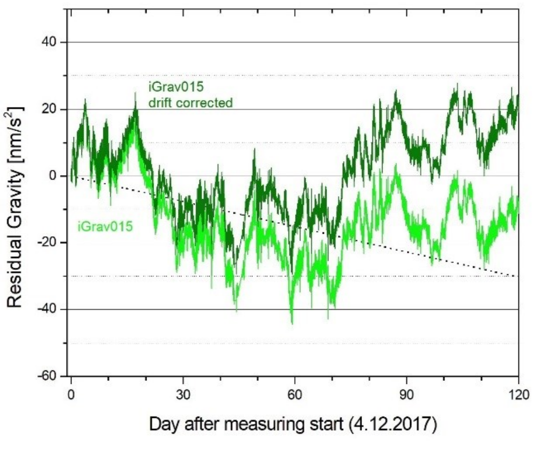


**Figure 6: Gravity time series from the first 120 days at Þeistareykir, showing gravity residuals of iGrav015 after tidal correction (bright green), long-term drift estimation (dotted lines) by comparison to AG (FG5#206) measurements and drift corrected residuals of iGrav015 (dark green).**

## 4. CONCLUSION AND OUTLOOK

We used three iGrav superconducting gravity meters for continuous gravity measurements. We made use of prior comparison measurements with an accurately calibrated observatory gravity meter, for calibration purposes, instrumental drift determination and performance estimation between the different instruments. The stability of the relative scale factors was determined to better than ±0.01%. Spectral noise analysis showed that noise levels are equally low for J9 (Strasbourg) and the summer days at Þeistareykir, whereas during the winter days, noise levels are about 40 dB larger. As a next step, to isolate the instrumental noise from environmental noise we want to apply a three-channel correlation technique (Rosat and Hinderer 2018) between the calibrated iGravs at J9 and between the iGravs within 2 km distance at Þeistareykir. Drift analysis of iGrav006 showed that there is an exponential drift component, which could have started after initialization at J9 and continues after installation in Iceland.

Alternatively, it could have started after the iGrav006 dewar and sensor warmed up to 8 K during shipment to Iceland. This drift component is typically slowly varying and monotonically decreasing over time. As a negative consequence of the cold transport, we observed an unexpected long-term drift for both iGravs 015 and 032 that is very likely due to a trapped flux within the gravity sensor. These effects have been observed not only in shipping iGravs from GWR to J9, and from J9 to Iceland, but also from GWR to other locations. For the 3 sites in Þeistareykir, we did a first approach of drift characterization by comparison to the AG (FG5#206) measurements, which we will validate and improve by further AG campaigns. Further comparison to time-lapse micro-gravimetry carried out at Þeistareykir (Portier et al., 2020), is planned to improve the understanding of the general spatial distribution of the gravity changes within the geothermal field.

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