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Intercomparing Superconducting Gravimeter Records in a Dense Meter-Scale Network at the J9 Gravimetric Observatory of Strasbourg, France

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Abstract

This study is a metrological investigation of eight superconducting gravimeters that have operated in the Strasbourg gravimetric Observatory. These superconducting gravimeters include an older compact C026 model, a new observatory type iOSG23 and six iGravs (6, 15, 29, 30, 31, 32). We first compare the amplitude calibration of the meters using measurements from FG5 #206 absolute gravimeter (AG). In a next step we compute the amplitude calibration of all the meters by time regression with respect to iOSG23 itself carefully calibrated by numerous AG experiments. The relative calibration values are much more precise than absolute calibration for each instrument and strongly reduce any tidal residual signal. We also compare the time lags of the various instruments with respect to iOSG23, either by time cross-correlation or tidal analysis for the longest records (about 1 year). The instrumental drift behavior of the iGravs and iOSG23 is then investigated and we examine the relationships observed between gravity and body temperature measurements. Finally, we compare the noise levels of all the instruments. A three-channel correlation analysis is used to separate the incoherent (instrumental) noise from the coherent (ambient) noise. The self-noise is then compared to a model of thermal noise (Brownian motion) using the known instrumental parameters of the damped harmonic oscillator. The self-noise of iGrav instruments is well-explained by the thermal noise model at seismic frequencies (between 10⁻³ and 10⁻² Hz). As expected, the self-noise of iOSG23 with a heavier sphere is also lower than that of iGravs at such frequencies.

Keywords (separated by '-')

Superconducting gravimeter - levitation - calibration - instrumental drift - noise

Footnote Information



Intercomparing Superconducting Gravimeter Records in a Dense Meter-Scale Network at the J9 Gravimetric Observatory of Strasbourg, France

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Abstract—This study is a metrological investigation of eight superconducting gravimeters that have operated in the Strasbourg gravimetric Observatory. These superconducting gravimeters include an older compact C026 model, a new observatory type iOSG23 and six iGravs (6, 15, 29, 30, 31, 32). We first compare the amplitude calibration of the meters using measurements from FG5 #206 absolute gravimeter (AG). In a next step we compute the amplitude calibration of all the meters by time regression with respect to iOSG23 itself carefully calibrated by numerous AG experiments. The relative calibration values are much more precise than absolute calibration for each instrument and strongly reduce any tidal residual signal. We also compare the time lags of the various instruments with respect to iOSG23, either by time cross-correlation or tidal analysis for the longest records (about 1 year). The instrumental drift behavior of the iGravs and iOSG23 is then investigated and we examine the relationships observed between gravity and body temperature measurements. Finally, we compare the noise levels of all the instruments. A three-channel correlation analysis is used to separate the incoherent (instrumental) noise from the coherent (ambient) noise. The self-noise is then compared to a model of thermal noise (Brownian motion) using the known instrumental parameters of the damped harmonic oscillator. The self-noise of iGrav instruments is well-explained by the thermal noise model at seismic frequencies (between 10^{-3} and 10^{-2} Hz). As expected, the self-noise of iOSG23 with a heavier sphere is also lower than that of iGravs at such frequencies.

Keywords: Superconducting gravimeter, levitation, calibration, instrumental drift, noise.

1. Introduction

Eight different superconducting gravimeters (SG) manufactured by GWR Instruments, Inc. have been operated at J9 gravimetric Observatory of Strasbourg. A compact C026 was the first SG installed in 1996, an iOSG-type (#23) in January 2016 and iGrav (#29) in July 2016, and five other iGrav-type (#6, #15, #30, #31, #32) at various intervals. Figure 1 shows the three different types of SG used in this intercomparison study.

The C026 was installed in July 1996 and proved to have very good time-stability (Calvo et al., 2014, 2017; Riccardi et al., 2009) and good performances in terms of noise levels (Rosat & Hinderer, 2011) enabling the study of very long-period geophysical phenomena and the analysis of small tidal constituents (e.g. Calvo et al., 2016). Experiences of intercomparison and validation tests of spring gravimeters, conducted in the past at J9, have benefited from the stability of the C026 and the low noise level in the observatory (Arnos et al., 2014). Since February 2016 the iOSG23 (see below) operated next to the C026 (Boy et al., 2017; <http://doi.org/10.5880/igets.st.11.001>). C026 had experienced many problems due to its very old electronics (more than 25 years old) and was turned off in November 2018. The C026 data were also not usable between November 2016 and April 2017 because of a failure of the data acquisition system.

The latest generation of single-sphere SGs are the iGrav and the iOSG using identical sensors, electronics and refrigeration systems. The iOSG uses a heavier sphere (17.7 g versus 4.3 g) and has a larger dewar (35 L versus 16 L) and consequently has a

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69 slightly lower instrumental noise level and a longer
 70 hold time during power failures. In contrast, the
 71 iGrav, which was designed for field use, is easier to
 72 move and operate at remote sites (Warburton et al.,
 73 2011). The iOSG23 was installed at J9 in January
 74 2016 and is the second iOSG installed in France; the
 75 first one was iOSG24 installed in July 2015 at the low
 76 background noise interdisciplinary ground and
 77 underground based research laboratory LSBB of
 78 Rustrel, in the south of France (Rosat et al., 2016).
 79 Only three iOSGs have been manufactured and the
 80 third, iOSG22, was installed at Metsähovi Geodetic
 81 Fundamental Research Station (ME), Finland in
 82 December 2016. The older compact C026 was a
 83 second generation of SG manufactured between 1994
 84 and 2002 with a 125 L dewar. The iOSG and iGrav
 85 instruments use SHI RKD 101 refrigerating systems
 86 to cool below 4 Kelvin and condense helium gas (He)
 87 to liquid inside the dewar so that there is no He loss
 88 and no need to transfer liquid He. In contrast, the
 89 C026 used an older APD Cryogenics DE202A cold-
 90 head with only 9 K cooling capability so He gas boils
 91 off slowly. As a result, the C026 required regular
 92 human intervention (about every 10 months) to refill
 93 the dewar with liquid He.

94 iGrav29, iGrav30 and iGrav31 were purchased in
 95 2016 in the framework of the Equipex CRITEX
 96 recently integrated in OZCAR (<https://www.ozcar-ri.org/ozcar/>), which is the French network of Critical
 97 Zone Observatories (Gaillardet et al., 2018). The
 98 iGravs are one type of equipment for this hydrology-

oriented project dedicated to the gravity monitoring
 of basin catchment and the study of the critical zone.
 These three iGravs were installed at J9 in July 2016.
 After operation at J9, iGrav30 was moved to the
 Strengbach catchment in the Vosges mountains (at
 70 km from Strasbourg) end of June 2017 and
 iGrav31 was moved in May 2019 to the surface sta-
 tion at LSBB (<https://lsbb.cnrs.fr>) in South of France.
 iGrav30 is used to investigate the water storage
 changes at the catchment scale (Chaffaut et al., 2020),
 while iGrav31 establishes together with iOSG24 (the
 twin meter of iOSG23 studied here) a differential
 gravity experiment that will be very useful to locate
 the underground water mass changes already detected
 by iOSG24 alone (Mouyen et al., 2019; Rosat et al.,
 2016, 2018). The eight SGs were installed in different
 rooms of the J9 bunker as illustrated in Fig. 2.

iGrav6, iGrav15, and iGrav32 were moved to the
 Strasbourg Observatory by German colleagues for a
 validation test in 2017 before being sent to Iceland in
 the frame of the “Microgravimotis” project for
 gravity monitoring of the Theistareykir geothermal
 site (Erbaş et al., 2019). The performances of these 3
 iGravs after transportation to Iceland in terms of
 calibration, drift and noise levels are investigated in
 Schäfer et al. (2020). As can be seen in the
 timetable (Fig. 3), end of August 2017 iGrav32 had
 to be sent back to the manufacturer GWR for
 instrumental upgrade and did come back to J9 only
 for a short time in October 2017; the period before
 the upgrade refers to 32a and after upgrade 32b.



Figure 1

A picture showing the types of SGs operating side by side and their physical installations in the J9 Observatory near Strasbourg (France): from left to right, C026 on a large isolated pillar; iOSG23 straddling a small isolated pillar; iGrav32 operating directly on the concrete floor; and iGrav30 with coldhead frame modified to fit on a small isolated pillar

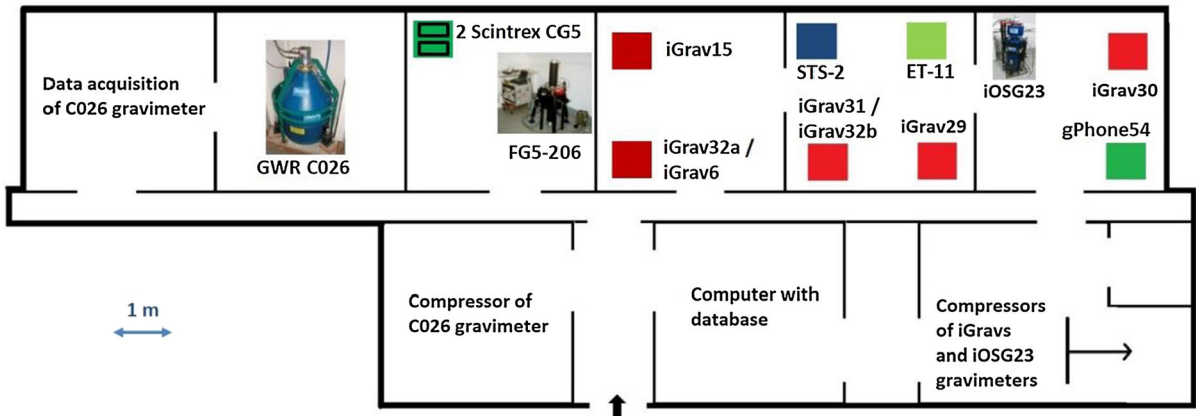


Figure 2

Floor plan of the Strasbourg Gravimetric Observatory (J9) indicating the location of the various instruments that are compared in this study

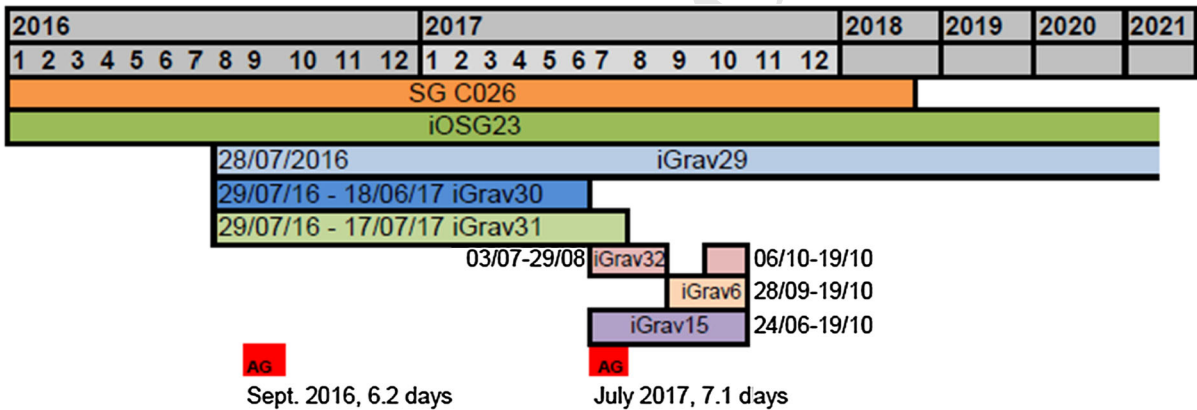


Figure 3

Timetable of the SG and AG measurements in the J9 Observatory

131 iGrav6 also came only for limited time end of
132 September 2017 before shipment to Iceland.

133 For both historical reasons and convenience, a
134 variety of methods as shown in Fig. 1 were used to
135 physically set SGs at J9. C026 was operated in its
136 own room and on a wide and deep pillar
137 (0.8 m × 0.8 m × 2 m) isolated from the floor that
138 was originally built for operating one of the early
139 GWR TT70 SGs. Two of the rooms at J9 have small
140 isolated pillars (0.6 m × 0.6 m × 0.6 m) previously
141 used for testing LaCoste and Romberg, Scintrex and
142 gPhone gravity meters. Although the base of the
143 iOSG23 dewar fits on the small pillar, its coldhead
144 isolation frame does not. Therefore, the coldhead
145 isolation frame straddles the pillar with two of its feet
146 on the pillar and one on the nearby concrete floor.

147 iGravs 29, 30, 31 and 32b were also operated on
148 small pillars; however, for these iGravs, the connect-
149 ing angles of the legs to the coldhead support
150 bracket were decreased during installation to reduce
151 their footprints to fit onto the small pillars. The
152 iGrav15, iGrav6 and iGrav32a were installed directly
153 on the concrete ground without any modification to
154 their coldhead frames. As a consequence, some differ-
155 ences between the physical installations for the
156 eight instruments could influence the measured noise
157 levels between them.

158 The timetable showing the available data sets is
159 given in Fig. 3. The maximum number of SGs mea-
160 suring simultaneously in our study is six because
161 there is no overlap between iGrav30 that left the

Table 1

Results for absolute calibration of SGs using SG/AG parallel records; V stands for volt

SG name	Length of calibration	Absolute calibration and error (nm/s ² /V)	Dimensionless error (%)
C026	Numerous experiments with FG5#206 during 1996–2018	-792 ± 1	0.1
iOSG23	6.2 days	-451 ± 2	0.4
iGrav15	7.1 days	-934 ± 3	0.3
iGrav29	6.2 days	-940 ± 4	0.4
iGrav30	6.2 days	-918 ± 4	0.4
iGrav31	6.2 days	-853 ± 4	0.5
iGrav32	7.1 days	-898 ± 3	0.3

162 Observatory for a remote installation before iGrav32
163 arrived.

164 In this paper, we compare the accuracy and pre-
165 cision of the time variations of gravity recorded by
166 the various SGs. We start by first testing the precision
167 of the scaling factors used to calibrate the SGs and we
168 estimate the time delays (phase lags) between the
169 instruments, either by directly comparing the time
170 series and their correlation, or by using tidal admit-
171 tances obtained from tidal analyses. Next, the
172 instrumental drift is carefully investigated, particu-
173 larly the initial drift subsequent to the installation of
174 each gravimeter. And finally, from the few months of
175 parallel records, we finally use a standard procedure
176 to compute power spectral densities (PSDs) using the
177 Welch's overlapped segment averaging estimator in
178 order to give reference noise levels for these instru-
179 ments. These PSDs are compared with the
180 seismological reference noise models and with other
181 relative mechanical gravimeters and a long-period
182 seismometer that have been recorded at J9. Self-noise
183 levels are also estimated and compared with a pre-
184 dicted thermal noise model.

185 2. Amplitude Calibration and Time Delay

186 2.1. Absolute Calibration

187 SGs are relative instruments that need to be
188 calibrated using an absolute reference. Since the
189 transfer function of the SGs is flat at frequencies
190 much lower than Nyquist frequency (0.5 Hz), the
191 calibration is usually achieved by estimating a scale

factor with tides recorded by parallel co-located
absolute gravity measurements performed with a FG5
ballistic instrument (Fukuda et al., 2005; Hinderer
et al., 1991; Imanishi et al., 2002; Tamura et al.,
2004). Following recent papers (Crossley et al., 2018;
Meurers, 2012; Van Camp et al., 2015), we used
parallel FG5 drop measurements to which a L1-norm
adjustment of the low-pass filtered SG data decimated
to 10 s is performed. This L1-normalization is used in
order to avoid the influence of outliers. The FG5 drop
standard deviations are considered in the fitting
process. Scale factors obtained in this way (absolute
calibration factors) are summarized in Table 1 as well
as the time periods during which the various instru-
ments were recording at J9.

Two specific AG/SG calibration experiments
were performed during the observation period: the
first one in September 2016 having a duration of
149 h (6.2 days) and used to calibrate iGrav29,
iGrav30, iGrav31, and iOSG23; the second one in
July 2017 having a duration of 170 h (7.1 days) and
used to calibrate iGrav15, iGrav32.

Note that numerous absolute calibration experi-
ments were done with C026 since 1996 (Amalvict
et al., 2001; Calvo et al., 2014; Crossley et al., 2018;
Riccardi et al., 2012; Rosat et al., 2009) leading to the
very well determined value of -792 ± 1 nm/s²/volt.

iGrav15 was first calibrated by FG5#206 in J9 and
after cold transportation to the Theistareykir geother-
mal site in Iceland it was calibrated again. The two
calibration factors found in J9 and Iceland lead to a
nearly identical value -935 ± 6 nm/s²/V (Schäfer
et al., 2020). No absolute calibration could be
performed for iGrav6 at J9.

226 2.2. Relative Calibration

227 It has been shown in previous studies that the
 228 internal SG stability ($\sim 0.1\%$) as derived from tidal
 229 analyses is more than ten times better than the
 230 stability that can be achieved by calibration repeti-
 231 tions with an absolute gravimeter (Calvo et al., 2014).
 232 Besides, absolute gravity measurements are affected
 233 by noise which will limit the precision of the
 234 retrieved scale factor. Assuming one of the SGs
 235 operating in our Observatory possesses an accurate
 236 calibration, we can estimate the scale factors of other
 237 SGs by minimizing the differences of raw time
 238 records that should measure the same changes in
 239 gravity being located at the same place (at least inside
 240 the same building). We may hence expect to improve
 241 the precision on the scale factor estimates. However,
 242 we have to state here that a relative calibration can
 243 never be more accurate than the calibration of the
 244 instrument used for the relative calibration. It can
 245 only enhance the precision of calibration but not the
 246 accuracy. Using another relative gravimeter to cali-
 247 brate an SG was already tested by Meurers (2012)
 248 and by Riccardi et al. (2012). The latter for instance
 249 applied this method to the C026 using the gPhone-54
 250 spring gravimeter data. Precision on the SG scale
 251 factor was around 0.01% while using absolute FG5
 252 measurements it was limited to 0.4%.

253 To obtain the relative scale factors we applied a
 254 multi-regression method on the SG raw signal (in
 255 volts) with respect to iOSG23 gravity (in nm/s^2) and
 256 to time (assuming a linear or second order poly-
 257 nomial drift). In addition, we also computed the scale
 258 factor for a moving window (2 days shifted by half a
 259 day) both with unfiltered data and filtered data using a
 260 band-pass filter centered on the tides, between 0.5 and
 261 2.5 cycle per day (cpd). The results given in Table 2
 262 are the mean values and standard deviation of the
 263 histogram of the scale factor estimates. In this way
 264 the error estimate is more robust than the formal error
 265 coming from the multi-regression on the entire
 266 duration.

267 A duration of one month of 60 s samples was
 268 chosen to have enough precision in the adjustment,
 269 except for iGrav32(b) and iGrav6 for which only 11
 270 and 23 days of recording at J9 were available,
 271 respectively. Since we do not have all the SG meters

running in parallel at the same time we used two
 different monthly periods: 1–31 May 2017 for
 iGrav30, iGrav31, iOSG23; 29 July–28 August
 2017 for iGrav29, iGrav15, iGrav32(a), and C026
 (GGP1 and TIDE), and additionally: 13–23 October
 2017 for iGrav32b and 1–23 October 2017 for
 iGrav6.

Different tests done on time spans of various
 lengths (from 11 to 31 days) have shown that there is
 a small variability of the relative scale factor (a few
 per mil) and correlation coefficient (less than 1‰)
 with time length. We also checked that the results are
 unchanged when we consider the time shift that may
 exist between different gravimeters. For instance, the
 largest time shift that is largely due to the TIDE filter
 of C026, which delays its signal 33 s with respect to
 iOSG23 (see section on time delays), causes a
 relative calibration change of $10^{-2} \text{ nm/s}^2/\text{V}$ which is
 negligible in Table 2.

As expected, the errors in relative calibration are
 much smaller than the errors in absolute calibration,
 mostly in the range 1×10^{-4} – 8×10^{-4} (dimension-
 less); all correlation coefficients are very high (at
 least > 0.999).

It is noticeable that for iGrav6, iGrav15 and
 iGrav32, the relative scale factors between pairs of
 instruments did not change after transport from J9 to
 Iceland, within 0.01% uncertainty (Schäfer et al.,
 2020).

2.3. Tidal Calibration Using K1 and M2

The aim of our method in this section is to find out
 whether the ratio of relative calibration versus
 absolute calibration inferred from the one-month
 (May 2017) is confirmed by tidal analysis. We used
 our longest common operation period of nearly
 1 year of iGravs 29, 30, 31 and iOSG23 from 04
 August 2016 to 19 June 2017 (321 days) to perform a
 tidal analysis with the help of ET34-ANA-V61A
 program (Ducarme & Schüller, 2018; Schüller,
 2018). To achieve a better determination of the
 diurnal and semi-diurnal tides we used an identical
 FIR zero phase high-pass filter (with 0.8 cpd corner
 frequency), based on Hanning-Window of 3001 min
 length) for all data sets. We also assume no phase lag

Table 2

Results for the absolute and relative calibrations of different SG meters in J9

SG and filter	Duration	Rel Cal and error (nm/s ² /V)	Abs Cal and error (nm/s ² /V)	Rel Cal–Abs Cal and error (nm/s ² /V)
iOSG23 (reference)		– 451 ± 0	– 451 ± 2	0 ± 2
C026 GGP1 No time shift	1 month 29/07/17–28/08/ 17	– 792.2 ± 0.1	– 792 ± 1	0.2 ± 1
C026 GGP1 with 2 s time shift	1 month 29/07/17–28/08/ 17	– 792.2 ± 0.1	– 792 ± 1	0.2 ± 1
C026 TIDE No time shift	1 month 29/07/17–28/08/ 17	– 791.5 ± 0.1	x	x
C026 TIDE with 32 s time shift	1 month 29/07/17–28/08/ 17	– 791.5 ± 0.1	x	x
iGrav6	October 2017	– 914.2 ± 0.2	x	x
iGrav15	1 month 29/07/17–28/08/ 17	– 932.3 ± 0.1	– 934 ± 3	1.7 ± 3
iGrav29	1 month 29/07/17–28/08/ 17	– 937.8 ± 0.1	– 940 ± 4	2.2 ± 4
iGrav29	1 month 1–31 May 17	– 937.7 ± 0.1	– 940 ± 4	2.3 ± 4
iGrav30	1 month 1–31 May 17	– 917.6 ± 0.1	– 918 ± 4	0.3 ± 4
iGrav31	1 month 1–31 May 17	– 850.5 ± 0.1	– 853 ± 4	2.5 ± 4
iGrav32 (a)	1 month 29/07/17–28/08/ 17	– 897.4 ± 0.7	– 898 ± 3	– 0.6 ± 3
iGrav32 (b)	OCT 2017 ~ 13 days	– 895.9 ± 0.1	x	x

316 between the different SG and use the absolute
317 calibration factor for each gravimeter.

318 The results for iGrav29, iGrav30 and iGrav31
319 compared to iOSG23 are shown in Table 3 and
320 plotted in Fig. 4, where we kept only the large tide
321 K1 in the diurnal band and M2 in the semi-diurnal
322 band. As expected, the tidal analysis confirms the
323 discrepancy between absolute and relative scale
324 factors.

325 In the last column of Table 3 the formal precision
326 of the tidal ratios is constant for all estimates and very
327 small (1×10^{-5}). However, the differences between
328 K1 and M2 tidal ratios are 5×10^{-5} for iGrav29,
329 46×10^{-5} for iGrav30, and 9×10^{-5} for iGrav31
330 that are larger (and more realistic) values than the
331 formal precision for each wave. Figure 4 shows the

332 excellent agreement of the tidal ratio with the relative
333 calibration ratio except for K1 in the iGrav30/
334 iOSG23 comparison; the definite reason for this is
335 unknown but we show later in Sect. 5.1 that the noise
336 level of iGrav30 is significantly higher at low
337 frequencies than the other iGravs.

2.4. Spectral Analysis of Tidal Residuals

338
339 Another way to test the calibration factors is to
340 perform a spectral analysis of the difference between
341 two calibrated time series which may reveal tidal
342 residuals. In the following we consider iGrav29
343 versus iOSG23. We will assume that iOSG23 is well
344 calibrated and will investigate the difference with
345 iGrav29 by using different relative scale factors for

Table 3

Comparison of ratio of relative calibration versus absolute calibration for iGrav29, iGrav30 and iGrav31 with respect to iOSG23 as inferred from tidal analysis and time regression

SG	REL. CAL (nm/s ² /V)	AG CAL (nm/s ² /V)	AG CAL/REL CAL	Wave: tidal ratio
iGrav29	- 937.8 ± 0.003	- 940 ± 4	1.00235 ± 0.004	K1: 1.00239 ± 0.00001 M2: 1.00244 ± 0.00001
iGrav30	- 917.6 ± 0.006	- 918 ± 4	1.00044 ± 0.004	K1: 1.00003 ± 0.00001 M2: 1.00049 ± 0.00001
iGrav31	- 850.5 ± 0.003	- 853 ± 4	1.00294 ± 0.004	K1: 1.00291 ± 0.00001 M2: 1.00282 ± 0.00001

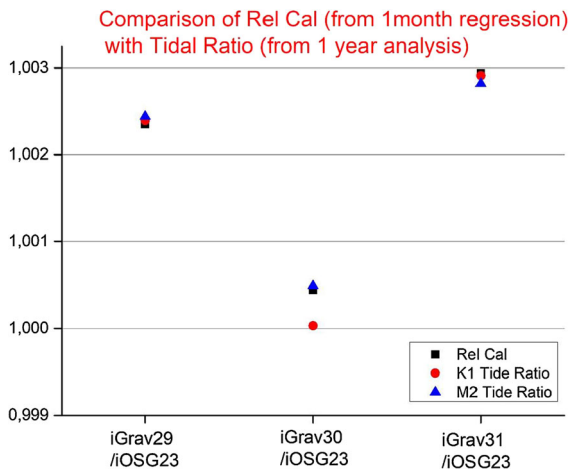


Figure 4

Ratio of relative calibration versus absolute calibration for iGrav29, iGrav30 and iGrav31 with respect to iOSG23 as inferred from tidal analysis (1 year) and time regression (1 month)

346 this meter with increments of 0.4 nm/s²/volt (\approx
347 0.04% in proportion) compared to 4 nm/s²/volt
348 uncertainty from AG/SG calibration (see Table 3).

349 The results based on one month (May 2017) 60 s
350 samples of iGrav29 are shown in Fig. 5 for 4
351 different relative scale factors close to the value
352 - 937.8 nm/s²/volt inferred from the one month
353 regression in May 2017 (see Table 3). It is clearly
354 visible that the smallest tidal residuals at 1 and 2 cpd
355 appear for this scale factor. If we correct for the 3 s
356 time shift between iGrav29 and iOSG23 (see Table 4)
357 then the tidal residuals in the spectrum of the gravity
358 difference almost vanish (in magenta in Fig. 5).
359 Similarly for iGrav30 and iGrav31 the minimal tidal

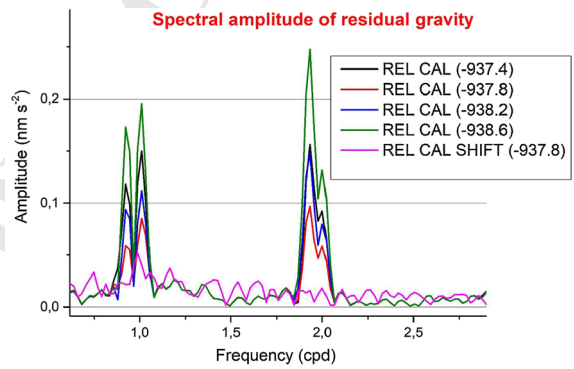


Figure 5

Spectral amplitude of residual gravity between iGrav29 (using different relative scale factors) and iOSG23; frequency units are cycle per day (cpd)

residuals correspond to the scale factors found from 360
time regression. 361

It is worth to note that using the absolute 362
calibration factor (- 940 nm/s²/volt) would lead to 363
tidal residuals that are 5–6 times larger when 364
compared to the adjusted relative calibration value 365
as shown on Fig. 6. 366

2.5. Time Delay 367

After having discussed the problem of amplitude 368
calibration, we focus now on the time delays that may 369
exist between the different SGs due to different 370
apparent spring constants (from the magnetic gradient 371
adjustment), masses, damping, filters and electronics. 372
The iOSG23 and the iGravs have a built-in Butter- 373
worth filter with corner period of 5 s and a time delay 374
of 1.54 s followed by an anti-aliasing lowpass FIR 375

Table 4

Time delays (in sec) between different SG using a cross-correlation method based on simultaneous data with various samplings and durations of analysis periods

	Time delay (s) 1 month of 1 s samples low pass filtered	Time delay (s) 1 month of 60 s samples after decimation	Time delay (s) 1 year of 60 s samples
iGrav6/iOSG23 ^a	3	3	X
iGrav15/iOSG23	3	3	X
iGrav29/iOSG23	3	3	2
iGrav30/iOSG23	2	2	3
iGrav31/iOSG23	2	2	1
iGrav32a/iOSG23	1	1	X
iGrav32b/iOSG23 ^b	1	1	X
C026 (GGP1)/iOSG23	3	2	2
C026 (TIDE)/iOSG23	33	32	31
C026(TIDE)/C026(GGP1)	30	30	30

^aOnly ~ 23 days available in October 2017

^bOnly ~ 13 days available in October 2017

376 filter consisting of 69 terms with a time delay of
377 4.25 s. In addition, there is a timing error of -0.62 s
378 in the firmware implementing the FIR filter so its
379 delay is reduced to 3.63 s. The SG C026 has a built-
380 in electronic low-pass filter called “GGP1” with a
381 corner period of 16.3 s and a time delay of 8.2 s
382 (Warburton, 1997). A TIDE filter is also integrated to
383 the electronics of the SG C026 with a corner period
384 of 72 s and a time delay of 32 s (Van Camp et al.,
385 2000).

386 As before, we will use the one-month time series
387 in May 2017 of iGrav29, iGrav30 and iGrav31 and
388 iOSG23 sampled at 1 s to investigate this point. We

also considered the time series of the older compact
SG C026 with data low pass filtered by two classical
electronic anti-aliasing filters widely used in the past
namely GGP1 and TIDE filters. For iGrav32 and
iGrav6 all available data in October 2017 were used
but one has to keep in mind that the time series are
shorter than one month and, even more important,
that these data are fully subject to initial drift (see
Sect. 3).

We apply a cross-correlation method between two
time series and determine the time of maximum
cross-correlation to estimate the time delay between
two time series.

If the instrumental response as a function of
frequency is identical (except timing error) for two
systems, calculating a cross-correlation between their
output will give a unique estimate of the difference in
timing. In the present context, this is not the case.
Then, applying a cross-correlation method will only
give an estimate of timing difference averaged over a
certain range of frequency. A reasonable result was
obtained because the largest signals are the semi-
diurnal and diurnal waves with frequency range
below $1e-3$ cycle/sec where the phase response is
almost flat (inferred from Fig. 7).

As expected, the same cross-correlation analysis
done on raw (unfiltered) 1 s samples led to slightly
different results (not shown) because of the influence
of high frequency content (microseisms, earthquakes)

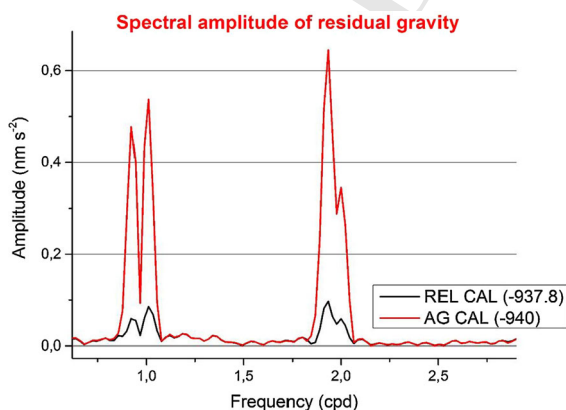


Figure 6

Spectral amplitude of residual gravity between iGrav29 (using best relative and absolute calibration factors) and iOSG23

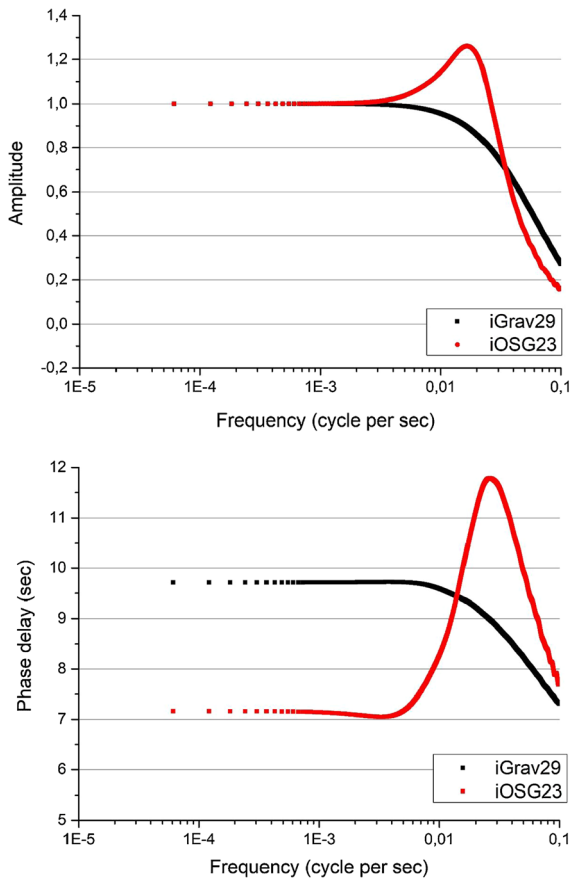


Figure 7

Amplitude and phase transfer function for iGrav29 and iOSG23

418 (see Table 4). The values of the time delays do not
 419 depend on the sampling (1 s or 1 min) if the high
 420 frequency content of the sec samples has been filtered
 421 out. The time delays derived from 1-year correlation
 422 analysis (August 2016–July 2017) for iGrav29,
 423 iGrav30 and iGrav31 are similar to the values
 424 inferred from one-month analysis. This analysis
 425 implies time invariance of the filter time delays. We
 426 also checked that the time delay combinations
 427 between channels obey the transitivity rule where
 428 $\text{cor}(A/C) = \text{cor}(A/B) + \text{cor}(B/C)$, as can be seen in
 429 Table 4 for the filtered data TIDE and GGP1
 430 implemented on C026.

431 A phase experiment test using the method
 432 outlined in Van Camp et al. (2000) where injecting
 433 known voltages (usually a sinusoidal or step-like
 434 functions) into the control electronics of the system
 435 enables one to determine time delay with a precision

of better than 0.1 s, was done on iGrav29 and 436
 iOSG23 to retrieve the full transfer function both in 437
 amplitude and phase delay of these two instruments. 438
 The time delay becomes constant for frequencies 439
 below 10^{-3} cpd (Fig. 7). The phase delay of iGrav29 440
 with respect to iOSG23 is found to be 441
 $9.71 \text{ s} - 7.16 \text{ s} = 2.55 \text{ s}$. Since these two SGs have 442
 identical electronics, this phase difference must be 443
 caused by the different masses of the spheres, the 444
 force gradient and damping in these instruments. As 445
 done before for the amplitudes, we also use the tidal 446
 analysis of 1 year of data to check the respective time 447
 delays by computing the M2 and K1 phase lags. The 448
 2.55 s phase delay between iGrav29 and iOSG23 is in 449
 close agreement with the tidal results (see Fig. 8). 450

A similar experiment that used injected sine 451
 waves rather than a step function was done on 452
 C026 in 2012 and led to a time delay of $9.7 \pm 0.4 \text{ s}$ 453
 from the GGP1 filtered data. 454

If we assume the time delay of iOSG23 is 7.16 s, 455
 the experimental phase delay of C026 with respect to 456
 iOSG23 would be 2.54 s. This value is very close to 457
 the ones plotted in Fig. 9. 458

3. General Initialization Procedures for SGs

Over many years a general procedure has been 460
 developed to minimize drift and offsets in SGs. 461

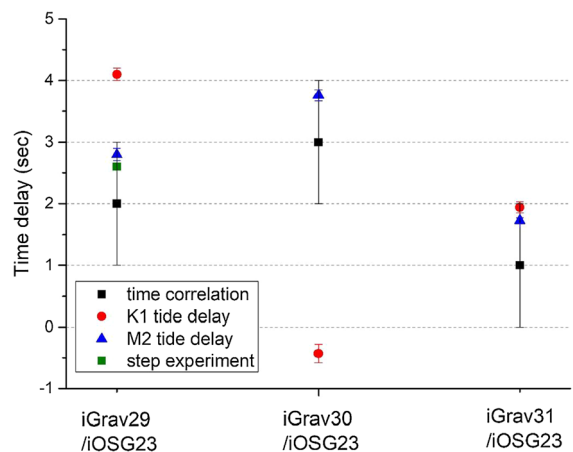


Figure 8

Comparison of time delays for iGrav29, iGrav30 and iGrav31 with 462
 respect to iOSG23, using time correlation or tidal analysis of major 463
 waves K1 and M2

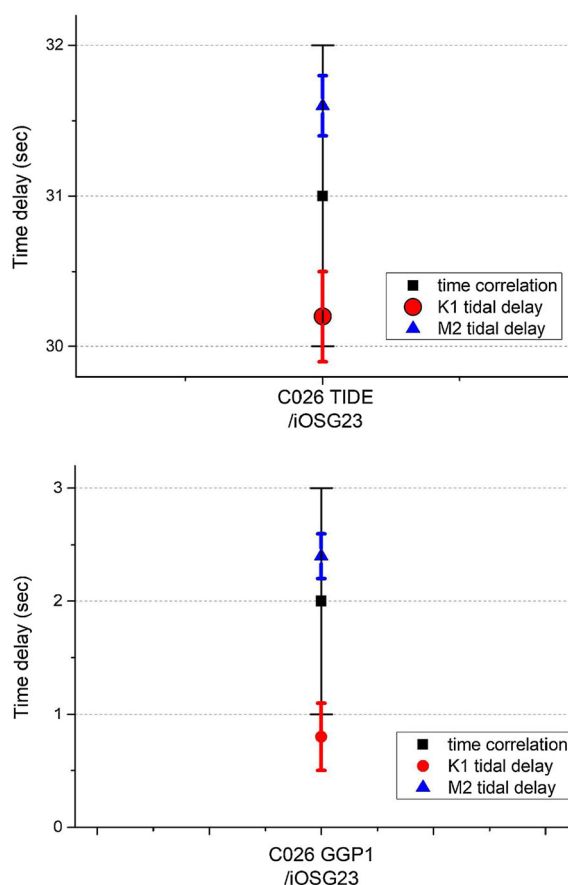


Figure 9

Comparison of time delays for C026 (TIDE filter) with respect to iOSG23, using time correlation or tidal analysis of major waves K1 and M2 (top); comparison of time delays for C026 (filter GGP1) with respect to iOSG23, using time correlation or tidal analysis of major waves K1 and M2 (bottom)

Figure 7 of Hinderer et al. (2015) shows a diagram of the SG sensor and its major components. The main superconducting components are the sphere, the magnet coils, the heat switches and the superconducting shield. The sphere position is sensed by the linear transducer consisting of the upper, central and lower capacitance plates. All of these components are mounted on or inside the Al or Cu body of the sensor which is positioned inside a vacuum can that is surrounded by a liquid helium bath at 4.2 K. The body is suspended from the lid of the vacuum can with three G-10 fiberglass laminate posts that thermally isolate the body from the helium bath. With this isolation, a Germanium thermometer operating in a Wheatstone bridge with a temperature control heater precisely

controls the temperature of the body at about 4.4 K or 0.2 K above the bath temperature. In addition, there are several components used only during the installation of the sensor: a Body heater and a Si diode thermometer reside on the top of the magnet form and are used to heat the magnet form (Body) and record its temperature (Body-T); a Mu metal shield surrounds the vacuum in order to reduce the Earth's magnetic field; and a charcoal getter to add and to extract gas from the vacuum can. The charcoal getter consists of a small Cu or Al cylinder that contains charcoal pellets glued to a heater. The getter cylinder can either be outside the vacuum can and connected by a tube as shown in the diagram or it can be inside the vacuum can. When the charcoal is at cryogenic temperatures it adsorbs He gas from the vacuum can. This gas can be released by activating the getter heater to heat the charcoal above 70 K.

After cooling the Dewar and gravity meter sensor to 4.2 K, initialization of SGs generally includes five standard procedures that are followed in a well determined order. First, a body heater is used to heat the sensor body and all the superconducting components inside the vacuum can above 32 K which is well above the superconducting transition temperature of Nb and the mu-metal shield is demagnetized. This minimizes the presence of the Earth's magnetic field trapped in the sphere and coils before levitation. Second, the sensor body is fast cooled to 4.2 K by briefly heating the charcoal getter. This releases He gas into the vacuum container which conducts heat directly between the body and the walls of the vacuum can. This cools the body in a few minutes versus the 10 to 12 h if cooling were only via the G-10 posts. After cooling to 4.2 K, the temperature control is turned on which raises the temperature to the control point near to 4.4 K. Third, the sphere is levitated, and the magnetic gradient adjusted. Fourth, the sensor is low temperature annealed by raising the temperature to about 5.2 K and lowered back to 4.2 K. This reduces the magnitude of offsets induced during excursions of the temperature control between 4.2 to 5.2 K. Then the temperature control is turned on again and the sensor returns to its control point near to 4.4 K. And fifth, the thermal levelers are used to tilt-desensitize the sensor.

Variations to the installation may occur: some iGravs have side coils and the field is trapped after the demagnetization but before the fast cooling; He gas may or may not be released from the getter to cool from 5.2 K during the low temperature annealing; and the order of low temperature annealing and tilting may be interchanged. In addition, some variations may occur due to operator error during set-up and initialization at a new site when site preparation is not complete or other difficulties occur. For example, during the July 2016 initialization at J9, two errors occurred. For iGrav29, the low temperature annealing was done improperly. The sensor was heated to 5.2 K, but it was then cooled back to its control point at 4.4 K rather than being cooled fully to 4.2 K before being returned to the control point while, for iGrav30, the low temperature annealing was omitted entirely.

4. Instrumental Drift

In this section we investigate the instrumental drift of the iGravs and iOSG23 collocated at J9. Previous studies have reported that the instrumental drift of SGs can be modelled by a short-term exponential function followed by a linear trend of 10 to 50 nm/s²/year (Crossley et al., 2004; Hinderer et al., 2015; Van Camp & Francis, 2007). However, for records longer than 10 years, Van Camp and Francis (2007) showed that the long-term drift for GWR C021 is better modelled by an exponential. More recent work by Schäfer et al. (2020) showed that the initial drifts in GWR iGrav SGs require additional short-term exponential functions to model rapid drifts that occur immediately after initialization and sphere levitation. In addition, Dykowski et al. (2019) have shown for iGrav27 that drifts also occur in the body temperature (Body-T) that are highly correlated (0.98) with the gravity drifts and that these can also be modelled by an initial exponential term followed by a linear drift.

In this work, we model the instrumental drift of SG as the sum of several exponential decaying functions (up to 3) and a linear term that remains very stable in time after the exponential terms become negligible.

The model of instrumental drift is hence as follows:

$$g(t) = g_0 + A_1 e^{-\frac{t-t_0}{\tau_1}} + A_2 e^{-\frac{t-t_0}{\tau_2}} + A_3 e^{-\frac{t-t_0}{\tau_3}} + C(t - t_0) \quad (1)$$

where $g(t)$ is the gravity as a function of time t , with initial values g_0 and t_0 , A_1 , A_2 and A_3 the amplitudes, τ_1 , τ_2 and τ_3 the time constants, and C the coefficient of the linear term. A Levenberg–Marquardt iteration algorithm is applied to reach convergence in the fit. The functional drift of the Body-T can also be approximated by exponential terms plus a linear term very similarly to what we do for the gravity signal. Long term changes in the Body-T sensor indicate that thermal gradients continue to change in the sensor over long periods of time. It is hypothesized that this is from the charcoal getter continuing to adsorb He gas out of the vacuum can and that this is one source of drift.

We first investigate the long-term behavior of iOSG23 which was installed in February 2016 and still operates today. This meter will act as reference gravimeter throughout this study. We use a series of 16 AG measurements taken at J9 with FG5#206 during the years 2016–2019 to infer the iOSG23 drift components. In another section we examine the initial drift and Body-T behavior of 3 iGravs (#29, #30 and #31) that were all initialized in June 2016 and re-initialized in October 2016. Also, since iGrav29 was re-levitated both in November 2020 and December 2020, we can investigate how the initial gravimeter drift and Body-T drift evolve during these additional re-levitations.

4.1. Long Term Drift of *iOSG23*

We investigate the drift behavior of iOSG23 using a 4.1 year-long record (1520 days from February 3, 2016 to April 20, 2020). To prepare the data, a first decimation filter is used from 1 to 60 s. The major gravity steps in iOSG23 are removed by comparison to a data record prepared in the same way for iGrav29 which was operating nearby at J9. Subsequently, spikes and large earthquakes are removed by interpolating over the disturbances. After all corrections

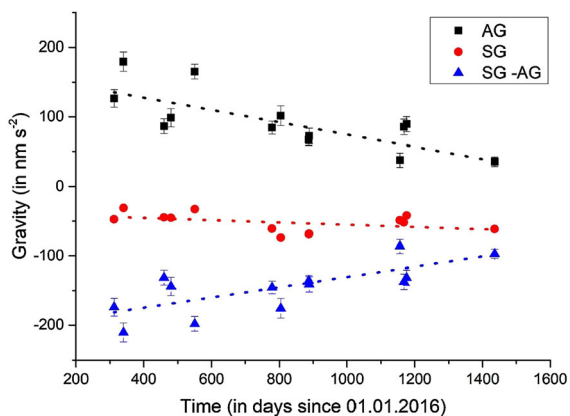


Figure 10

Determination of iOSG23 instrumental linear drift rate using AG (FG5#206) values

608 are made a second decimation filter reduces the data
609 to hourly intervals.

610 In the following we determine the long-term
611 linear drift by fitting AG data to the last 3 years of
612 iOSG23 data. In this case we are not considering the
613 exponential drift that typically occurs immediately
614 after the initialization of the gravimeter. Then, after
615 removing this linear drift from the entire data set, we
616 use a non-linear curve fitting tool based on several
617 exponentials.

618 Before applying this procedure, we first need to
619 compare the iOSG23 residual values (observations
620 corrected for the local tide, barometric pressure and
621 polar motion) to measured AG values at J9 using
622 FG5#206 over the same period (corrected exactly in
623 the same way).

624 In Fig. 10, the black squares show the values of
625 the AG measurements minus the mean value of the
626 AG measurements taken in the period from 3 October
627 2016 to 12 June 2019, which covers the record of
628 iOSG23 data. These values are offset by 100 nm/s² so
629 that the 3 plots of the AG (black squares) values, the

Table 5

Drift rates: results of the linear fit to AG (FG5#206) and SG (iOSG23) data

	Linear trend and error (nm/s ² /year)
AG (FG5#206)	- 32.3 ± 7.5
SG (iOSG23)	- 6.0 ± 5.1
SG-AG	27.0 ± 6.3

630 SG (red dots) values and the difference SG-AG (blue
631 triangles) values do not overlap and provide an easier
632 visual inspection.

633 In the determination of the SG linear drift, we
634 excluded the first 3 points in 2016 which are likely to
635 be affected by getter pump out and are part of the
636 initial exponential drift term.

637 The results of the linear fitting procedure of the
638 data sets shown in Fig. 10 are given in Table 5.

639 For the AG points, we measure a decrease in
640 gravity of - 32.3 nm/s²/year with R² = 0.59 most
641 probably of hydrological origin since vertical motions
642 due to tectonics are too small as inferred from GPS
643 measurements at J9. For the iOSG23 data we measure
644 a smaller decreasing rate of - 6 nm/s²/year with
645 R² = 0.11 and for the difference SG-AG, we get a
646 positive rate of + 27.0 nm/s²/year with R² = 0.59.

647 This result indicates that the instrumental linear
648 drift determined for iOSG23 by comparison to the
649 AG measurements is + 27.0 nm/s²/year which is a
650 typical value for other SGs. However, there is a high
651 relative uncertainty (23.3%) for this drift rate. The
652 dispersion of the points in Fig. 10 that are not
653 perfectly aligned on a straight line is not clear. It is
654 possible that the AG errors are underestimated or that
655 the AG senses slightly different hydrological effects
656 due to its placement in the vault.

657 After removing the drift inferred from the AG
658 points, the iOSG23 residual gravity data have been
659 fitted to a combination of exponential and linear
660 terms according to Eq. (1). The fit results are given in
661 Table 6 and Fig. 11 shows the superposition of the
662 fitted model to the iOSG23 gravity data.

663 The fitted iOSG23 instrumental linear drift rate of
664 24.4 nm/s²/year is close to the value of 27.0 nm/s²/
665 year in Table 5 but differs because the fitting
666 procedure uses all the hourly data from iOSG23 in
667 one case and only the few episodic AG/SG parallel
668 measurements on the other case.

669 After removing a linear term of 0.3 mK/year, a
670 similar method is used to fit to the Body-T data for
671 iOSG23. The Body-T time constants are shown in
672 Table 6 and a comparison of the data and the fit curve
673 are shown in Fig. 12. Two of the time constants for
674 gravity and Body-T are similar with a very short time
675 delay t1 less than half a day and a very long one t3
676 close to 150 days. The fitting process for the Body-T

Table 6

Results for the exponential and linear fitting of iOSG23 gravity and Body Temp signal; symbols in the header are the same as in Eq. (1)

Data starts 03/02/2016	A_1	t_1	A_2	t_2	A_3	t_3	C
Record length 1520 days							
iOSG23 gravity	nm/s ²	days	nm/s ²	days	nm/s ²	days	nm/s ² /year
3 exp fit	- 131.2	0.4	x	x	- 144.4	153.5	24.4
iOSG23 Body Temp	mK	days	mK	days	mK	days	mK/year
3 exp fit	- 1.8	0.4	- 0.3	57.2	- 0.4	143.2	0.3

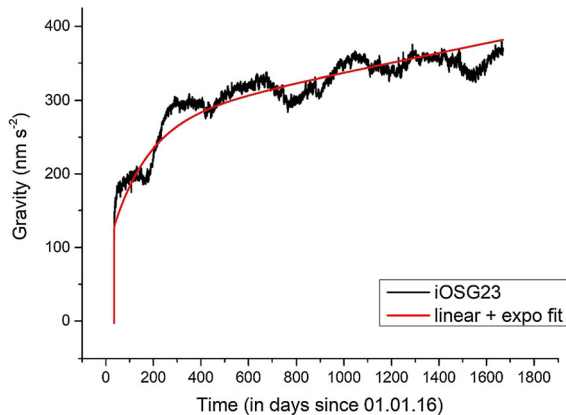


Figure 11

Gravity residual signal of iOSG23 as a function of time; the observations are in black and the best fit combining exponential and linear terms according to Table 6 are in red

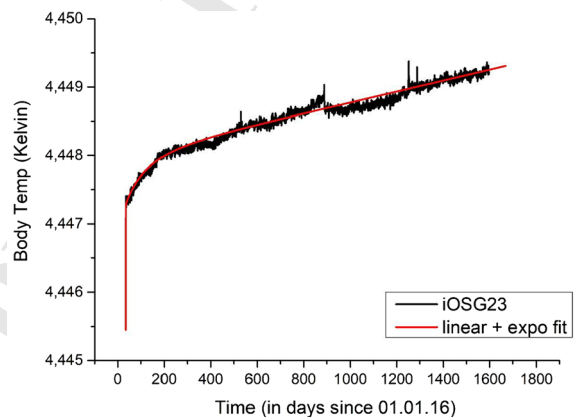


Figure 12

Body-T signal of iOSG23 as a function of time; the observations are in black and the best fit combining exponential and linear terms according to Table 6 in red

677 converges to find the intermediate terms ($A_2 = - 0.3$
 678 mK, $t_2 = 57.2$ days) but does not converge to find
 679 similar intermediate terms for the gravity residual
 680 signal.

681 The correlation we already introduced between
 682 gravity and body temperature drifts appears very
 683 clearly on Fig. 13. The left part is coming from the
 684 strong exponential initial drift occurring on both
 685 signals. Later during instrument operation, gravity
 686 and Body-T are still correlated but the correlation is
 687 noisier.

688 As observed by Dykowski et al. (2019), the
 689 instrumental drift highly correlates with Body Temp.
 690 This is true for the exponential part after levitation as
 691 well as for the long-term linear part. The correlation
 692 factor between gravity and Body-T signals for
 693 iOSG23 is rather large (0.88). This suggests that the
 694 long-term linear drift (or part of it) in SGs might in

695 fact be due to this continued adsorbing process of the
 696 getter.

4.2. Drift Behavior of iGravs 697

4.2.1 Overview of Data 698

699 iGrav29, iGrav30 and iGrav31 were first initialized in
 700 July 2016 at J9. Since there were many disturbances
 701 during and after this installation, it was decided to
 702 repeat the entire initialization process on iGrav29 and
 703 iGrav30 in October 2016; while only low-tempera-
 704 ture annealing of iGrav31 was done to complete its
 705 previous initialization. iGrav #30 and #31 then
 706 operated at J9 until the end of June 2017 at which
 707 time iGrav30 was shipped cold for installation at the
 708 Strengbach catchment in the French Vosges moun-
 709 tains (Chaffaut et al., 2020) while iGrav31 was
 710 warmed to room temperature for its future shipment

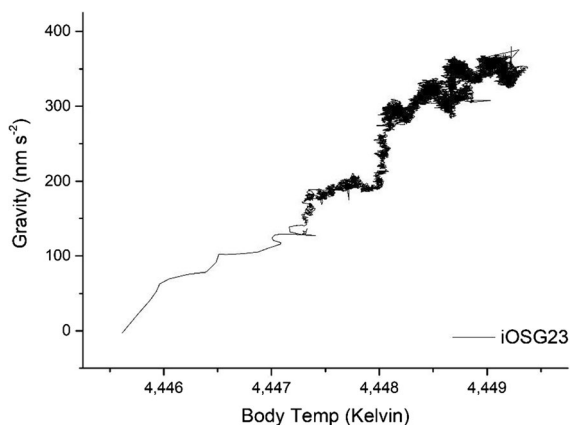


Figure 13

Correlation between iOSG23 gravity residuals and body temperature signals using the 4.2-year data set

711 in late March 2019 to a mountain site directly above
 712 GWR iOSG24 which is operating in the LSBB
 713 underground laboratory in Rustrel. iGrav29 was also
 714 scheduled to move to another water catchment of the
 715 Ozcar network (Gaillardet et al., 2018) but, due to
 716 COVID-19 restrictions, it continues to operate at J9
 717 presently. For reasons discussed below, it was
 718 warmed to room temperature in October 2019 and
 719 reinitialized for a 3rd time. In December 2020 an
 720 experiment was done where—without activating the
 721 getter—the sphere was lowered, and the magnets
 722 purged of currents. Then after a few days the sphere
 723 was again re-levitated without using the getter.

724 In analyzing data from these iGravs, we used
 725 iOSG23 as a reference instrument so that we could
 726 look directly at the difference signals iGrav29–
 727 iOSG23, iGrav30–iOSG23 and iGrav31–iOSG23.
 728 It is a major advantage to use iOSG23 as a reference
 729 rather than a calculated tide model because iOSG23
 730 provides a precise measure of all gravity changes
 731 while any model is incomplete: the model does not
 732 include hydrological signals, it assumes a constant
 733 admittance to the atmosphere, and it approximates
 734 many of the long-period tidal signals. We first correct
 735 the iOSG23 data for the linear and exponential drifts
 736 previously found (see Table 6). Then the gravity
 737 differences are taken between the three iGravs and
 738 the corrected iOSG23 signal using the calibration
 739 factors listed in Table 2. Earthquakes, offsets and
 740 other disturbances are removed, and the data are
 741 further filtered and decimated to hourly intervals.

742 The results for the initial drifts of iGrav29–
 743 iOSG23, iGrav30–iOSG23 and iGrav31–iOSG23 are
 744 plotted in Fig. 14 (where arrows show the initializa-
 745 tion events) along with the residual gravity signal for
 746 iOSG23 calculated with a tidal model and corrected
 747 for its exponential and linear drifts from Table 6.
 748 Long-period tides, polar motion and hydrology are
 749 not corrected for, so they appear clearly on the
 750 iOSG23 residual signal but they do not appear on the
 751 difference signals. The difference drift curves are
 752 very smooth since all the unmodelled signals that
 753 show up in the iOSG23 curve are eliminated in the
 754 iGrav29, iGrav30 and iGrav31 difference curves. It is
 755 not possible to measure such drifts with this high
 756 precision without using a reference SG. Figure 15
 757 shows the Body temperature data over the same time
 758 period as shown for the gravity data in Fig. 14.

759 There are several features on these data that stand
 760 out. In Fig. 14, a negative drift is observed immedi-
 761 ately after the first initialization of iGrav29 in July
 762 2016 (red line). After the second initialization in
 763 October 2016, the residual drift for iGrav29 looks
 764 reasonable at first, but after about 180 days it turns
 765 into a negative drift rate of about $-51.9 \text{ nm/s}^2/\text{year}$
 766 which was observed for the next 2 years (green line).
 767 We also observe increasing noise levels in both
 768 iGrav29 and iOSG23 at the start of this negative drift
 769 period. This is likely from build-up of ice in neck of
 770 iGrav29. In contrast to Fig. 14, all the Body-T drifts
 771

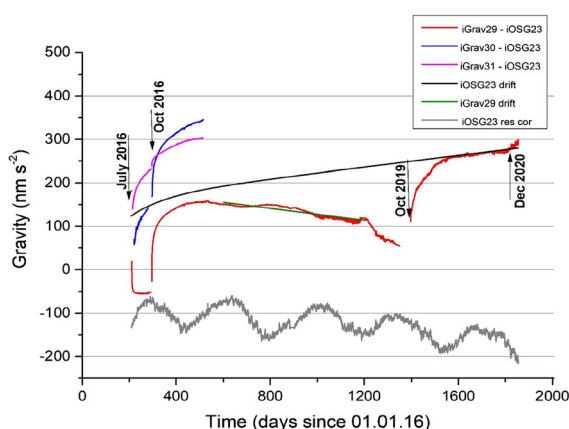


Figure 14

Gravity difference signals between iGrav29, iGrav30 and iGrav31 and iOSG23 corrected for its drift curve for the entire 4.5 year-long record at J9, Strasbourg



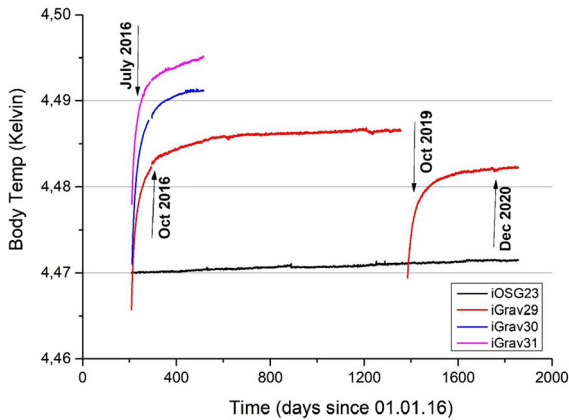


Figure 15

Body temperature signals for iGrav29, iGrav30 and iGrav31 and for iOSG23 for 4.5 year-long record at J9, Strasbourg

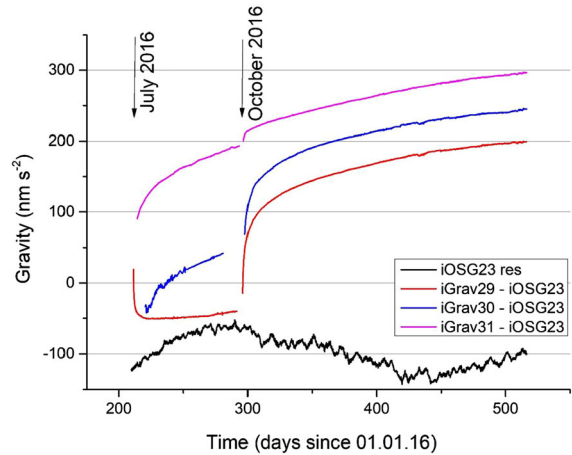


Figure 16

Initial drift curves of gravity differences iGrav29-iOSG23, iGrav30-iOSG23, iGrav31-iOSG23 and iOSG23 residual signal after initialization in July and October 2016 through to March 5, 2017 and after correcting iGrav29-iOSG23 and iGrav30-iOSG23 for the negative drift observed in Fig. 14

771 in Fig. 15 are smooth curves in the positive direction.
 772 The only uncertainty in the Body-T data is the offset
 773 that occurs in the iGrav29 Body-T after the October
 774 2019 re-initialization. This is most likely a problem
 775 with the thermometry circuitry measuring the Body-T
 776 but this remains unproven.

777 We separate the data into three sections to model
 778 the drift curve function according to Eq. 1 and to
 779 examine the correlation between the gravity residual
 780 and Body-T. The present section includes the July
 781 and October 2016 initializations, the next section
 782 examines the initialization in October 2019, and the
 783 third the re-levitation in December 2020.

784 4.2.2 July and October 2016

785 Figure 16 shows the data from July 28, 2016 to
 786 March 5, 2017 in more detail. These data include two
 787 specific time spans: a first one that lasted about
 788 75 days after the installations on July 28, 2016; a
 789 second one that lasted 219 days after the re-initial-
 790 izations of iGrav29 and iGrav30 and the low
 791 temperature annealing of iGrav31 (that occurred on
 792 October 23, 2016). The data for iGrav31-iOSG23 are
 793 the same as in Fig. 14. However, before fitting the
 794 data for iGrav29-iOSG23 to Eq. 1, they must be
 795 corrected for its negative drift. Otherwise, the neg-
 796 ative drift will interfere with the fitting parameters for
 797 the longer-term exponential functions. A decision
 798 was also made to correct iGrav30-iOSG23 for the
 799 same negative drift since it appears that the iGrav30-

800 iOSG23 data was also beginning to trend negative in
 801 Fig. 16. With these corrections made, the drift curves
 802 for all 3 iGravs are similar for the last 100 to
 803 150 days of Fig. 16.

804 There is a striking difference between the gravity
 805 difference data of Fig. 16 and the Body-T data of
 806 Fig. 17 in that the Body-T curves behave contin-
 807 uously across the October 2016 re-levitation while
 808 there is a discontinuity in the gravity differences after
 809 the October 2016 levitation in terms of generation of
 810 a new initial drift. This is slightly misleading since
 811 rapid drifts do occur in the Body-T data immedi-
 812 ately after the initialization procedures, for example for
 813 iGrav29 Body-T rapid drifts of about 50 to 70 mK
 814 occur at the beginning of both the July and October
 815 installations; however, since they last less than 1 h,
 816 they are removed by the filtering and decimation
 817 process. Corresponding drifts occur in the gravity
 818 differences, but these are difficult to observe since
 819 they occur during the initialization procedures.
 820 Nonetheless, the long-term Body-T rapidly returns
 821 to its previous functional form as displayed in
 822 Fig. 17.

823 The continuity of the Body-T data shows that the
 824 gas released from the getter and the distribution of
 825 gas in the vacuum can may depend upon the history
 826 of its use. The gas could be bound more tightly to the

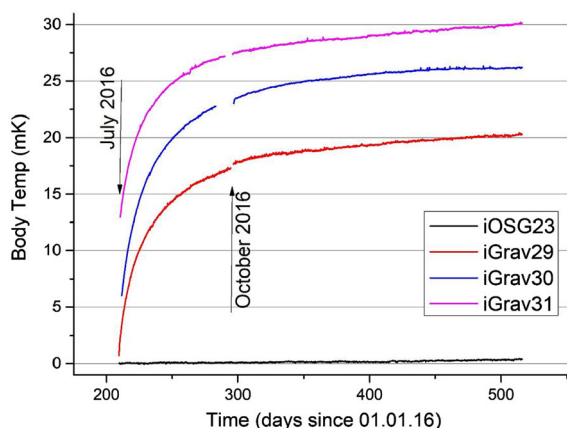


Figure 17

Initial drift curves of Body temperatures for iGrav29, iGrav30 and iGrav31 after the initializations in July and October 2016 through to March 5, 2017

827 getter material after it has remained cold for a long
 828 time so that less gas is released when it is heated.
 829 Also, there are different time constants associated
 830 with gas pumped out of or reentering different
 831 locations inside the gravity sensor. For example,
 832 short time constants for the open volume inside the
 833 vacuum can, intermediate time constants for gas
 834 located between the shield and vacuum can, and long-

time constants for gas trapped inside the magnet
 coils.

In Table 7, we show the fit coefficients of two
 exponential functions to both the gravity difference
 and Body-T data shown in Figs. 16 and 17; the used
 formalism is the same as in Eq. (1), but neglecting
 the third exponential ($A_3 = 0$). For the Body-T data,
 we fit a linear drift to the last 60 days data and
 subtracted it before fitting with two exponential
 functions. We see remarkably similar functions for
 iGrav29, iGrav30 and iGrav31 Body-T exponentials
 with: A_1 varying between -6 to -9 mK; t_1
 between 8 to 12 days; A_2 between -8 to -10
 mK; t_2 between 40 to 60 days; while the linear terms
 vary more widely between 0.5 to 2.7 mK/year.

A similar fitting procedure was done for the
 Gravity difference data starting October 2016. In this
 case, the fitting functions for iGrav29-iOSG23 and
 iGrav30-iOSG23 were very close: with A_1 between
 -56 and -74 nm/s²; t_1 between 3.2 and 3.7 days;
 A_2 between -70 to -74 nm/s²; t_2 between 44 and
 51 days; and linear terms both close to 71 nm/s²/year.
 The amplitudes for the iGrav31-iOSG23 days are
 smaller ($A_1 = -12$ and $A_2 = -41$ nm/s²) while t_2
 is shorter (1.4 days) and t_2 longer (84.9 days) with a

Table 7

Amplitude and time constants of the exponential fitting of iGrav29-iOSG23, iGrav30-iOSG23 and iGrav31-iOSG23 gravity signal for 72 days after July 2016 levitation and 219 days after October 2016 levitation and for iGravs 29, 30 and 31 body temperatures after July 2016 initialization (291 days)

Gravity differences	A_1 nm/s ²	t_1 days	A_2 nm/s ²	t_2 days	C nm/s ² /year
July 2016 (72 days) data					
iGrav29-iOSG23 ^a	44.4	0.6	18.1	8.2	N/A
iGrav30-iOSG023	-33.3	7.1	-104.8	154.3	N/A
iGrav31-iOSG023 ^b	-31.7	7.4	-78.7	71.6	N/A
October 2016 (219 days)					
iGrav29-iOSG23	-74.1	3.2	-74.4	50.8	70.8
iGrav30-iOSG023	-55.6	3.7	-70.1	43.7	71.1
iGrav31-iOSG023 ^c	-12.2	1.4	-41.4	84.9	77.2
Body temperatures	A_1 mK	t_1 days	A_2 mK	t_2 days	Linear mK/year
July and October 2016 (291 days)					
iGrav29 Body-T	-6.0	8.1	-10.0	40.1	2.3
iGrav30 Body-T	-9.0	12.6	-10.0	61.3	0.5
iGrav31 Body-T	-6.0	10.1	-8.0	40.2	2.7

^aLow temp. annealing done improperly

^bNo low temp. annealing done ^cLow TEMP. annealed only

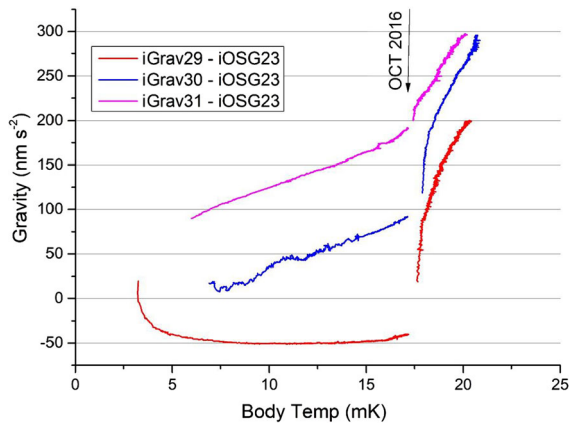


Figure 18

Correlation between iGrav-iOSG23 difference signals and Body Temperatures for iGrav29, iGrav30 and iGrav31 for both the July and October 2016 initializations

860 steeper linear fit of $77 \text{ nm/s}^2/\text{year}$. It is not surprising
 861 that these amplitudes (seen both in Table 7 and
 862 Fig. 16) are much smaller for iGrav31 than for iGrav
 863 29 and 30. The iGravs 29 and 30 were completely re-
 864 initialized (sphere lowered and magnet currents
 865 purged, bodies heated to 32 K and fast cooled to
 866 4.2 K by adding gas from the getter, spheres relevi-
 867 tated, bodies low temperature annealed, and sphere
 868 recentered). In contrast iGrav31's body was simply
 869 low temperature annealed and then the sphere
 870 recentered.

871 We have also fit 2 exponential functions to the
 872 gravity differences following the July 2016 initial-
 873 ization. In these cases, due to the shorter records, we
 874 chose to fit 2 exponential terms without first
 875 subtracting a linear term. In spite of the shorter
 876 records, the different analysis techniques and the
 877 quality of the data, the fits for iGrav30-iOSG23 and
 878 iGrav31-iOSG23 are still similar to the October 2016

879 fits although both the t_1 and t_2 time constants are
 880 longer. In contrast, the fit of iGrav29-iOSG23 is
 881 clearly anomalous with positive amplitudes for both
 882 A1 and A2. This is most certainly due to the
 883 incomplete low temperature anneal procedure done
 884 for iGrav29 in July 2016.

885 An alternative method to determine the relation-
 886 ship between the gravity difference signals and the
 887 Body temperatures is to measure the correlation
 888 between these two data sets directly. Strictly speaking
 889 the iGrav-iOSG23 gravity differences should obey a
 890 function of the iGrav-iOSG23 Body-Temp differ-
 891 ences but since the Body-Temp changes for iOSG23
 892 are so small (see Fig. 12) compared to the iGrav
 893 changes we have neglected them. The results of this
 894 analysis are shown in Fig. 18 for both the July and
 895 October 2016 initializations and shows a more
 896 complicated relationship between the initial drift
 897 and the Body-T than the nearly linear relationship
 898 that was observed in Fig. 13.

899 For the sake of completeness, we have also
 900 indicated in Table 8 the initial drift values we found
 901 for iGrav6, iGrav32a and iGrav32b (before and after
 902 upgrade at GWR respectively) and iGrav15 which
 903 were installed in summer and fall 2017. Notice that
 904 some of the fits are done on very short records
 905 because of the short availability at J9 (especially
 906 iGrav32a and iGrav32b). We do not discuss here the
 907 impact of transportation in cold state (or warmed up)
 908 on the initial drift rates of SGs. Such a discussion for
 909 iGrav6, 15 and 32 after transportation from J9 to
 910 Iceland is done in Schäfer et al. (2020).

911 In Table 8 the short time constant t_1 is close to
 912 0.4 day and t_2 in the range 1.7–3.3 days. In terms of
 913 amplitude, the largest one is for iGrav6 (both for A₁

Table 8

Amplitude and time constants of the initial exponential fitting of iGrav6, iGrav32a, iGrav32b, iGrav15 gravity signal using two exponentials (A_1 , t_1 , A_2 , t_2)

2 exponential fit after linear term removed	A_1 (nm/s ²)	t_1 (days)	A_2 (nm/s ²)	t_2 (days)
iGrav6-iOSG23 (25.1 days)	- 39.3	0.4	- 67.8	3.3
iGrav32a-iOSG23 (15.8 days)	- 10.4	0.4	- 40.9	2.1
iGrav32b-iOSG23 (10.4 days)	- 4.4	0.3	- 24.6	2.0
iGrav15-iOSG23 (18.3 days)	- 4.1	0.3	- 33.3	1.7



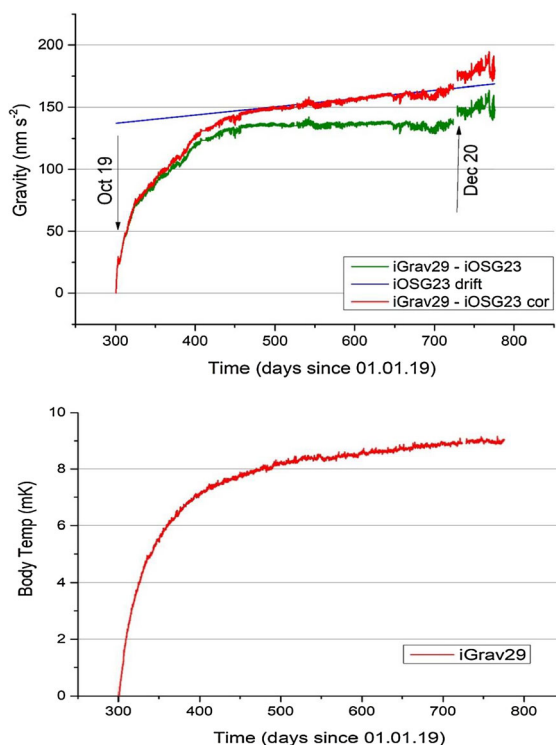


Figure 19

Gravity difference iGrav29–iOSG23 (top) and Body-T (bottom) for October 2019 re-initialization and December 2020 re-levitation

914 and A_2). Because of the short available durations only
 915 short-term exponential terms can be estimated and
 916 the long-term drift behavior remains unknown.

917 4.2.3 October 2019

918 In October 2019 we decided to re-initialize iGrav29
 919 for a 3rd time. The reason was to confirm the premise

(Schäfer et al., 2020) that iGravs with negative drifts 920
 could be restored to normal operation by warming 921
 them to room temperature and re-initializing them. In 922
 addition, it was recommended not to trap flux with 923
 the side coils if there were plans to move an iGrav in 924
 the future. Therefore on September 12, 2019, the 925
 refrigeration system was turned off and the liquid He 926
 evaporated in about 10 days. On October 1, the 927
 Dewar was pumped out for 48 h with a primary and 928
 turbomolecular pump to reduce its pressure from 56 929
 to 5.6 Pascal; and on October 3, the refrigeration 930
 system was turned back on. Cooling and refill with 931
 liquid He took an additional 22 days, so the re- 932
 initialization took place on October 26, 2019. In this 933
 case, all the initialization steps were rigorously 934
 followed, and no flux was trapped in the side coils. 935

Figure 19 shows the drift analysis of 423 days 936
 following the October 2019 initialization. The green 937
 trace in the top panel is the direct difference signal 938
 iGrav29–iOSG23 while the lower panel shows the 939
 Body-T. Since the green curve becomes flat, it means 940
 the drift rate of iGrav29 is nearly identical to that of 941
 iOSG23. The red curve is the difference curve with 942
 the drift correction made to iOSG23, while the blue 943
 line is the calculated drift of iOSG23. This important 944
 result confirms that the negative drift in iGrav29 had 945
 been eliminated by warming it to room temperature 946
 and re-cooling and re-initializing it without trapped 947
 flux. 948

Table 9 shows the fitting parameters for the 949
 gravity difference and the Body-T, while Fig. 20 950
 compares the correlation between iGrav29–iOSG23 951
 difference and Body-T for October 2019 with the 952

Table 9

Amplitude and time constants of the exponential fitting of iGrav29–iOSG23 and Body-T for 423 days after October 2019 levitation; symbols in the header are the same as in Eq. (1)

Gravity differences	A_1 nm/s ²	t_1 days	A_2 nm/s ²	t_2 days	C nm/s ² /year
October 2019 (423 days) iGrav29- iOSG23	- 22.9	4.9	- 113	62.9	18
Body temperatures	A1 mK	t1 days	A2 mK	t2 days	Linear mK/year
October 2019 (423 days) iGrav29 Body-T	- 3.3	17.1	- 4.8	73.8	0.68

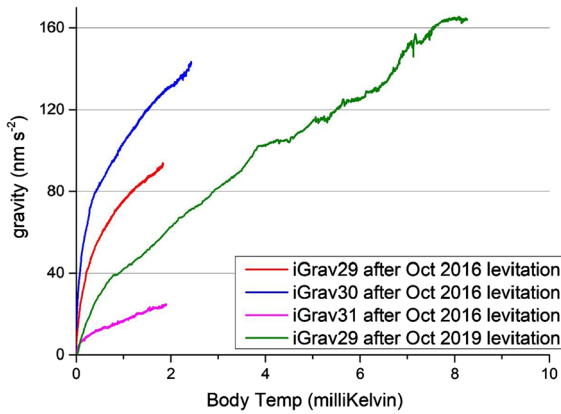


Figure 20

Gravity differences (iGrav-iOSG23) versus Body Temp signals for iGrav29, iGrav30 and iGrav31 after October 2016 levitation (and October 2019 for iGrav29)

953 correlations between iGrav-iOSG23 differences and
954 Body-T for iGrav29, iGrav30 and iGrav31 for
955 October 2016.

956 From these data and from earlier data (Figs. 18,
957 13), there is clearly a linear relationship between
958 gravity drift and Body-T as the second exponential
959 fits (A2 and t2) become dominant (after 2–3 months).
960 There may also be a linear relationship immediately
961 after the initialization (for the first 2 months) but it
962 clearly is with a different slope after 2–3 months. We
963 note, however, that a linear slope on the Gravity-
964 Body-T plot means that both Gravity and Body-T
965 have the same functional form, not that they are both
966 linear. So, a likely interpretation is that both gravity
967 drift and Body-T have nearly identical exponential
968 functions early after the initialization (first 2 months)
969 and a combination of different exponential and linear
970 functions after 2–3 months. After 2 months a curva-
971 ture is seen in the correlation plot (Fig. 18) which
972 indicates that the gravity drift and Body-T drift
973 functions are not identical. This is also seen by the
974 fact that the t1 time constants of the Body-T data are
975 generally longer than that of the gravity drift
976 functions.

977 4.2.4 December 2020

978 As a final experiment, on December 26, 2020, the
979 sphere was carefully lowered and the magnet coils
980 purged of currents without activating the getter, so

that no additional He gas was released. Then after 981
2 days, the sphere was re-levitated, a low temperature 982
annealing performed, and the tilt rechecked. Most 983
importantly, the low temperature annealing was 984
performed without using the getter. As we see from 985
Fig. 19, there is no observable change in drift in 986
either the Body-T or the gravity difference signals. 987
While this test positively confirms that initial drifts in 988
iGravs are due to the getter adsorbing gas out of the 989
vacuum can, it cannot establish with certainty that 990
remaining linear drifts (10–50 nm/s²/year) are caused 991
by continued gas removal or if there is some 992
additional drift mechanism. 993

4.2.5 Moving SGs 994

From the data in Schäfer et al. (2020) and the data of 995
this study, we can recommend preferable methods for 996
moving SGs. 997

- 998 1. As a rule, it is always safest to move an SG warm 999
and at room temperature and to re-evacuate the 1000
dewar before cooling it at a new site. 1001
- 1002 2. Any iGrav that uses trapped flux should be 1003
warmed to room temperature before it is moved. 1004
As discussed in Schäfer et al. (2020), shipping 1005
cold iGravs with flux trapping coils activated has 1006
produced large negative drifts. 1007
- 1008 3. Some users may want to move their SG cold at 1009
4.2 K and with the dewar filled with liquid He. 1010
First, this eliminates the requirement to cool and 1011
fill the dewar with liquid He at a remote site which 1012
takes about 10 days. Second—in both cases (1) 1013
and (2) above—the initial drift curve will return at 1014
the new site and more frequent AG measurements 1015
will be necessary to determine the drift curve. In 1016
this case, the user can lower the sphere and 1017
carefully purge the coils of superconducting 1018
currents before moving the instrument, then re- 1019
levitate and low temperature anneal at the new 1020
site. If this is done carefully—without using the 1021
getter to release He gas—either when lowering the 1022
sphere or re-levitating the sphere at the new site, it
will eliminate the repetition of the initial drift
curve of the iGrav at the new location.

1023 5. Environmental and Instrumental Noise Levels

1024 5.1. Observed Noise Levels

1025 In order to have a complete comparison of the SG
 1026 recording at J9 during a certain amount of time (from
 1027 a few weeks to several years), we applied a
 1028 standardized procedure to estimate a noise level that
 1029 was statistically significant, knowing that these
 1030 instruments did not always record simultaneously.
 1031 We focus here on the SGs but include some other
 1032 instruments. These are the absolute gravimeter
 1033 FG5#206 of Micro-g LaCoste, the three spring
 1034 gravimeters (LaCoste & Romberg Earth Tide
 1035 gravimeter ET-11, Micro-g LaCoste gPhone-54,
 1036 LaCoste-Romberg Graviton-EG1194) and the long
 1037 period seismometers STS-2 which were also operated
 1038 in J9 in parallel to the SG C026 and analyzed in
 1039 Riccardi et al. (2011), Arnosso et al. (2014), Rosat
 1040 et al. (2015) and Rosat and Hinderer (2018).

1041 Similar to the procedure by Berger et al. (2004)
 1042 for stations of the global seismographic network
 1043 (GSN), we computed power spectral densities (PSDs)
 1044 of calibrated raw data (1 s sampling) using a modified
 1045 Welch periodogram (Welch 1967) method applied on
 1046 12 h time windows overlapped by 6 h. From the
 1047 density distribution of PSDs, we computed the 1st,
 1048 5th, 25th and 50th percentiles but we have selected
 1049 only the 5th-tile for the plots in Figs. 21 and 22 to be
 1050 compared with the GSN noise models of Berger et al.
 1051 (2004). The new low noise model (NLNM) of
 1052 Peterson (1993) and the more recent statistical low
 1053 noise model (SLNM) by Castellaro and Mulargia
 1054 (2012) are also plotted for reference. Note that the
 1055 NLNM corresponds to the lower envelope of seismic
 1056 PSDs computed at that time, so it represents the
 1057 lowest noise level reached by seismometers anywhere
 1058 in the world.

1059 Fifth percentile of PSD noise levels of the eight
 1060 GWR Superconducting Gravimeters (C026, iOSG23,
 1061 iGrav6, iGrav15, iGrav29, iGrav30, iGrav31,
 1062 iGrav32) that were recording at the J9 Gravimetric
 1063 Observatory of Strasbourg are shown on Fig. 21.

1064 The SGs present the lowest noise magnitude in
 1065 the seismic band between 10^{-3} and 10^{-2} Hz for
 1066 gravimeters. However, STS-1 long period seismome-
 1067 ters provide lower noise above 1.5×10^{-3} Hz as

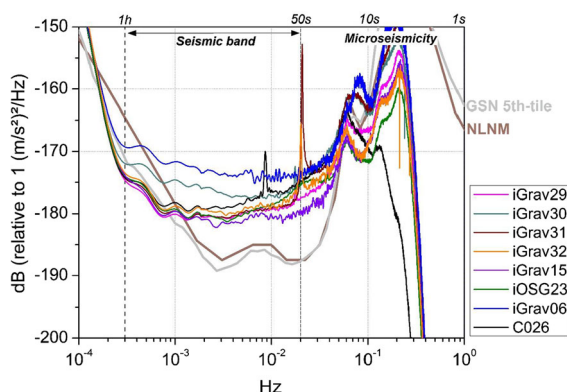


Figure 21

Fifth percentile of PSD noise levels computed on 1-s sampling data of the eight GWR Superconducting Gravimeters (C026, iOSG23, iGrav6, iGrav15, iGrav29, iGrav30 and iGrav31 and iGrav32) that were recording at the J9 Gravimetric Observatory of Strasbourg (France). The new low noise model (NLNM) of Peterson (1993) is represented by the thick brown line. In solid gray lines, we have plotted the 5th percentile of the PSD levels obtained by Berger et al. (2004) for the Global Seismographic Network (GSN 5th-tile)

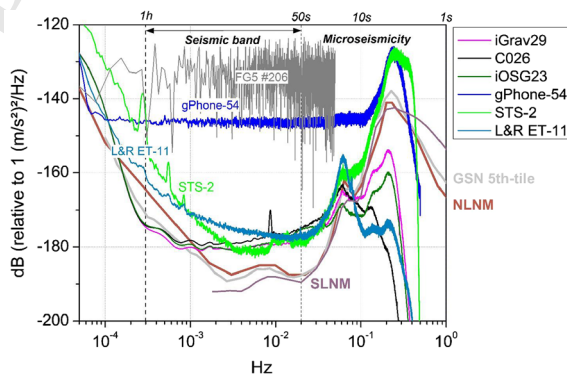


Figure 22

Fifth percentile of PSD noise levels computed on 1-s sampling data of the 3 GWR Superconducting Gravimeters (C026, iOSG23, iGrav29), of the STS-2 seismometer, of the Micro-g LaCoste gPhone-54 and of the LaCoste and Romberg ET-11 gravimeter that were recording at the J9 Gravimetric Observatory of Strasbourg (France). The FG5#206 drop files were also used to compute the corresponding PSD. The New Low Noise Model (NLNM) of Peterson (1993) is represented by the thick brown line and the SLNM of Castellaro and Mulargia (2012) is represented by the thick dashed pink line. In gray lines, we have plotted the 5th percentile of the PSD levels obtained by Berger et al. (2004) for the Global Seismographic Network (GSN 5th-tile). Figure modified from Rosat and Hinderer (2018)

indicated by the NLNM (Widmer-Schmidrig, 2003). 1068
 Noise increases at the right part of Fig. 21 because of 1069
 the microseismic signals. At the high frequency end 1070
 of the spectrum there is a steep roll-off (drop in 1071

1072 amplitude) till the Nyquist frequency of 0.5 Hz
 1073 because of the built-in low pass anti-aliasing filters
 1074 of the SGs. Some individual lines sticking out of the
 1075 noise are the so-called parasitic modes of the SG
 1076 (Imanishi, 2009).

1077 The excellent agreement between the noise levels
 1078 of six of the eight SGs as shown in Fig. 21 is one of
 1079 the most important results of this study. Indeed the
 1080 noise levels of C026, iOSG023 and iGravs 15, 29, 31
 1081 and 32 all agree within a few dB (relative to $1 \text{ (m/s}^2\text{)}^2\text{/Hz}$) in the seismic band. From this result, we
 1082 conclude that the various pillar designs used at J9 and
 1083 shown in Fig. 1 do not significantly affect the noise
 1084 of the SGs. Mounting an iGrav directly on the floor
 1085 operates as quietly as an SG installed on an isolated
 1086 pillar. In addition, the noise levels of the iGravs and
 1087 iOSG match that of the older Compact C026, so the
 1088 performance of the iGravs remains equal to previous
 1089 SGs.
 1090

1091 In contrast, we observe that the noise levels of two
 1092 iGravs (iGrav30 and iGrav6) are significantly higher
 1093 (5 db and 8 db) than the other six SGs. The auxiliary
 1094 channels show that both the tilt noise and dewar
 1095 pressure noise are 15 dB higher for iGrav30 than for
 1096 iGrav31. This was later diagnosed as caused by a
 1097 faulty pressure sensor in the head of the dewar
 1098 leading to a tension of the vibration isolation
 1099 diaphragm larger than nominal and hence transmit-
 1100 ting coldhead and tilt noise to the gravity sensor; this
 1101 pressure sensor was replaced before iGrav30 was
 1102 moved to Strengbach. And, the iGrav06 was installed
 1103 during the shortest time-period (~ 25 days) in which
 1104 several earthquakes occurred. Since we have picked
 1105 the 5th tile among these 25 days, it is more difficult to
 1106 obtain quiet days in such a short time window. For
 1107 other SGs, we have picked up the 5th-tile among at
 1108 least 100 daily PSDs. Because the iOSG23, C026 and
 1109 iGrav instruments are located in a similar environ-
 1110 ment, differences in the observed noise levels can be
 1111 investigated by extracting the coherent and incoher-
 1112 ent noise from the observed noise. We refer to the
 1113 work by Rosat et al. (2015) and Rosat and Hinderer
 1114 (2018) for detailed comparisons of SG noise levels
 1115 with other spring gravimeters (ET-11, gPhone-054), a
 1116 STS-2 seismometer and the absolute gravimeter
 1117 FG5#206 recording at J9.

iGrav30 and iGrav6 provide a note of caution to 1118
 all users of iGravs, SGs and other scientific instru- 1119
 ments that are designed to operate for years to 1120
 decades. It is wise to periodically check the perfor- 1121
 mance of SGs to make sure they are meeting their 1122
 noise specifications rather than wait until the end of a 1123
 project to analyze data and then find problems that 1124
 interfere with the project goals. Checking the noise 1125
 levels is very easy with iGravs that were designed 1126
 compatible to TSoft (Van Camp & Vauterin, 2005) 1127
 and feature software can be set up to reassure users 1128
 that all is well, or to warn of pending instrumental 1129
 problems. It is highly recommended that all users of 1130
 iGravs activate the data system feature that automat- 1131
 ically send emails to the user(s) that include both a 1132
 summary table of operating variables and a short 1133
 TSoft file. The TSoft file is automatically calculated 1134
 at the end of the day and a GWR_`summaryScript` 1135
 (iGrav User's Guide, 2019). This summaryScript 1136
 immediately provides the daily residual and temporal 1137
 noise throughout the day and can easily be edited by 1138
 the user. 1139

1140 For the sake of completeness, we have plotted in
 1141 Fig. 22 the fifth percentile of PSD noise levels of SGs
 1142 together with other spring gravimeters (ET-11,
 1143 gPhone-054), the STS-2 seismometer and the abso-
 1144 lute gravimeter FG5#206. For this meter we used
 1145 drop measurements performed every 10 s. Each drop
 1146 corresponds to one free fall of the test mass. In Rosat
 1147 et al. (2015), the PSD for the FG5 was computed on
 1148 set values at an hourly sampling with a noise level of
 1149 -125 dB at 10^{-4} Hz. Here we can see that using
 1150 10-s drop values, we have slightly reduced the noise
 1151 level to around -130 dB. This level is still the
 1152 largest of all meters in the seismic band and comes
 1153 from the fact that absolute measurements are con-
 1154 taminated by aliased microseismic noise (see e.g.
 1155 Crossley et al., 2001) which explains the rather flat
 1156 FG5 noise spectrum. A similar aliasing is observed in
 1157 the gPhone-54 PSD.

1158 The spring relative meters have lower noise levels
 1159 than the FG5#206 and range from -145 dB for the
 1160 gPhone-54 to -175 dB for ET-11 and the STS-2
 1161 seismometer.

1162 At higher frequencies, the STS-2 shows similar
 1163 performances like the SGs. At sub-seismic frequen-
 1164 cies (below 10^{-3} Hz), the SGs show lowest noise

1165 levels; while the ET-11 spring gravimeter noise is
 1166 10 dB higher and the gPhone is 30 dB higher. We
 1167 refer to the work by Rosat et al. (2015) for detailed
 1168 comparisons and self-noise analysis for these instru-
 1169 ments. In the following we only focus on the SGs and
 1170 their instrumental performances.

1171 5.2. Self-Noise Levels

1172 The observed noise level for an instrument at a
 1173 site consists of the Earth's environmental background
 1174 noise (containing all geophysical processes) and the
 1175 instrumental noise, including the noise coming from
 1176 the digital acquisition system and the electronics and
 1177 some possible effects of the physical installation
 1178 itself (e.g. placement in a building, or an installation
 1179 directly on the building floor or on a pillar isolated
 1180 from the building vibrations). In order to separate the
 1181 instrumental noise from the ambient noise, Sleeman
 1182 et al. (2006) have proposed a three-channel correla-
 1183 tion analysis. Compared to a two-channel analysis,
 1184 this technique has the advantage that we do not need
 1185 to know the transfer functions of the instruments. The
 1186 main assumption is that the internal noise between
 1187 two channels is uncorrelated to each other and to the
 1188 common input signal. The self-noise power spectral
 1189 density of channel i can hence be written as:

$$N_{ii} = P_{ii} - P_{ji}P_{ik}/P_{jk}, \quad (2)$$

1191 where P_{ii} is the PSD of channel i , and P_{ji} (respec-
 1192 tively P_{ik} , P_{jk}) is the cross-PSD between channels j
 1193 and i (i and k , j and k). The equation for self-noise
 1194 PSD can also be expressed as:

$$N_{ii} = P_{ii}(1 - C_{ji}C_{ik}/C_{jk}), \quad (3)$$

1196 where C_{ji} (respectively C_{ik} , C_{jk}) is the coherency
 1197 between channels j and i (i and k , j and k). The noise
 1198 cross-power spectra N_{ij} (resp. N_{ik} , N_{jk}) of internal
 1199 noise for channels i and j (i and k , j and k) are
 1200 assumed to be zero for $i \neq j$ ($i \neq k$, $j \neq k$).
 1201 According to these conventions, the instrumental
 1202 self-noise will be defined by N_{ii} and the common
 1203 geophysical noise viewed by the instruments is rep-
 1204 resented by $P_{ii} - N_{ii}$.

1205 In order to apply the three-channel correlation
 1206 analysis of Sleeman et al. (2006), we compute the
 1207 PSDs and the cross-PSDs of the various calibrated

1208 SG records using a modified Welch periodogram
 1209 method applied by averaging 9 segments of 48-h SG
 1210 time-windows overlapped by 75% on two selected
 1211 time-periods of 15 days. Two time-periods, April
 1212 8–23, 2017 and August 10–25, 2017 were selected
 1213 because of the joint availability of records from at
 1214 least three instruments free of disturbances due to
 1215 human intervention.

1216 Theoretically, the noise of the SG sensor is due to
 1217 the thermal noise associated with Brownian motion of
 1218 the levitating sphere. The expression of the power
 1219 spectral density of a damped harmonic oscillator due
 1220 to Brownian motion can be written as (Richter et al.,
 1221 1995; Aki & Richards, 2009eqn. 12.40):

$$P_{thermal} = 4k_B T \frac{\omega_0}{mQ}, \quad (4)$$

1223 where ω_0 is the natural angular frequency of the
 1224 oscillator, Q its quality factor and m is the mass of the
 1225 oscillating sphere; k_B is the Boltzmann constant and
 1226 T the absolute temperature within the sensor. When
 1227 there is no difference in the noise characteristics
 1228 between three instruments (if instruments are equally
 1229 installed at the same site for instance), the self-noise
 1230 should be well explained by the thermal noise model.

1231 In Eq. (4) we use the Q value of the magnetic
 1232 levitation system of the SG modeled as a mechanical
 1233 damped oscillator. The measured Q value (Table 10)
 1234 is low (0.109 for iOSG23 and 0.055 for iGrav29)
 1235 because the sphere's motion is strongly damped by
 1236 eddy currents in the non-superconducting materials in
 1237 the sensor (in the nearby Al plates and in the magnet
 1238 form). This damping is much larger than that caused
 1239 by the viscous drag on the sphere moving in the
 1240 surrounding helium gas. Moreover there are other
 1241 noise sources that include temperature control noise,
 1242 tilt noise, electronic noise, noise from the boiling He,
 1243 coldhead vibrations, and digitization noise; some of
 1244 which are difficult to quantify. However these noise
 1245 sources seem below the thermal noise of the iGrav as
 1246 is discussed hereafter.

1247 The parameters that are needed to compute the
 1248 thermal noise PSD of iGrav29 and iOSG23 are given
 1249 in Table 10.

1250 The three-channel correlation analysis was
 1251 already applied by Rosat et al. (2015) on the STS-2
 1252 seismometer, the LaCoste-Romberg ET-11



Table 10

Harmonic oscillator parameter values used in Eq. 4 to compute the spectral acceleration-noise power density due to Brownian motion

Parameter	Unit	iGrav29	iOSG23
Mass m	kg	$4.02 \cdot 10^{-3}$	$17.7 \cdot 10^{-3}$
Frequency f_0	Hz	0.238	0.105
Q		0.109	0.055
Spring constant k	N/m	0.0090	0.0077
Damping factor b	kg/s	0.055	0.214
Mean PSD	dB	- 181	- 188

gravimeter and the SG C026 recording at J9. Because of different band-pass frequencies and different digital acquisition system (DAS), it was however not possible to extract the sensor noise from the noise of the DAS. Here, we have the possibility to evaluate the sensor noise since the DAS used for every iGrav and for the iOSG23 is identical. A similar study was already done in Rosat and Hinderer (2018) but on a more limited number of iGrav instruments.

The results of the three-channel correlation analysis applied to the iGravs and the iOSG recording at J9 are shown in Fig. 23. We can see that at seismic frequencies higher than 1 mHz and lower than the start of the roll-off due to the low-pass anti-aliasing filter, the thermal noise model (- 181 dB, Table 10) agrees well with the extracted self-noise PSD for iGravs with a difference of a few dB (< 5 dB), except for iGrav30, which had a problem due to a faulty dewar pressure sensor previously discussed in Sect. 4.2 and previously shown in Fig. 21. The close matching of the thermal noise to the observed noise of the SG simply means that other noise sources of the SG are below its thermal noise.

Because of its heavier levitated sphere, the thermal noise for iOSG23 should be just below the NLNM seismic noise and a few decibels lower than the thermal noise of iGrav instruments (- 188 dB, Table 10).

The fact that the self-noise of iOSG23 results to be about 5 dB larger than its thermal noise model in the seismic band (mHz frequency range) is likely due to additional noise sources previously mentioned. That the iOSG noise is lower than the iGrav self-noise is likely the influence of its larger mass in

agreement with Eq. (4). We also point out that the thermal noise of the STS1 long-period seismometer is lower than that of the SG, and that this also is likely due to its mass being much larger (600 g) and perhaps its lower damping (Richter et al., 1995).

We can see that the self-noise for iGrav15 and 32 which were installed directly on the ground are similar to the one of the iOSG23 at periods larger than 1 h and similar to the one of iGrav29 at seismic frequencies. We conclude that the variations in physical installations at J9 did not significantly affect the noise levels and that installation on the concrete ground is as good as on a small or large isolated pillar.

Two parasitic noise peaks around $2 \cdot 10^{-2}$ Hz (one at 57 s for iGrav30 and one at 48 s for iGrav29 and iGrav31) are visible in the PSDs (Fig. 23). These vibrations correspond to the low-frequency parasitic mode (Richter et al., 1995; Van Camp, 1999) due to horizontal displacements of the sphere that turn into an orbital mode (Hinderer et al., 2015). For iGrav32, this mode appears at 20 mHz (Schäfer et al., 2020). Peaks at 0.24 Hz and harmonics may be due to some other parasitic modes associated with other degrees of freedom of the sphere (Imanishi, 2009), coldhead noise, or other unidentified effects.

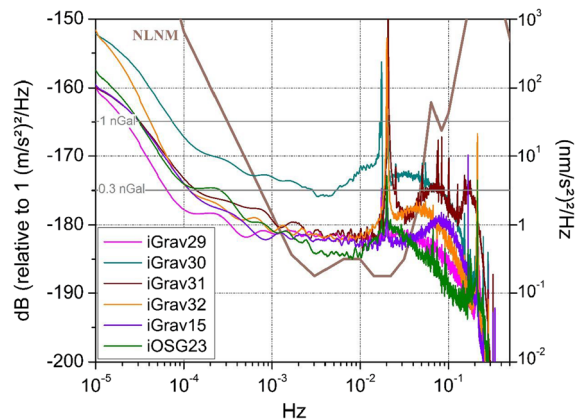


Figure 23

Results of the three-channel correlation analysis applied on the 1-s data for iGrav30 and iGrav31 and iOSG23 on the 15-day time period 2017, April 8th to 23rd and for iGrav32, iGrav29 and iGrav15 on the 15-day time period between 2017, August 10th and 25th. Common noise was removed by this method and only self-noise PSDs are plotted



1313

6. Conclusion

1314 Superconducting gravimeters (SG) are currently
1315 the most sensitive relative gravimeters with the
1316 lowest drift rates which, as demonstrated in our study,
1317 can be modelled and reduced with the help of abso-
1318 lute gravity measurements. Therefore, these sensors
1319 are particularly suitable for studying a wide range of
1320 geophysical processes which induce weak gravity
1321 effects over time intervals of minutes to years.

1322 We compared in detail eight SGs located inside
1323 the Strasbourg Gravimetric Observatory including
1324 five of the latest generation of field SGs, the so-called
1325 iGravs, one iOSG with a heavier sphere and an older
1326 compact meter C026. The calibration of the instru-
1327 ments was investigated both in an absolute way, by
1328 parallel absolute measurements, as well as in a rela-
1329 tive way by computing the regression between
1330 parallel SG time series. We found out that relative
1331 calibration determined from different SGs at the same
1332 site can be much more precise than absolute cali-
1333 bration. We could also demonstrate that using relative
1334 scale factors strongly reduces the tidal residuals
1335 between two different SGs which is not the case when
1336 using absolute calibration.

1337 We checked the instrumental time delays (phase
1338 lag) of the various SGs from cross-correlation anal-
1339 ysis between different parallel time series. All the
1340 iGravs have similar time delays of a few seconds with
1341 respect to iOSG23. Moreover, the time delays for a
1342 specific gravimeter inferred from a one year long
1343 tidal analysis, step experiments and time regression
1344 were all found to agree.

1345 We discussed the instrumental drift of the SGs
1346 and found that all the meters exhibit an initial expo-
1347 nential drift best approximated by two exponentials
1348 with different time constants, followed by a long-
1349 term linear drift. We could also show the conse-
1350 quences of the initialization/levitation procedures on
1351 the instrumental drift, especially for iGrav29 that was
1352 used as test instrument in this study. A rather strong
1353 correlation was found between the gravity drift and
1354 the body-temperature signal but it is not a straight-
1355 forward or linear relationship.

1356 Furthermore, we have performed a noise level
1357 analysis of all the iGravs and the ~~iOSG023~~. A three-
1358 channel correlation technique was applied to identify

the common noise and the self-noise of the various
iGravs and the iOSG. However, small differences in
self noise are not caused by the installation method
(on concrete pillars or directly on the floor) or
instrumental configurations; but they may be caused
by differences in their transfer functions.

Small differences in self-noise could possibly be
interpreted in terms of local noise effects that are
incoherent between the various instruments separated
by a few meters. For example, lateral contrast in local
soil moisture in the loess layer above the Observatory
could lead to slightly different signals of each
gravimeter.

The present metrological study is of importance
for several geophysical applications. A good knowl-
edge of the instrumental drift is essential for the study
involving long-period gravity changes. We can
mention for instance the difficulty of separating post-
glacial rebound effects from present-day ice-melting
where the combination of AG and SG observations
helped considerably to reduce the uncertainty in the
AG estimated decrease due to ice melting in Svalbard
(Memin et al. 2014). Furthermore, studies on slow
recharge processes in magma chambers could benefit
greatly from a thorough knowledge of the drift of the
gravimeters used to monitor active volcanoes
(Okubo, 2020; Riccardi et al., 2008). Knowledge of
the purely instrumental noise and separation from
environmental noise can help to detect small signals
which are hidden in the overall noise (e.g. Rosat &
Hinderer, 2018). Accurate calibration of the SGs is
essential for the determination of tidal amplitudes and
phases that is fundamental for tidal tomography and
investigation of lateral heterogeneity effects (Meti-
vier et al. 2007; Latychev et al., 2009).

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1414 igets.st.11.001](http://doi.org/10.5880/igets.st.11.001).

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