# Accuracy and Time Stability of the Hannover Absolute Gravimeters JILAg-3 and FG5-220

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## Abstract

In this paper, we discuss the differences, accuracies and stabilities of the two absolute gravimeters operated in Hannover, JILAg-3 and FG5-220. We consider measurements of both instruments on different sites in Germany, but also results from international comparison campaigns. An offset between the two gravimeters of about 9 µGal has been found, which is to be analyzed in the context of the various comparisons.

## 1. Introduction

With the receipt of the transportable free-fall gravimeter JILAg-3 (Fig. 1 *left*, Faller et al. 1983) at the Institut für Erdmessung (IfE, Leibniz Universität Hannover (LUH)) in 1986, projects were initiated with a main objective to improve national and international gravimetric networks. Deficiencies from relative gravimetry in the definition of the absolute datum (gravimetric scale and level) could be overcome. As a second goal, absolute gravity determinations were performed to support the geodynamic research in regions where geophysical phenomena deform the Earth's surface. The JILAg-3 was successfully employed in more than 130 absolute gravity determinations at more than 80 different stations worldwide.

The FG5 gravimeters are the follow-up of the JILAg series. In Germany, the Institut für Angewandte Geodäsie (IfAG), now Bundesamt für Kartographie und Geodäsie (BKG), acquired the FG5-101 already in 1993 (Carter et al. 1994) with the first main objective to survey the German zero-order base net. At IfE, the FG5-220 (Fig. 2 *right*, Niebauer et al. 1995) was obtained in 2002. To compare the results of JILAg-3 with recent observations of FG5 meters, no systematic difference due to the gravimeters themselves should exist, or the instrumental offset should be well-known. Therefore, comparisons of results with the German absolute gravimeters among themselves and with other instruments were performed.

*Figure 1:* *The two absolute gravimeters of the Leibniz Universität Hannover: left JILAg-3 employed from 1986 to 2000 (here reference measurements in Hannover), right FG5-220 operated since 2003 (tent measurements in Denmark)*

## 2. Measuring Accuracy and Time Stability

The manufacturers of the JILAg and of the FG5 systems performed an error budget analysis to determine the single instrumental uncertainty contributions through calculations and measurements of known physical effects. Niebauer (1987) derived a total error of 3 μGal for JILAg instruments. In Niebauer et al. (1995) a total uncertainty of 1.1 μGal is obtained from the FG5 instrumental error budget.

To assess the accuracy of the transportable absolute gravimeters from the user point of view, the experiences with the Hannover instruments JILAg-3 and FG5-220 are used to derive an empirical accuracy estimate. For both instruments, the accuracy and stability have been continuously controlled by comparisons with other absolute gravity meters, and with repeated measurements in several stations after time intervals of some months to a few years. A rigorous control of the absolute accuracy with respect to a "true" gravity value at the epoch of an absolute gravity measurement is not possible. The real g-value with a superior accuracy is not known, and a "standard" absolute gravimeter which is superior to the state-of-the-art FG5 meters does not exist. Therefore, the empirical accuracy estimates have to be understood as describing the agreement of the instruments' measuring level and their time stability with regard to the international absolute gravity datum definition. Here, the international datum is defined by the physical standards (time and length) and, in addition, as the average result obtained from all operational absolute gravimeters participating in the international comparison campaigns.

For JILAg-3, Torge (1991) estimated the short- and long-term accuracy of a station determination between 5 and 10 μGal. On average, an accuracy estimate of 7 μGal was obtained. The instrumental precision by itself is assumed to be 4−5 μGal which does not consider errors introduced by real gravity changes, e.g. due to subsurface water variation. For FG5-220, a realistic mean accuracy estimate seems to be about 3 μGal (cf. Timmen et al. 2006; Francis and van Dam 2006; Francis et al. 2010; Bilker-Koivula et al. 2008).

These empirical estimates incorporate

- instrumental errors, e.g. due to instrumental vibrations or laser instabilities;
- gravitational "noise" due to incomplete modelling and reduction of gravity variations with time (Earth tides, polar motion, atmospheric mass variation).

Because most of the IfE measurements serve for local and regional gravimetric control, especially for geodynamic investigations in tectonically active areas, the long-term measuring stability of the two gravimeters is a major concern. To compare the results of JILAg-3 with recent observations of FG5-220, no systematic difference due to the gravimeters themselves should exist, or the instrumental offset should be well-known. Within this context the instrumental offset should be understood as a mean measuring offset (bias) valid for a long time period, e.g. some years or even the gravimeters lifetime. One possibility for detecting such an offset is to compare observation series of both instruments performed at a reference station where long-term stable gravity acceleration can be assumed (no significant secular change). The JILAg-3 reference station Clausthal in the Harz Mountains (stable bedrock) was occupied by FG5-220 at four different epochs in 2003 (January, May, June and October) to derive a reliable mean g-value for 2003, and in June 2009. In Table 1, the mean result is compared with the mean from 29 gravity determinations with JILAg-3 performed in the period 1986−2000. The standard deviation of the mean values is about 1 μGal in both cases. An obtained discrepancy of +9.0 μGal indicates a significant offset between the measuring levels of these two absolute gravimeters. Similar discrepancies have also been reported by

***Table 1:*** *Mean gravity values for station Clausthal (Germany) derived with JILAg-3 and FG5-220. The given $s_i$ are standard deviations for a single gravity determination.*

| **JILAg-3/FG5-220 Comparison** | **Gravimeter** | **Period** | **Mean g-result [μGal]** |
|---|---|---|---|
| Clausthal (Harz Mountains) JILAg-3 reference station | JILAg-3 | 1986 to 2000 | 981115734.5<br>$s_i$=4.9, n=29 |
| | FG5-220 | Jan. to Oct. 2003<br>Jun 2009 | 981115725.5<br>$s_i$=2.2, n=5 |
| | | | Δg = **+9.0** |

***Table 2:*** *Gravity differences (JILAg-3 minus FG5-101) obtained from the International Comparisons of Absolute Gravimeters (ICAG) in Sèvres 1994 and 1997, and during the surveying of the national German base network DSGN94 (five identical stations), and from three comparisons at the Clausthal reference station, after Torge et al. (1999)*

| **Comparisons of JILAg-3 (IfE) and FG5-101 (BKG, Torge et al. 1999)** | **Discrepancy [μGal]** |
|---|---|
| ICAG94, BIPM, pier A0 | +9.0 |
| ICAG97, BIPM, pier A | +8.1 |
| DSGN94 | +8.2 |
| Clausthal reference station | +9.4 |

Torge et al. (1999) when comparing measurements from FG5-101 (BKG) and JILAg-3 performed in the years 1994−1997. These comparisons showed a discrepancy varying between +8.1 and +9.4 μGal (Table 2). For the Canadian gravimeter JILA-2, a systematic offset of +4.1 μGal has been found in Liard et al. (2003). Some hints are given in Wilmes et al. (2003) that similar offsets may exist for other JILA gravimeters with respect to FG5 meters.

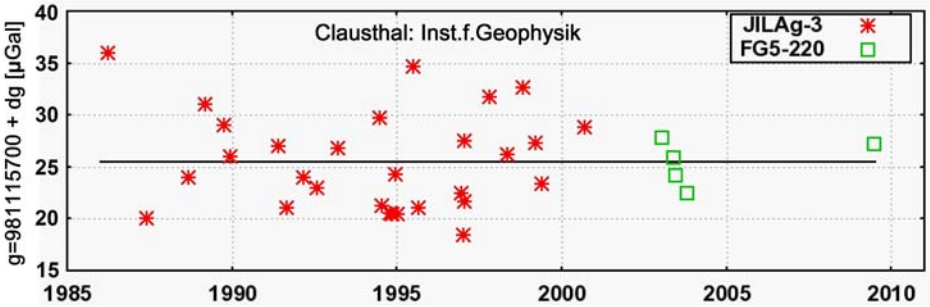

***Figure 2:*** *Absolute gravity determinations with JILAg-3 and FG5-220 at station Clausthal (CLA522, trend −0.1 ±0.2 μGal per year). An instrumental offset of −9 μGal (±1 μGal) was applied to the JILAg-3 results*

Fig. 2 shows the time series of absolute gravity determinations at station Clausthal (point 522) observed with the two Hannover instruments (offset correction applied). The decline in the four observed g-values at the Clausthal station in 2003 should be connected to the very dry season in northern Germany. A similar but much stronger gravity change was measured in Hannover when the groundwater table fell by 70 cm accompanied by a gravity decrease of about 13 μGal.

With taking the offset correction of −9 μGal into account for all JILAg-3 observations, a stable measurement level for a time span of more than 20 years is assumed to be available with the two Hannover instruments. This is in accordance with the present knowledge that the FG5 series is presently the best instrumental realisation of absolute gravimeters. Nevertheless, to meet the accuracy requirements for long-term research over many decades and for comparability with other instruments, the observation level of the JILAg-3/FG5-220 couple has to be verified by comparisons with other absolute gravimeters. Since the 1980s, International Comparisons of Absolute Gravimeters (ICAG) are performed at the Bureau International des Poids et Mésures (BIPM) in Sèvres, and since 2003, with a 4-years time interval, also at the European Centre of Geodynamics and Seismology (ECGS) in Walferdange, Luxembourg. Such extensive comparison campaigns with a large number of absolute gravimeters may reveal biases not only between single instruments but also between different instrumental developments and technological realisations. Table 3 summarises the results from the comparisons ICAG89 (Boulanger et al. 1991), ICAG94 (Marson et al. 1995) and ICAG97 (Robertsson et al. 2001). In 1989, five JILA-type instruments and five individual developments participated. The JILAg-3 result differed from the mean of the JILA group by +1.8 µGal, from the mean of the group with individual developments by +3.3 µGal, and in the average by +2.4 µGal from the mean of all 19 stations determinations performed by the 10 instruments. In 1994, for the first time FG5 instruments contributed to the comparison, and the discrepancy of JILAg-3 to the mean result of all 11 gravity meters was +2.8 µGal. These two comparisons may indicate a small offset of about +2 or 3 µGal for JILAg-3. In 1997, the situations changed somewhat. The sites A and A2 were observed, and for both points the JILAg-3 result was +5.5 µGal above the average of all instruments. In addition to these external comparisons with other gravimeters, the lower part of Table 4 shows an internal comparison for JILAg-3. Looking at the Clausthal series with respect to the whole time span (1986−2000), and the two periods 1986−1996 and 1997−2000, a systematic change in the measuring level can not be detected. The Clausthal series neither confirms nor contradicts the ICAG97 experience. Both results are consistent considering the precision estimate of 4−5 µGal for a single station determination with JILAg-3.

Interpreting the results of the international comparisons in Sèvres with respect to the instrument groups, a systematic error, inherent in the instrumental design of the JILAg or FG5 gravimeters, does not exist or is within the 1−2 µGal accuracy level. Nevertheless, temporary biases for single instruments are possible, e.g. due to not-detected changes within the instrumental adjustments.

To investigate the stability of the presently employed gravimeter FG5-220 of IfE, Table 4 gives the result from the international comparisons in Walferdange (Luxembourg) in 2003 and 2007 (external comparisons, Francis and van Dam 2006; Francis et al. 2009), and FG5-220 reference measurements in Bad Homburg (station of BKG, Wilmes and Falk 2006) from 2003 to 2008. Within 2 µGal, the

***Table 3:*** *JILAg-3 absolute gravity meter controlled by external (international) and internal (repetition) comparisons to ensure consistent long-term measurement accuracy (n: number of observations)*

| **JILAg-3 External comparisons** | **Remarks** | **Gravimeter group** | **Mean g-result [µGal]** | **Std. Dev. of a single observ. [µGal]** | **Δg [µGal] (JILAg-3 minus Mean)** |
|---|---|---|---|---|---|
| ICAG89, BIPM (Boulanger et al. 1991, Table 7) | Referred to **site A**, ref.height 0.050 m, 19 station determinations with 10 abs. gravimeters | 5 JILA | 980925975.4 | ±6.2, n=11 | +1.8 |
| | | GABL, BIPM, IMGC, NIM, NAO | . . . 73.9 | ±9.2, n= 8 | +3.3 |
| | | all 10 meters | . . . 74.8 | ±7.4, n=19 | **+2.4** |
| | | only JILAg-3 | . . . 77.2 | n= 2 | |
| ICAG94, BIPM (Marson et al. 1995, Table 4) | Referred to **site A0**, ref.height 0.900 m, 12 observations with 11 abs. gravimeters | 4 JILA | 980925710.3 | ±4.9, n= 4 | +2.7 |
| | | 6 FG5 | . . . 10.4 | ±2.8, n= 7 | +2.6 |
| | | 1 IMGC | . . . 09.0 | n= 1 | +4.0 |
| | | all 11 meters | . . . 10.2 | ±3.3, n=12 | **+2.8** |
| | | only JILAg-3 | . . . 13.0 | n= 1 | |
| ICAG97, BIPM (Robertsson et al. 2001, Table 5) | Occupied **site A** with 12 instruments, ref. height 0.900 m | 4 JILA | 980925708.1 | ±5.5, n= 4 | +5.6 |
| | | 7 FG5 | . . . 07.0 | ±3.7, n= 7 | +6.6 |
| | | 1 GABL-E | . . . 14.4 | n= 1 | −0.8 |
| | | all 12 meters | . . . 08.1 | ±4.5, n=12 | **+5.5** |
| | | only JILAg-3 | . . . 13.6 | n= 1 | |
| ICAG97, BIPM (Robertsson et al. 2001, Table 5) | Occupied **site A2** with 13 instruments, ref.height 0.900 m | 4 JILA | 980925716.6 | ±3.5, n= 4 | +3.5 |
| | | 6 FG5 | . . . 73.7 | ±2.9, n= 6 | +6.4 |
| | | IMGC, NIM-2a, ZZB | . . . 13.9 | ±0.1, n= 3 | +6.2 |
| | | all 13 meters | . . . 14.6 | ±5.0, n=13 | **+5.5** |
| | | only JILAg-3 | . . . 20.1 | n= 1 | |
| **JILAg-3 Internal comparisons** | **Remarks** | **Observation Period** | **Mean g-result [µGal]** | **Std. Dev. of a Single Observ.** | **Δg [µGal]** |
| Clausthal, Harz | IfE ref. station for JILAg-3, 29 obs. over 15 years, floor level | 1986 to 2000 | 981115734.5 | ±4.7, n=29 | |
| | | only 1986 to 1996 | . . . 34.1 | ±4.8, n=20 | **−0.4** |
| | | only 1997 to 2000 | . . . 35.4 | ±4.6, n= 9 | **+0.9** |

***Table 4:*** *FG5-220 absolute gravimeter controlled by external (international) and internal (repetition) comparisons to ensure consistent long-term measurement accuracy*

| **FG5-220 External comparison** | **Remarks** | **Epoch** | **Δg [μGal] (FG5-220 − Mean g)** |
|---|---|---|---|
| ICAG2003, ECGS (Francis and van Dam 2006, Tab. 16) | 13 abs. meters,<br>14 points,<br>52 determinations | Nov. 2003 | −1.9<br>std.dev. (single instr.) 1.8 |
| ICAG2007, ECGS (Francis et al. 2010, Tab. 3) | 19 abs. meters,<br>16 points,<br>73 determinations | Nov. 2007 | +2.4<br>std.dev. (single instr.) 2.0 |
| **FG5-220 Internal comparison** | **Remarks** | **Epoch** | **Δg (FG5-220) [μGal] (Single − Mean g)** |
| Bad Homburg (gravimetry lab. of BKG, Wilmes and Falk 2006) | Reference station for FG5-220 since 2003, point BA | Feb. 2003 | +0.9 |
| | | Nov. 2003 | −0.8 |
| | | Apr. 2005 | +1.2 |
| | | Apr. 2006 | +0.7 |
| | | Nov. 2007 | +0.2 |
| | | Sep. 2008 | −2.1 |
| | | mean | 0.0 ±1.3 |

Hannover FG5 instrument agrees with the internationally realised measuring level. With respect to the FG5-220 observations in Bad Homburg, it has to be mentioned that the differences between the single epochs also contain real gravity changes due to time-varying environmental effects like seasonal hydrological variations. As shown in Table 4, the six stations determinations agree very well, better than expected from empirical estimates, with a mean scatter of 1.3 μGal only (standard deviation). An instrumental instability could not be identified. Similar experiences are also gained from the yearly repetition surveys and from the comparisons with the other FG5 absolute gravimeters involved in the Nordic absolute gravity project, to determine the Fennoscandian land uplift, cf. Timmen et al. (2006) and Bilker-Koivula et al. (2008).

## 3. Conclusions

From Tables 3 and 4, it may be concluded that JILAg-3 and FG5-220 were or are well embedded in the international absolute gravity definition. Overall, a larger discrepancy to other instruments or group of instruments did not really become obvious during the international comparisons. But for JILAg-3, a bias to the international standard, here defined as the average of all participating gravimeters at BIPM, of up to +5 µGal cannot be excluded. From the ICAG94 and ICAG97 comparisons, a measurement offset of +9 µGal becomes visible when just comparing JILAg-3 with FG5-101 as already mentioned. Thus, from the Hannover point of view, the offset correction for JILAg-3 has mainly to be considered as a bias with respect to the gravimeters FG5-220 and FG5-101, and not to the international standard.

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