Absolute gravity measurements in the town hall (“Rathaus”) of Bad Frankenhausen with the Hannover gravity meter FG5X-220 in June 2015

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1. Absolute gravimetry with the FG5X-220 free-fall absolute gravimeter

The upgraded absolute gravimeter FG5X-220 is deployed by IfE since summer 2012. Compared with the predecessor version FG5-220, the instrument has a different free-fall length (about 30 cm instead of 20 cm) and a different measuring segment along the vertical (from 138 cm to 108 cm above floor level instead of 128 cm to 108 cm). Additional information about the Hannover instruments can be found in *Timmen (2010)*. Descriptions of the FG5 and FG5X gravimeters are given in *Niebauer et al. (1995)* and *Niebauer et al. (2013)*.

2. Absolute accuracy

The expression “absolute” is based on the fact that the time and length standards (rubidium clock, iodine stabilized helium-neon laser) are incorporated as components of the gravimeter system. Thus, each absolute gravimeter allows an independent traceability to the SI units of time and length through the frequency calibrations of the laser and the rubidium clock. To validate the uncertainty of the whole gravimeter system, comparisons are performed between different absolute meters as well as reference measurements are carried out on well-known stations with an appropriate history.
Repeatability and accuracy of the FG5-220 or FG5X-220 system has routinely been controlled (especially before and after field projects) at the reference stations Hannover (gravimetric laboratory of IfE) and Clausthal (TU Clausthal, Geophysics, Harz Mountains). It has to be mentioned that the differences between single epochs contain also real gravity changes due to time-varying environmental effects like seasonal hydrological variations.
Since the 1980s, International Comparisons of Absolute Gravimeters (ICAG) were performed with a 4-years’ time interval at the Bureau International des Poids et Mésures (BIPM) in Sèvres until 2009. Since 2003, European comparison campaigns have been held at the European Centre of Geodynamics and Seismology (ECGS) in Walferdange, Luxembourg. After BIPM abandoned the international comparisons in Sèvres, the ICAG2013 was organized at ECGS. 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.
The first comparison at ECGS was held in November 2003 with 13 simultaneously observing instruments, assigned for research in geophysics (e.g. geodynamics) or for metrological purposes (definition of standards), cf. Table 1. The excellent agreement between the gravimeters was 18 nm/s² (standard deviation). The recent international comparison at ECGS in Walferdange was carried out in November 2013 and included the Hannover FG5X-220 instrument for the first time.
For us from the Hannover group it becomes obvious that our FG5 system is still in the measurement level of the international community. Within 0.02 µm/s², the Hannover instrument agrees with the internationally realized measuring level. Here, the international datum is defined by the physical standards (time and length) and, in addition, as the average result obtained from all qualified absolute gravimeters participating in the international comparison campaigns.

Tab. 1: Absolute gravimeter FG5-220 or FG5X-220 (after upgrade, 2012) are controlled by external (international) comparisons to ensure consistent long-term measurement accuracy and stability. Comparison reference values (CRVs) are defined by all participating qualified gravimeters

FG5-220 External Comparison	**Remarks**	**Epoch**	**Δg [µm/s²] (FG5(X)-220 − CRV)**
ECAG2003, ECGS (*Francis, van Dam 2006*, Tab. 16)	13 abs. meters, 14 points, 52 determinations	Nov. 2003	**−0.019** s(single meter) = 0.018
ECAG2007, ECGS (*Francis et al. 2010*, Tab.5. 3)	19(17) abs. meters, 16 points, 73 determinations	Nov. 2007	**+0.024** s(single meter) = 0.020
ICAG2009, BIPM (*Jiang et al. 2012*) Tab. 11 and 13)	21 abs. meters, 5 points, 63 determinations	Oct. 2009	**+0.017** s(single meter) = 0.042
ECAG2011, ECGS (*Francis et al. 2013*, Tab. 5)	21 abs. meters, 15 points, 63 determinations	Nov. 2011	**+0.018** s(single meter) = 0.031
ICAG2013, ECGS (Francis et al. 2015, Annex B)	25 absolute meters, 15 points, 75 determinations	Nov. 2013	**+0.023** s(single meter) = 0.033

We may conclude that an overall accuracy (long-term stability and agreement within the group of internationally operating absolute gravimeters) of better than 30 nm/s^2 is indicated for a single station determination with the Hannover absolute gravimeter.

3. Absolute gravimetric measurements in Bad Frankenhausen

The absolute gravimetric results are presented in Table 3. A statistical assessment is given in Fig. 1. The annex shows photographs about the absolute sites in the basement of the town hall. The gravimetric impact of air pressure variations on the absolute measurements were reduced by applying the factor -3.0 nm/s^2 per hPa. Table 4 compiles the applied Earth tide parameter for the tidal reduction. The vertical gravity gradient along the plump line was determined by relative gravimetry above the ground mark by the author of this report using the relative gravimeter Scintrex CG3M-4492. To avoid or minimize any deterioration of the absolute gravimetric result (g-value) caused by uncertainties of the vertical gradient, which is actually not a constant, the final absolute result is transferred to the sensor height h = 1.250 m above floor level where the influence of the gradient becomes almost zero ("dead-gradient-point"). That ensures that the vertical gradient is only needed to transfer the g-value from the setup depending sensor height (corresponds to the effective measuring height of the FG5X-220, see Timmen 2003) to the reference height of 1.250 m over the small distance of less than 2 cm only. In this way, the station time series (history) of the gravimeter point can be used best to investigate a secular gravity change over years to decades. The reference height is useful to compare with other gravimeters and with older gravity determinations. The gravity tie between the absolute gravity point in the basement of the "Rathaus" to the outdoor point in front of the "Rathaus"(start point for relative measurements) were determined with the Scintrex CG3M meter of IfE on the 23rd of June 2015:

$$\Delta g\,(\text{abs. point, h=0.000m} \rightarrow \text{rel. point, outdoor, wall bolt}) = -4.631\ \mu m/s^2\ ,\ \text{std.dev} = 0.015\ \mu m/s^2\ .$$

Table 2: Used coordinates of the absolute gravity sides occupied by the Hannover meter FG5X-220 in Bad Frankenhausen in June 2015

Station at "Rathaus"	φ [deg]	λ [deg]	H [m]	Description
Cellar vault	51.3557	11.1005	130	Old "historical" basement of town hall; high air humidity; heating in small tent necessary for temperature stabilization; no permanent ground mark

Table 3: Absolute gravity values of the FG5X-220 measurements on "Rathaus" point (cellar vault). The gradient insensitive sensor height ("dead-gradient-point") depends on the gravimeter setup and is about 1.25 m above floor level. Thus, the reference height h=1.250 m (above floor point) is chosen for comparison reasons. The applied vertical gradient is assumed to be a constant and, because of the chosen reference height, the effect of its uncertainty of the absolute value can be neglected. The gradient δg/δh was measured with Scintrex CG3M-4492 between the sensor positions 25.1 cm and 116.5 cm above floor point (dh:91.4, std.dev. 0.009 $\mu m/s^2$). For relative gravimetry, the derived g-value at h=0.000 m is also given.

Site **Rathaus**	Measurement run (orientation)	Date in 2015	Drops	δg/δh [$\mu m/s^2$ / m]	$g_{h=1.250}$ [$\mu m/s^2$]	$g_{h=0.000}$ [$\mu m/s^2$]
Setup 1	20150622a (N)	22./23. June	998	-2.678	9811717.488 s=0.001	
Setup 2	20150623a (W)	23. / 24. June.	798	-2.678	9811717.458 s=0.001	
Average		22. – 24. June.	1796	-2.678	**9811717.473**	**9811720.820**

Tab. 4: Applied Earth tide parameter for Bad Frankenhausen from Timmen and Wenzel 1995, IAG Symp. 113, 92-101, Springer

Frequency [cpd] Start	End	Amplitude	Phase Lead[°]	Tidal Group
0.000000	0.000000	1.0000	0.0000	DC
0.000100	0.249951	1.1808	0.0285	Long
0.721500	0.906315	1.1506	-0.1352	Q1
0.921941	0.974188	1.1490	0.0865	O1
0.989049	0.998028	1.1479	0.1818	P1
0.999853	1.216397	1.1335	0.1282	K1
1.719381	1.906462	1.1726	1.8810	N2
1.923766	1.976926	1.1825	1.5649	M2
1.991787	2.002885	1.1837	0.5844	S2
2.004710	2.182843	1.1786	0.4562	K2
2.753244	3.081254	1.0691	0.0000	M3

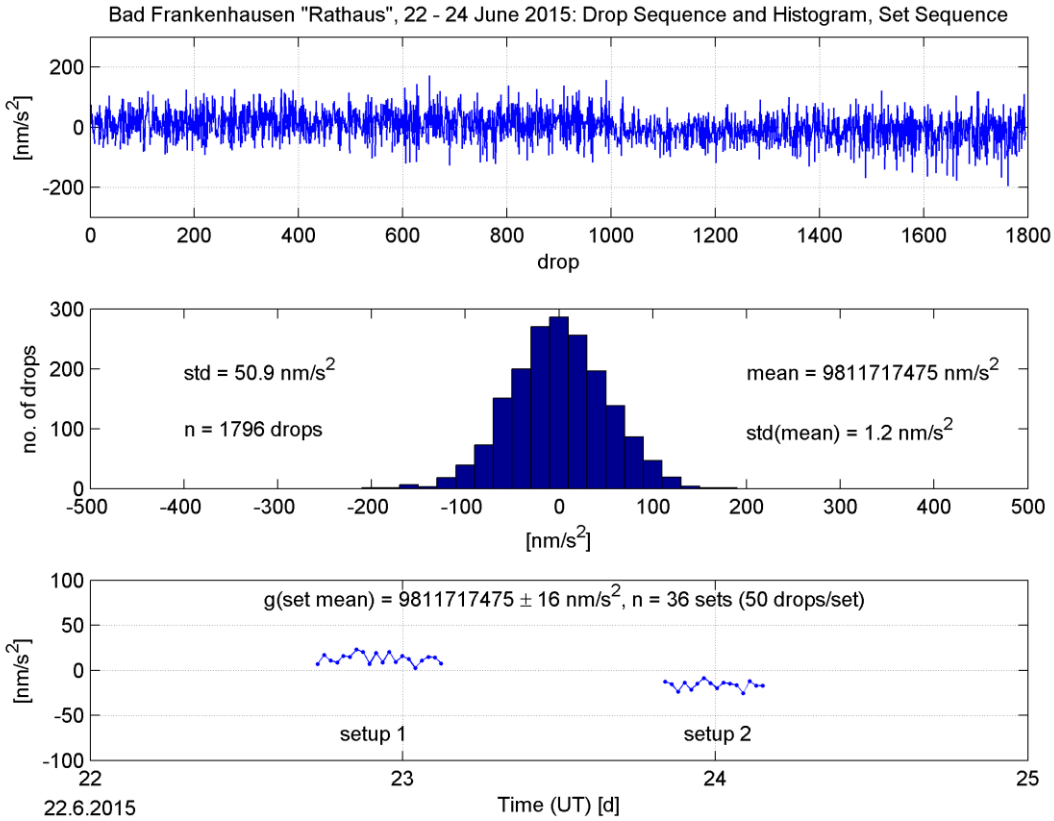

Fig.1: Statistical compilation of the station determination with the Hannover FG5X-220 absolute gravimeter at the "Rathaus" in Bad Frankenhausen, June 2015.

References

Francis, O., Henri Baumann,Tomas Volarik, Christian Rothleitner, Gilbert Klein, Marc Seil, Nicolas Dando, Ray Tracey, Christian Ullrich, Stefaan Castelein, Hu Hua, Wu Kang, Shen Chongyang, Xuan Songbo, Tan Hongbo, Li Zhengyuan, Vojtech P´alink´as, Jakub Kosteleck´y, Jaakko M¨akinen, Jyri N¨ar¨anen, S´ebastien Merlet, Tristan Farah, Christine Guerlin, Franck Pereira Dos Santos, Nicolas Le Moigne, C´edric Champollion, Sabrina Deville, Ludger Timmen, Reinhard Falk, Herbert Wilmes, Domenico Iacovone, Francesco Baccaro, Alessandro Germak, Emanuele Biolcati, Jan Krynski, Marcin Sekowski, Tomasz Olszak, Andrzej Pachuta, Jonas Agren, Andreas Engfeldt, Ren´e Reudink, Pedro Inacio, Daniel McLaughlin, Geoff Shannon, Marc Eckl, Tim Wilkins, Derek van Westrum and Ryan Billson (2013):
The European Comparison of Absolute Gravimeters 2011 (ECAG-2011) in Walferdange, Luxembourg: results and recommendations. Metrologia **50,** 257–268.

Francis, O., and van Dam, T. (2006):
Analysis of results of the International Comparison of Absolute Gravimeters in Walferdange (Luxembourg) of November 2003. In: Cahiers du Centre Europeen de Geodynamique et de Seismologie 26, 1-23, Luxembourg.

Francis, O., van Dam, T., Germak, A., Amalvict, M., Bayer, R., Bilker-Koivula, M., Calvo, M., D'Agostino, G.-C., Dell'Acqua, T., Engfeldt, A., Faccia, R., Falk, R., Gitlein, O., Fernandez, Gjevestad, J., Hinderer, J., Jones, D., Kostelecky, J., Le Moigne, N., Luck, B., Mäkinen, J., McLaughlin, D., Olszak, T., Olsson, P., Pachuta, A., Palinkas, V., Pettersen, B., Pujol, R., Prutkin, I., Quagliotti, D., Reudink, R., Rothleitner, C., Ruess, D., Shen, C., Smith, V., Svitlov, S., Timmen, L., Ulrich, C., Van Camp, M., Walo, J., Wang, L., Wilmes, H., Xing, L. (2010):

Results of the European Comparison of Absolute Gravimeters in Walferdange (Luxembourg) of November 2007. In: Mertikas, Stelios P. (ed.): “Gravity, Geoid and Earth Observation”, IAG Symp. 135: 31-36, Springer, Berlin, Heidelberg.

Francis, Olivier; Baumann, Henri; Ullrich, Christian; Castelein, Stefaan; Camp, Michel Van; Sousa, Mauro Andrade De; Melhorato, Rodrigo Lima; Li, Chunjian; Xu, Jinyi; Su, Duowu; Wu, Shuqing; Hu, Hua; Wu, Kang; Li, Gang; Li, Zhe; Hsieh, Wen-Chi; Pálinkás, Pecný Vojtech; Kostelecký, Jakub; Mäkinen, Jaakko; Näränen, Jyri; Merlet, Sébastien; Santos, Franck Pereira Dos; Gillot, Pierre; Hinderer, Jacques; Bernard, Jean-Daniel; Moigne, Nicolas Le; Fores, Benjamin; Gitlein, Olga; Schilling, Manuel; Falk, Reinhard; Wilmes, Herbert; Germak, Alessandro; Biolcati, Emanuele; Origlia, Claudio; Iacovone, Domenico; Baccaro, Francesco; Mizushima, Shigeki; De Plaen, Raphaël; Klein, Gilbert; Seil, Marc; Radinovic, Remi; Sekowski, Marcin; Dykowski, Przemyslaw; Choi, In-Mook; Kim, Min-Seok; Borreguero, Ana; Sainz-Maza, Sergio; Calvo, Marta; Engfeldt, Andreas; Agren, Jonas; Reudink, René; Eckl, Mark; Westrum, Derek Van; Billson, Ryan; Ellis, Brian (2015):
CCM.G-K2 key comparison. Metrologia 52(1A), Technical Supplement 2015, 07009.
http://iopscience.iop.org/0026-1394/52/1A/07009

Jiang, Z.; Pálinkás, V.; Arias, F.E.; Liard, J.; Merlet, S.; Wilmes, H.; Vitushkin, L.; Robertsson, L.; Tisserand, L.; Pereira Dos Santos, F.; Bodart, Q.; Falk, R.; Baumann, H.; Mizushima, S.; Mäkinen, J.; Bilker-Koivula, M.; Lee, C.; Choi, I.M.; Karaboce, B.; Ji, W.; Wu, Q.; Ruess, D.; Ullrich, C.; Kostelecký, J.; Schmerge, D.; Eckl, M.; Timmen, L.; Le Moigne, N.; Bayer, R.; Olszak, T.; Ågren, J.; Del Negro, C.; Greco, F.; Diament, M.; Deroussi, S.; Bonvalot, S.; Krynski, J.; Sekowski, M.; Hu, H.; Wang, L.J.; Svitlov, S.; Germak, A.; Francis, O.; Becker, M.; Inglis, D.; Robinson, I. (2012):
The 8th International Comparison of Absolute Gravimeters 2009: the first Key Comparison (CCM.G-K1) in the field of absolute gravimetry. Metrologia 49, 666–684, doi:10.1088/0026-1394/49/6/666.

Niebauer T. M., G. S. Sasagava, J. E. Faller, R. Hilt, F. Klopping (1995):
A new generation of absolute gravimeters. Metrologia, Vol. 32, 159-180.

Niebauer, T. M., Billson, R., Schiel, A., van Westrum, D., Klopping, F. (2013):
The self-attraction correction for the FG5X absolute gravity meter. Metrologia, Vol. 50, 1-8.

Timmen, L. (2003):
Precise definition of the effective measurement height of free-fall absolute gravimeters. Metrologia, Vol. 40, 62-65.

Timmen, L. (2010):
Absolute and relative Gravimetry. In: Guochang Xu (ed.), Sciences of Geodesy-I, Advances and Future Directions, 1-48, Springer, 2010.
http://link.springer.com/chapter/10.1007/978-3-642-11741-1_1#page-1

Timmen, L., Wenzel, H.-G. (1995):
Worldwide synthetic gravity tide parameters. In: H. Sünkel and I. Marson (Eds.), Gravity and Geoid, Proceed. IAG Symp. No. 113, 92-101, Springer-Verlag Berlin Heidelberg New York, 1995.

Annex:

Absolute gravity site occupied with the Hannover absolute gravimeter FG5X-220 in June 2015: Bad Frankenhausen ("Rathaus"); for relative gravimetry, an outdoor point has been established in front of the town hall, and the top of the wall bolt (levelling bench mark) is the reference height of the Δg result. The horizontal distance to the wall bolt is 30 cm.