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# Traceability of the Hannover FG5X-220 to the SI units

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The absolute measurement of $g$ is currently realized through the laser interferometric measurement of a free falling retro-reflector. The Micro-g LaCoste FG5X is a free-fall gravimeter with a laser interferometer in Mach-Zehnder configuration which uses simultaneous time and distance measurements to calculate the absolute value of $g$. Because the instrument itself contains the necessary working standards for precise time and length measurements, it is considered independent of external references. The timing is kept with a 10 MHz rubidium oscillator with a stability of $5 \times 10^{-10}$. The length unit is realized by the laser interferometer. The frequency calibrated and iodine stabilized helium-neon laser has a wavelength of 633 nm and an accuracy of $2.5 \times 10^{-11}$.

In 2012 the FG5-220 of the Institut für Erdmessung (IfE) was upgraded to the FG5X-220. The upgrade included a new dropping chamber with a longer free fall and new electronics including a new rubidium oscillator. The metrological traceability to measurement units of the Système International d'unités (SI unit) is ensured by two complementary and successive approaches: the comparison of frequencies with standards of higher order and the comparison of the measured $g$ to a reference measured by absolute gravimeters defined as primary standards within the SI. A number of experiments to test the rubidium oscillator were performed. The oscillator showed a linear drift of $0.2 \times 10^{-3}$ Hz per month ($= 0.3\,\mathrm{nm\,s^{-2}}$ per month) in the first 18 months of use. A jump in the frequency of 0.01 Hz ($= 20\,\mathrm{nm\,s^{-2}}$) was revealed recently and the drift rate changed to $-0.4 \times 10^{-3}$ Hz/month.

Since the upgrade of the absolute gravimeter the instrument participated in several international comparisons, which showed no significant measuring offset between the instrument prior and after the upgrade.

**Schlagworte:** absolute gravimetry, frequency standard, gravimeter comparison, SI units

## 1 Introduction

Absolute gravimetry allows monitoring of secular gravity variations over time spans of several years to decades. Postglacial land-uplift in northern Europe is just one example of slow changes which have been measured by the Hannover absolute gravimetry group (Gitlein et al., 2008; Timmen et al., 2011). In the center of the Fennoscandian land uplift area gravity decreases with approximately $20\,\mathrm{nm\,s^{-2}}$/year. The determination of this rate and even smaller ones further away from the central area, requires annual measurements for at least 5 to 10 years with current generation absolute gravimeters. These instruments reach a long-term stability of $20\,\mathrm{nm\,s^{-2}}$ or even better in the occupied laboratories. For most applications in geodynamics the observation of temporal gravity variations are important and a constant measuring offset to the true value of $g$ can be accepted. For the reproducibility of the instruments measurement a stable offset to the true value of $g$ over several years is a necessity. Otherwise, an unknown change of the offset might be interpreted as a geophysical signal. A rigorous control of the absoulte accuracy with respect to a true gravity value at the moment 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, international key comparisons are organized periodically with absolute gravimeters as primary standards maintained by national metrology institutes or designated institutes. These key gravimeters define official reference values within the traceability chain of SI for all sites occupied by the key instruments and are provided to the other participating gravity meters, see e. g. Francis et al., 2015. In addition, two or more gravimeters may be combined within a geodynamics project, and the offsets between the instruments are controlled by episodic comparisons during the project live time outside of the official traceability chain (Timmen et al., 2015).

The most commonly used absolute gravimeters are the Micro-g LaCoste FG5 and the latest development, the FG5X (Niebauer et al., 1995; Niebauer et al., 2013). Micro-g LaCoste offers an upgrade from the FG5 to the FG5X, in which major parts of the instrument are replaced.

The Hannover FG5-220 was upgraded in 2012 which leads to two questions: 1) How well can absolute gravimeter measurements be traced back to the SI units for comparability?, and 2) How does the FG5-220 upgrade affect the comparability of measurements performed prior and after the aforementioned upgrade?

## 2 The absolute gravimeters FG5-220 and FG5X-220

After 10 years of reliable deployment without hardware updates the FG5-220 was upgraded to the FG5X-220 (cf. Fig. 1) in 2012. The upgrade included a new dropping chamber. The drag-free cart is now mounted centrically between opposing sides of the lifting mechanism, and counterweights are added, accelerating in the opposite direction of the test mass to minimize vibrations and reduce recoil effects. The free-fall time was extended by 50 ms corresponding to a change of length from 20 cm to 31 cm. The elongated dropping distance resulted in a change of the instrumental reference height[1] from approximately 120 cm to 125 cm. The number of interferometer fringes used for the calculation of $g$ doubled from 600 to more than 1200. This corresponds to every 1000th acquired fringe for the FG5-220 and every 800th acquired fringe for the FG5X-220. These numbers vary between different FG5(X) currently employed. The complete electronics were replaced in addition to the new dropping chamber. This includes the rubidium oscillator, discriminator circuit for fringe detection, and superspring controller. The superspring itself and the laser system were not replaced. Due to the different hardware components the self attraction correction changed from $-15\,\mathrm{nm\,s^{-2}}$ to $-12\,\mathrm{nm\,s^{-2}}$ (Niebauer et al., 2013).

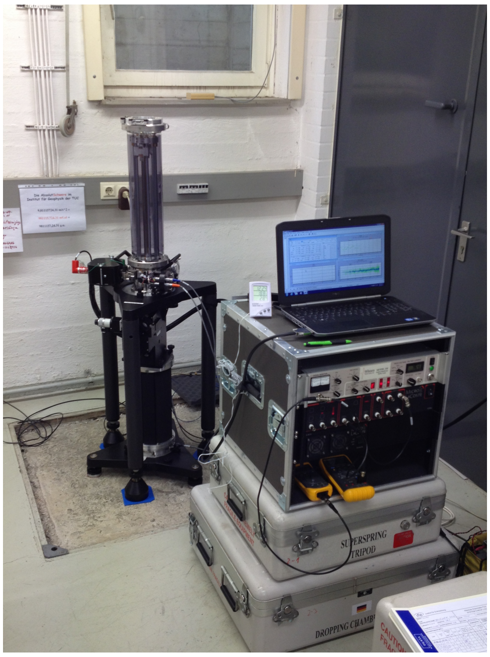

***Figure 1:*** *FG5X-220 at the Institute for Geophysics, Clausthal University of Technology, Germany.*

## 3 Traceability of the FG5X-220

The traceability of absolute gravimeter measurements to SI units has most recently been described by the Working Group on Gravimetry (CCM-WGG) of the Consultative Committee for Mass and Related Quantities (Marti et al., 2015). In general, the traceability can be established by a) the independent calibration of the integrated working standards, and b) by comparison of the instrument with a reference instrument (primary standard) or station (measured with a primary standard). These two approaches are not mutually exclusive and should be combined. Absolute gravimeters like the FG5(X) incorporate two frequency units. First, a 10 MHz rubidium oscillator provides the timing. Secondly, the frequencies of an iodine stabilized helium-neon laser are calibrated and are defining the corresponding wavelengths. Those are used for scaling the interference measurements within

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[1] This is the reference height above floor level in which the vertical gravity gradient does not affect the derived $g$-result.

the laser displacement interferometer. The latter realizes the length unit of the gravimeter (Vitushkin, 2011, 2015). Additional external references are not needed. But even proper calibration of these working standards does not ensure correct measurements of $g$. It should be mentioned that the calibration of frequencies is usually not performed on drop level timescales of a few tenths of a second, but with averaging over durations of minutes to hours (Vitushkin, 2015). The comparison with a reference, on the other hand, is a test of the whole instrument. This includes a proper calibration of the absolute gravimeters barometer and the setup of the interferometer with the fringe acquisition components. The latter is necessary because the diffraction correction is beam waist dependent (Robertsson, 2007) and measured $g$ varies with fringe signal amplitude and distortion (Křen et al., 2015). These effects combined can reach some tens of $\mathrm{nm\,s^{-2}}$. Additionally, the instrumental setting itself is to some degree ($10\,\mathrm{nm\,s^{-2}}$ to $20\,\mathrm{nm\,s^{-2}}$) influenced by the operator, e. g. due to imprecise verticalisation of the instrument.

## 3.1 Standards of time and length

**Rubidium oscillator** The 10 MHz rubidium oscillator of the FG5 is originally described by Niebauer et al., 1995[2]. The relative uncertainty of the frequency is given with $3.4 \times 10^{-10}$ and a linear drift of $4 \times 10^{-11}$/month which translates to $0.4 \times 10^{-3}$ Hz/month. The effect of a difference between the nominal and actual frequency of $\Delta f = 5 \times 10^{-3}$ Hz corresponds to a systematic change in gravity of $10\,\mathrm{nm\,s^{-2}}$. If $0.4 \times 10^{-3}$ Hz/month is the upper limit of the drift, an annual calibration of the rubidium oscillator would be sufficient to keep the influence of the accumulated drift below $10\,\mathrm{nm\,s^{-2}}$.

The FG5X-220 electronics includes a new rubidium oscillator requiring a new characterisation. A GPS receiver is also incorporated in the FG5X electronics, allowing a GPS disciplined operation of the FG5X rubidium. However, this feature is not used, because most stations do not offer the possibility to connect to a GPS antenna outdoors. During measurements at geodetic observatories or metrology institutes the FG5X rubidium oscillator is compared to the local frequency standards of higher order accuracy ($1 \times 10^{-14}$ or even better). In Hannover and during longer campaigns a GPS stabilized rubidium clock (GRP[3]) is compared with the FG5X rubidium oscillator. With GPS stabilisation the GRP accuracy is given with $2 \times 10^{-12}$. Without GPS assistance the accuracy is $1.5 \times 10^{-11}$ $\left(5 \times 10^{-11}\right)$ after a day (month) of free run. During a comparison with a 10 MHz signal provided by the local hydrogen maser at the Onsala Space Observatory (OSO, Sweden) the frequency of the GRP oscillator without GPS assistance deviated by $0.3 \times 10^{-3}$ Hz from 10 MHz.

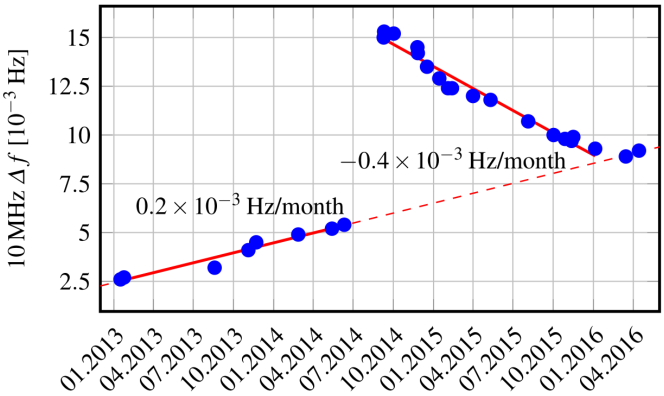

***Figure 2:*** *Frequency comparison of FG5X-220 rubidium oscillator with reference oscillators. The jump in frequency in July 2014 might be caused by a helium event and would result in an error of* $20\,\mathrm{nm\,s^{-2}}$*, if not corrected.*

The FG5X-220 rubidium oscillator is usually compared with the GRP oscillator prior to measurement campaigns. The comparison of the FG5X-220 rubidium oscillator at institutions offering a 10 MHz reference allows the indirect comparison of the GRP oscillator with the FG5X rubidium as traveling standard. The results of all frequency comparisons are shown in Fig. 2. During the first 18 months of deployment the rubidium oscillator showed a linear drift of $0.2 \times 10^{-3}$ Hz/month. After a stay at the Black Forrest Observatory in Schiltach (BFO, Germany) for the calibration of the local superconducting gravimeter (SG) a jump in the FG5X-220 rubidium oscillator of $10 \times 10^{-3}$ Hz was discovered using the GRP oscillator and confirmed during a visit at a metrology institute. This is equal to a change in measured $g$ of $20\,\mathrm{nm\,s^{-2}}$. The most likely cause is an intrusion of atmospheric helium into the rubidium cell (Riehle, 2004; van Westrum et al., 2014), as the underground laboratory in Schiltach is not ventilated and helium can ac-

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[2] The FG5-220 featured a Datum LPRO rubidium oscillator and the FG5X-220 a Microsemi (formerly Symmetricon) SA.22c rubidium oscillator. Both oscillators are comparable in stability and drift to the original Efratom FRK-L.

[3] Meinberg GPS-receiver Rubidium Portable (GRP) frequency reference.

cumulate in the tunnel leading to the superconducting gravimeter. The FG5X-220 was installed at BFO for approximately 48 hours. Similar effects have been reported, e. g., by Mäkinen et al., 2015. In theory this effect can be avoided by not measuring in the vicinity a superconducting gravimeter, which bear the risk of a higher helium concentration in the air. This is, however, an unlikely scenario as SGs depend on FG5 measurements for calibration and drift determination. It should also be noted that the FG5X-220 measured alongside several SGs, e. g., for almost two weeks of continuous operation at OSO in February 2015, without an effect on the rubidium oscillator. The more likely course of action is to limit the time of exposure to potentially higher helium concentrations (e. g. after helium refill or coldhead change of the SG) of the affected FG5X and to monitor the rubidium frequency directly prior and after a co-location with a SG. After the detection of the frequency jump the FG5X rubidium oscillator was compared more often to a reference to determine the development of the effect. The resulting drift was $-0.4 \times 10^{-3}$ Hz/month, although an exponential function is a better fit. Both van Westrum et al., 2014 and Mäkinen et al., 2015 observed, that keeping the rubidium oscillator turned on supports a quicker reversal to the original driftrate. The FG5X-220 is only powered on during measurements, thus elongating the time for reversal. It is still under investigation if the driftrate reverts to $0.2 \times 10^{-3}$ Hz/month. The last two comparisons shown in Fig. 2, conducted by the Mexican national metrology laboratory (CENAM, Querétaro) and after air transport back to Hannover, align with the projected drift of the first 18 months of operation.

**Laser** The WEO Model 100 laser in the FG5 and FG5X is an iodine stabilized helium-neon laser with a wavelength of 633 nm, a frequency reproducibility of 5 kHz and a relative frequency stability of $2 \times 10^{-13}$ (Chartier et al., 1993). This implementation is a realization of the definition of the SI meter by the Comité International des Poids et Mesures (Quinn, 2003). The length unit itself is established by the interferometric measurement. The wavelengths of laser light resulting from the peaks of iodine spectroscopy are determined by the manufacturer and are, up to now, not directly compared to a reference. For the Hannover FG5(X)-220[4], Winters Electro-Optics, Inc., specifies a frequency accuracy of $2.5 \times 10^{-11}$ for the WEO Model 100 laser (S/N 193). A significant change of frequency would be uncovered during comparisons with other absolute gravimeters. The other aforementioned effects related to the laser interferometer are accounted for by careful setup and adjustment (e. g. beam waist diameter, fringe signal amplitude) of the instrument.

## 3.2 Comparison of the instrument with a reference in g

The $g$-result of absolute gravimeter measurements depends not only on the calibration of working standards but also on the setup and measurement protocol followed by the operators. It is possible to judge the performance of the whole instrument and ensure its traceability to the SI unit by comparison with a reference. However, there is no absolute gravimeter of higher order accuracy available for the FG5(X). The reference is, as described in Marti et al., 2015, provided either by a group of absolute gravimeters during a key comparison (KC) or at a reference station monitored by an independently calibrated and validated absolute gravimeter and possibly a continuously recording SG.

**Comparison of absolute gravimeters** Gravimeter comparisons in Europe are currently organized every two years, alternating between International and European Comparisons of Absolute Gravimeters (ICAG and ECAG or CCM.G-K$x$ and EURAMET.M.G-K$x$ according to the CIPM MRA[5]). ICAGs were held directly at the Bureau International des Poids et Mesures (BIPM) until 2009. Since 2013 the ICAG is held in the Walferdange Underground Laboratory for Geodynamics, which also hosts the ECAG. At these comparisons, with more than 20 attending absolute gravimeters, the instruments measure simultaneously during several setups. The attendees from national metrology institutes (NMI) and designated institutes (DI) participate in the KC. The key comparison reference value (KCRV) including its uncertainty of each measurement position is calculated from these measurements. All other attending gravimeters, including the FG5(X)-220, participate in the pilot study (PS). Their measurements, or more specifically the measured differences on the different positions, enter the adjustment of the KCRV as constraints. The result of the comparison is the degree of equivalence (DoE, Cox, 2002) and the compatibility index $E_n$ (Steele and Douglas, 2006) for each

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[4] FG5(X)-220 refers to the original FG5-220 and the upgraded version.

[5] Comité International des Poids et Mesures Mutual Recognition Arrangement, a framework ensuring the comparability of national metrology services.

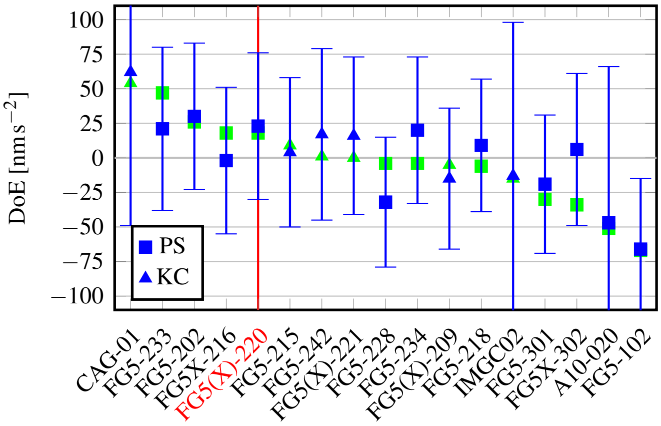

***Figure 3:*** *Result of common instruments of ECAG-2011 and ICAG-2013 in Walferdange (Luxembourg) sorted by degree of equivalence of ECAG-2011 (Francis et al., 2013, 2015). Error bars represent the RMS of the expanded uncertainties of three setups of the AG in ICAG-2013. Instruments identified as FG5(X) were upgraded between ECAG-2011 and ICAG-2013.*

absolute gravimeter measurement. The DoE is essentially the average difference between the measured gravity $x_i$ and the KCRV $x_{i,KCRV}$ of position $i$ over $n$ setups of the respective gravimeter:

$$DoE = \frac{\sum_{i=1}^{n} x_i - x_{i,KCRV}}{n} \tag{1}$$

The compatibility index $E_n$ is the ratio of the difference between measured gravity and KCRV, and the expanded uncertainty $u$ (k=95%) of this difference:

$$E_n = \frac{x_i - x_{i,KCRV}}{\sqrt{u^2(x_i) + u^2(x_{i,KCRV})}} \tag{2}$$

A ratio larger than 1 indicates that the measured gravity value $x_i$ and the KCRV for the same position are not compatible. Only a single measurement out of more than 70, performed by all participants during the last comparison, was not compatible with the final KCRV (Francis et al., 2015).

Comparisons are linked by common NMI/DI participants. For the full description of the levels and interconnections of absolute gravimeter comparisons and CIPM terminology, we refer to Marti et al., 2015.

Figure 3 shows the resulting DoE of the instruments which participated in both the ECAG-2011 (green) and ICAG-2013 (blue). The FG5-220 (highlighted in red) was upgraded to the FG5X-220 between these comparisons. Instruments participating in only one of these comparisons are omitted in Fig. 3 and the complete results can be found in Francis et al., 2013, 2015. The zero-level is determined by KC instruments only. The difference in DoE between the FG5-220 and FG5X-220 is 5 nm s$^{-2}$ only and not significant. For some instruments the change in DoE is above 20 nm s$^{-2}$, which is the level of stated uncertainty (reproducibility) for FG5 instruments. A more extensive collection of four international comparisons is described in Francis et al., 2013. The results of key comparisons are also listed in the key comparison database[6] starting in 2009.

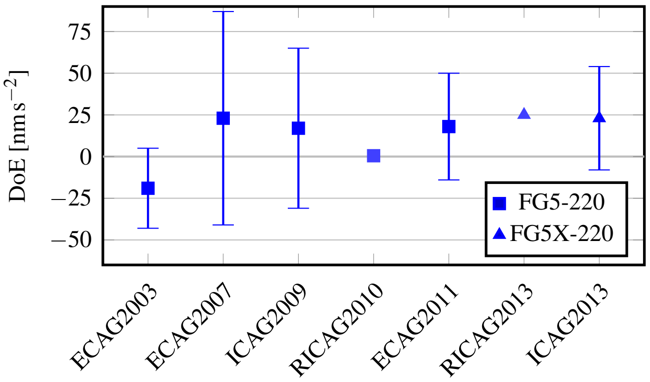

***Figure 4:*** *Regional and international comparisons of the FG5(X)-220 with uncertainties according to the respective final report (standard deviations of expanded uncertainties of multiple setups). RICAG are organized by the German Federal Agency for Cartography and Geodesy (BKG) in Wettzell with 6 participating AGs. The FG5(X)-220 results of RICAG are deviations to the mean of the participants. Because the RICAG results are not published yet, no error bars are depicted here.*

Figure 4 shows the results of all comparisons of absolute gravimeters the FG5(X)-220 participated in (Francis et al., 2005; Francis et al., 2010; Jiang et al., 2012; Francis et al., 2013, 2015). The listed results of RICAG are from comparisons carried out at the Geodetic Observatory Wettzell by the Federal Agency for Cartography and Geodesy (BKG, Germany). The number of participants in this regional comparison is relatively small and the plotted results for the FG5(X)-220 are the deviation of the mean from all six instruments. RICAG2013 was held in January and ICAG2013 in November of the same year. The result from ECAG2003 is most likely caused by a hardware fault which was discovered after the comparison. Generally, the DoE of the FG5(X)-220 shows only a small variation from 17 nm s$^{-2}$ to 25 nm s$^{-2}$ since 2007,

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[6] http://kcdb.bipm.org

documenting a stable level of measurements. Moreover, since the upgrade of the instrument, the level has not changed.

**Reference station** In addition to a comparison with a number of other absolute gravimeters (primary standards), a reference $g$ can also be provided at a station, which is measured by a gravimeter that participated in a KC, and which is carefully monitored by a SG. As suggested by the CCM-WGG (Marti et al., 2015), this only applies to locations monitored by NMIs and DIs, e. g. the respective home laboratory at a NMI/DI. IfE is not a NMI/DI but has a long history of gravimetric measurements at several stations which are used mainly for quality control between KCs. Clausthal is located in the Harz mountains close to Hannover and measurements started in 1986 with the JILAg-3 gravimeter.

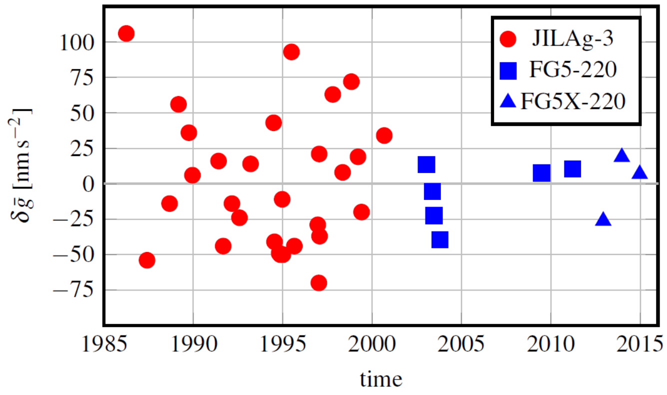

***Figure 5:*** *Measurements of IfE AGs at TU Clausthal since 1986. Results shown refer to a height of* 1.05 m, *the mean height between JILAg and FG5X reference height. A bias of* 90 nm s$^{-2}$ *was removed from JILAg-3 results (Timmen, 2010).*

Figure 5 shows the time series of all observations performed at the Institute for Geophysics, Clausthal University of Technology (Germany), with the Hannover gravimeters. The scatter of the JILAg-3 is also a result of its lower instrumental accuracy of about 50 nm s$^{-2}$ (Torge, 1991) compared to the FG5(X). The decline in the four observed $g$-values in 2003 should be connected to the very dry season in central Europe. The Geodetic Observatory Wettzell reported a decrease of 150 nm s$^{-2}$ in the same period of time (Creutzfeldt et al., 2012). No significant trend has been found in this time series of 30 years length. It should be noted, that a systematic bias of 90 nm s$^{-2}$ has been removed from all JILAg-3 measurements (Timmen, 2010). A similar bias was reported by the Austrian group for their JILAg gravimeter (Ruess and Ullrich, 2011). The Clausthal series does not reveal a systematic change in the measuring level between FG5-220 and FG5X-220. These episodic measurements serve as a validation for the correct functioning of the gravimeter showing its measuring strength and precision over a period of some days. Larger gravity variations occur during extreme weather conditions and seasonal hydrological variations. Clausthal is not a reference station in the scope of Marti et al., 2015.

The Hannover group has performed measurements at the Onsala Space Observatory since 2003. Onsala is located on the border of the Fennoscandian land-uplift area with only a small trend in uplift and the results have been published in Timmen et al., 2015. Here, the secular land-uplift trend serves also as a validating signal to prove the stability of the absolute gravimeter. Due to a large number of $g$-determinations, seasonal and short periodic variations as well as instrumental errors are averaged out to a certain extend, which helps to reveal a long-periodic trend after some years. The observational trend is compared with rates predicted by geophysical modeling. A measurement in February of 2015, which is not part of that publication, agrees within 10 nm s$^{-2}$ to the predicted trend.

The laboratory in Hannover itself is not well suited to characterize the long-term stability of the gravimeter due to hydrological effects and extensive construction work in close vicinity.

## 4 Summary

All modern absolute gravimeters hold incorporated working standards of length and time thus making measurements independent of external references. One method to establish the traceability to the SI units is by comparing these standards to those of higher order. Regular comparisons of the FG5X-220 rubidium oscillator showed a linear drift of $0.2 \times 10^{-3}$ Hz/month for the first 18 months of operation. A jump of 0.01 Hz in the frequency, equal to an offset of 20 nm s$^{-2}$, and the subsequent change of the drift rate to $-0.4 \times 10^{-3}$ Hz/month underlines the necessity for a regular validation of the rubidium oscillator. An adaptation of the measurement regime at superconducting gravimeter sites is needed for affected FG5(X) instruments with rubidium oscillators which are sensitive to helium gas concentrations in the air.

The second complementary method, which is also obligatory, is the regular comparison of the absolute gravimeter with references, either at key comparisons with other gravimeters (primary standards) or at reference stations. The participation at several international comparisons since 2007 with the FG5-220 and the upgraded FG5X-220 shows a non-significant variation of the respective DoE of less than $10\,\mathrm{nm\,s^{-2}}$ and no offset since the upgrade in 2012. In addition to the international comparisons, the time series at the stations Clausthal and Onsala, reoccupied episodically as required or annually, do also not indicate any change in the gravimeter measuring level after the upgrade of FG5-220 to FG5X-220 in 2012.

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