# GRAVITY MONITORING AT THE CONRAD OBSERVATORY

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## Abstract

**Key words**: absolute gravimeter, superconducting gravimeter, Rubidium oscillator drift, gravimeter drift

*The Conrad observatory (CO) (Austria) hosts a permanently running superconducting gravimeter (GWR C025) since 2007. Superconducting gravimeters do not measure the modulus of the gravity vector, but its temporal variation. In addition, they have a small instrumental drift. Therefore, they have to be calibrated regularly by absolute gravimeters observing common gravity signal side by side. Absolute gravity measurements at CO were performed by the absolute gravimeter JILAg-6 between 2007 and 2009 and by FG5-242 since 2010. The observation data is analyzed together with the SG results. Although the FG5 gravimeters represent the newest standard in absolute gravimetry, the measurements were affected by abnormal helium concentration in the gravity laboratory of the observatory originating from small but permanent liquid helium loss of the superconducting gravimeter. Therefore, all gravity measurements of the Austrian FG5/242 have been checked accurately for the oscillator influence. Since 2011 the pulse frequency of the oscillator and its drift rate are regularly checked at the BEV metrology department.*

## The SG at Conrad observatory (Austria)

Since 2007, the superconducting gravimeter (SG) GWR C25 has been operating at the seismological Conrad observatory (CO), a geodynamical research facility situated at 1045 m a.s.l. within the Northern Calcareous Alps (Austria), about 50 km SW of Vienna. CO consists of a 150 m long tunnel, which has been drilled into the mountain slope, for seismological instrumentation and, just in front of the tunnel, an underground building housing office and laboratory rooms. One of them is the gravity laboratory and contains the SG. The SG is installed on a huge pillar, which also offers space for hosting absolute gravimeters (AG). The latter are required for determining the SG scale factor (e.g. Francis et al. 1998; Hinderer et al. 2007) and the SG instrumental drift. It has to be pointed out, that AG and SG are in the same room during a calibration experiment without walls separating both instruments as at other SG sites. Calibration experiments have been repeated regularly at CO in order to achieve the scale factor with an accuracy better than 1 per mille (e.g. Van Camp et al. 2015). Absolute gravimeter observations were performed at least twice a year using the FG5-242 operating each time at the same point and with almost the same instrumental setup. Due to this strategy, there is no need for tying the AG observations to a common reference by relative gravimeters.

## Gravity error due to Rubidium oscillator frequency changes

Absolute gravimeters use Rb-oscillators for providing a sufficiently exact time reference. Exposure to atmospheric helium typically causes a permanent frequency increase of about 1 mHz/yr (Van Westrum 2014). Frequent calibrations with cesium-based GPS clocks are required to correct for time reference errors. If an AG operates side-by-side with a SG as commonly done for the determination of the SG scale factor, then the Rb oscillator might be exposed to an abnormal helium environment depending on the SG type and the experiment setting. This causes a strong increase of the pulse frequency (nominally 10 MHz) of the Rb-oscillator associated with an apparent gravity decrease if the frequency shift remains uncorrected. After the clock has been removed from the abnormal helium environment its pulse frequency decreases back towards the nominal value following an exponential decay. The decay rate depends on whether the oscillator is powered on or off (Van Westrum 2014). This clock oscillator frequency problem was widely unknown to the AG community, and never had been communicated by the AG manufacturer before Van Westrum (2014) or Mäkinen et al. (2015) firstly published papers quantifying the effect of helium contamination on the results of absolute gravity observations. Mäkinen et al. (2015) show that the helium influence on the Rb-oscillator depends on the individual Rb-oscillator type as well. For the first time, they present observed Rb-oscillator offset time series and link them to the helium exposure typically appearing at SG sites.

The gravity error caused by a variable clock frequency can be simply estimated. The gravity $g$ results from measuring the time $\Delta t$ taken by the falling object when passing the falling distance $\Delta s$. $\Delta t$ is calculated by counting the number $n$ of pulses provided by a Rb-oscillator with the pulse frequency $f$:

$$g \approx \frac{2\Delta s}{\Delta t^2} = \frac{2\Delta s}{n^2} f^2 .$$

If the Rb-oscillator frequency varies, the number $n$ varies as well for the same time interval $\Delta t$. Let be $f_e$ and $n_e$ be the actual frequency and the number of pulses respectively. Since

$$\frac{f^2}{n^2} = \frac{f_e^2}{n_e^2} \quad \Rightarrow \quad n_e^2 = n^2 \frac{f_e^2}{f^2}$$

we get an erroneous gravity $g_e$, if we use $f$ instead of $f_e$:

$$g_e \approx \frac{2\Delta s}{n_e^2} f^2 = g \frac{f^2}{f_e^2} .$$

Therefore, the error in gravity $\Delta g$ reads as

$$\Delta g = g_e - g \approx g\left(\frac{f^2}{f_e^2} - 1\right)$$

and is about -2 nm/s$^{-2}$ for an increase of 1 mHz when $f$ is equal to 10 MHz. Mäkinen et al. (2015) report on SG related helium release events at Metsähovi (Finland). They caused an episodic frequency increase of roughly 50 mHz, which would mimic an apparent gravity change of about -100 nm/s$^{-2}$.

**Comparison of AG and SG observations at CO**

Absolute gravity measurements with FG5-242 have been performed at the CO since 2010. As the phenomenon of the oscillator frequency bias was unknown at the beginning, there was no reason to keep the Rb-oscillator outside the room housing the SG. Both laser and Rb-oscillator were calibrated regularly at the metrology department of the Federal Office of Metrology and Surveying (BEV) since October 2011. Table 1 presents the history of AG observations, Rb-oscillator calibrations and SG maintenance work that might be associated with an increased helium release.

The first calibration of the Rb-oscillator in October 2011 revealed a strong downward drift of 125 mHz/yr although the oscillator was never exposed directly to an abnormal helium gas concentration as, for example, during the liquid helium refill or other SG maintenance work. Obviously, the permanent helium flow into the laboratory due to evaporation of liquid helium inside the SG dewar causes considerable gas concentration within the laboratory. The SG dewar contains 125 liters of liquid helium. The average helium loss is 0.17% per day under normal operating conditions equivalent to 0.2 liters/d, which diffuses into the air volume of approximately 220 m$^3$. Considering the ratio between the density of liquid and gaseous helium this amount of helium gas needs a volume of 0.15 m$^3$. This is less than 1‰ of the air volume in the room, but much when compared to the helium content of the Earth's lower atmosphere which is of 5.222 ± 0.017 ppm by volume (Oliver et al. 1984). However, how much helium remains in the room or diffuses towards outside is unknown. Therefore, the increase of the helium concentration due to permanent helium source is unknown as well. The next Rb-oscillator calibration in January 2012 showed a large drift again and increased measurement uncertainty. Therefore, the clock was replaced by a new one and the old clock was sent back to the manufacturer. However, after storing the AG in the CO gravity laboratory the new Rb-oscillator was again outside the normal drift rate (Figure 1). The third Rb-oscillator was purchased in 2013 and is operated outside the gravity laboratory since then.

| date | | | Rb-oscillator frequency | | | |
|---|---|---|---|---|---|---|
| | | | Offset [mHz] | Drift [mHz/d] | # | |
| 2010 05 20 | | | | | | HR |
| 2010 09 23 – 09 28 | A | | | | 1 | |
| 2010 11 16 – 11 17 | A | | | | 1 | |
| 2010 11 18 | | | | | 1 | CM |
| 2010 12 03 – 12 06 | A | | | | 1 | |
| 2011 06 09 – 06 18 | A | | | | 1 | |
| 2011 06 30 | | | | | | HR |
| 2011 08 20 | | | | | | CM |
| 2011 09 06 | | | | | | CM |
| 2011 10 21 – 10 24 | | C | 50.1 | -0.34 | 1 | |
| 2011 11 21 – 12 01 | A | | | | 1 | |
| 2011 12 20 – 12 28 | | C | 67.3 | -0.56 | 1 | |
| 2012 01 11 – 01 19 | | C | 60.8 | -0.54 | 1 | |
| 2012 01 31 | | C | 1.1 | | 2 | |
| 2012 02 08 | A | | | | 2 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| 2012 04 27 – 05 03 | | C | 169.5 | -1.61 | 2 | |
| 2012 05 31 – 06 10 | A | | | | 2 | |
| 2012 06 12 – 06 22 | | C | 196.9 | -1.87 | 2 | |
| 2012 06 13 | | | | | | HR |
| 2012 10 04 | A | | | | | |
| 2012 11 25 | | C | 424.0 | | 2 | |
| 2013 01 07 – 01 17 | A | | | | 3 | |

Table 1: History of absolute gravimeter observations (A), Rb-oscillator frequency calibrations and SG maintenance work (HR: liquid helium refill, CM: coldhead maintenance) associated with increased helium release. Rb-oscillator type: Symmetricom SA.22c (#1 and 2), Chronos GPS disciplined Rb-clock (#3)

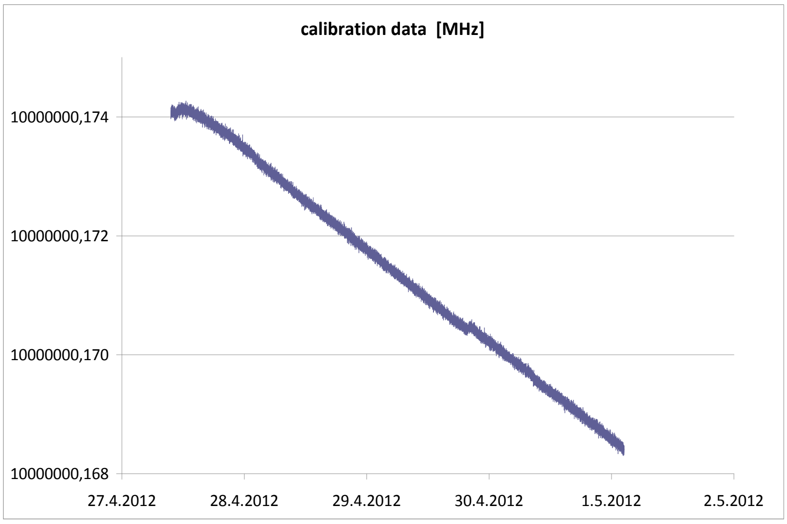


Fig. 1. Drift rate of the Rb-oscillator (about 5 mHz in 4 days), after storing the AG for a few months at CO.

Therefore, all gravity measurements of FG5-242 ever performed were reprocessed carefully trying to eliminate the effect of the frequency shift where possible. Corrections were based on the frequency offsets detected at the BEV metrology department (see Table 1). When applying these numbers, AG results of the same instrument outside the gravity laboratory of CO are within the usual FG5 measurement uncertainty, which was demonstrated at the international intercomparison campaigns at Walferdange in 2011 and 2013 (Francis et al. 2013, 2015).

AG observations have been evaluated using the g-soft version 9 software package provided by Microg-LaCoste Inc.. Air pressure variations with respect to the mean pressure value at the site are corrected for by applying a single admittance factor of -3.0 nms$^{-2}$/hPa. The tides are modeled by adding the Schwiderski ocean load to the Earth body tides using an amplitude factor of 1.160 for long period tides. The gravity pole tides are considered with an amplitude factor of 1.164 based on IERS data.

The SG residuals are calculated by subtracting a local tide model from the observed gravity. The tide model was derived from the tidal analyses including the pole tide and the LOD correction. The amplitude factors for the long period constituents, pole tide and air pressure admittance are the same as used for the AG data. The average differences in the tidal models are roughly 1 nms$^{-2}$ and thus far below the AG accuracy.

Figure 2 shows the comparison of AG (green dots) and SG residuals (red) in which hydrological effects dominate. During the snow accumulation (pink) or heavy rainfall (magenta) gravitationally effective masses are located largely above the SG sensor due to terrain and station geometry and thus produce a decrease in observed gravity. If the amount of surface water exceeds a certain threshold, for example after rapid snowmelt or long-term rain, the water flows from the surface down below the SG sensor and causes a very rapid increase in residual gravity. The subsequent run-off process is much slower. It takes several weeks each until the residuals have recovered the undisturbed level again. Several events associated with periods of heavy rain or intensive snowmelt could be identified so far (Meurers et al. 2013).

The AG results in Figure 2 represent the average over all sets of an individual AG measurement. The first two series of AG observations in 2010 clearly reflect the helium contamination effect. Nevertheless, the AG observations fit quite well to the SG residuals. Repeated Rb-oscillator calibrations available since October 2011 provide results that are more reliable since that time, while there is some uncertainty before. The AG observations confirm the extremely low drift rate of the SG and the relevance of the hydrological effects observed at CO.

The downward drift in the AG drop results induced by Rb-oscillator frequency shift is visible in all experiments before 2013, when the Rb-oscillator was exposed to presumably abnormal helium concentration during operation. Since 2013, the clock has been operating outside the gravimeter laboratory. Figure 3 presents typical examples. The left-hand panel of Figure 3 shows the calibration experiment in May/June 2012. The long-term SG gravity residuals (red) reveal the local hydrological process described above and reflect the surface water flow from the topography (predominantly above the SG) down into the ground and storage below the SG sensor. The AG time series exhibits much stronger downward drift reflecting the effect of Rb-oscillator frequency increase due to abnormal exposure to helium. This situation has changed since the Rb-oscillator is separated from the gravity laboratory as in June 2013 (Figure 3, right panel): AG and SG residuals now fit together almost perfectly. Adjusting an appropriate model of the differential drift between SG and AG is therefore required for evaluating the SG scale factor correctly, otherwise the scale factor might be systematically biased (Meurers 2012).

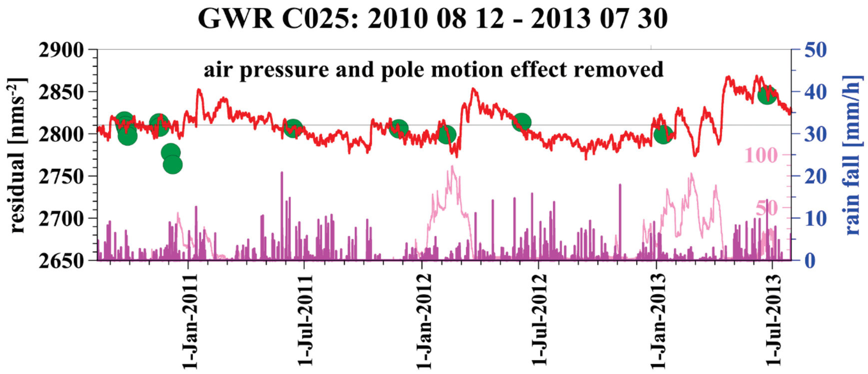


Fig. 2. Comparison of AG and SG residuals. Red: SG residuals, green: AG observations, magenta: hourly rainfall, pink: snow level [cm].

**Summary**

The drift of the Rb-oscillator used in AG measurements causes systematic errors. This effect was unknown at the beginning. Repeated oscillator calibrations revealed abnormal frequency drift rates as well as offsets, which, if not corrected for, biases the AG results. Regular oscillator calibrations started in October 2011 and allow for estimating the frequency offset. Reprocessing the AG measurements leads to improved gravity data, which match the SG residuals very well. They confirm the physical relevance of the hydrologically induced gravity signals and, in addition, suggest that the SG instrumental drift rate is close to zero. A comparison with the SG residuals in high temporal resolution reveals clearly the apparent gravity decrease associated with the helium contamination of the Rb-oscillator during operation. The frequency drift caused by the helium exposure, which generates an apparent AG drift is appropriately modelled in the adjustment procedure so that it does not affect the calibration of the SG scale factor.

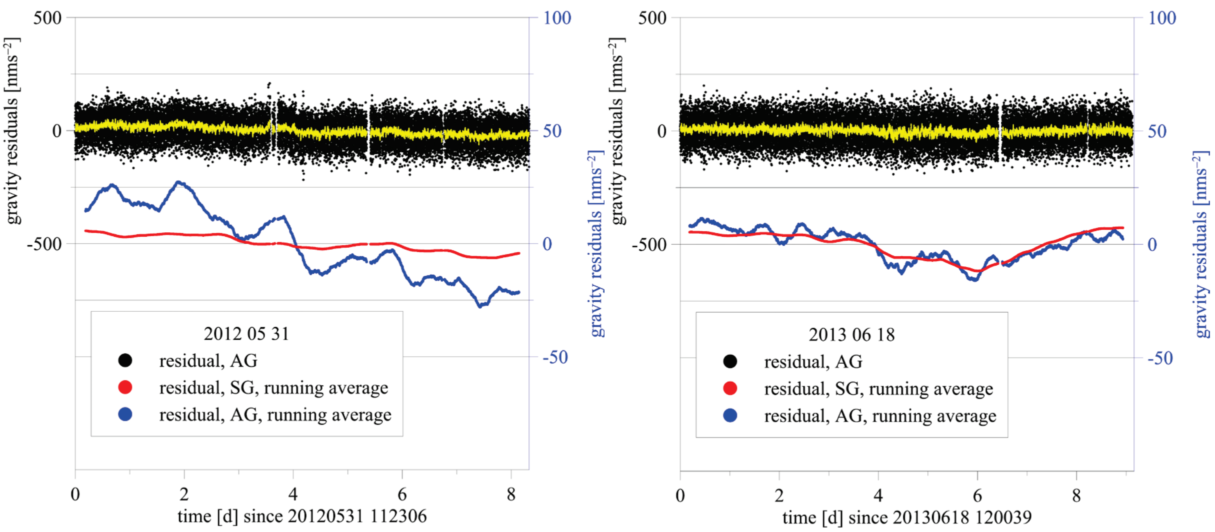


Fig. 3. Calibration experiments at CO in May/June 2012 (left) and in June 2013 (right). In contrast to 2013, the AG Rb-oscillator was exposed to abnormal helium gas in 2012. Black: single AG drops, yellow: their moving average (21 samples, yellow), red: SG residuals (moving average, 1001 samples), blue: AG drops (moving average, 1001 samples).

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