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Intercomparisons of the Absolute Gravimeters FG5-202, FG5-206 & FG5-209

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Michel Van Camp[1], Philippe Richard[2], Marc Hendrickx[1], Roger Siegenthaler[2], Simon Thies[2], B. Luck[3]

Bern (CH), June and November 2000, February-March and May 2002.
Membach (B), November 2002.

[1] Royal Observatory of Belgium, Avenue Circulaire, 3, B-1180 Bruxelles, Belgium. mvc@oma.be
[2]Swiss Federal Office of Metrology and Accreditation, metas, Lindenweg 50, CH-3003 Bern-Wabern, Switzerland. philippe.richard@metas.ch

[3]EOST, Strasbourg

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Introduction

Three inter-comparison campaigns between the FG5-202 and FG5-209 absolute gravimeters were performed during June and November 2000, and May 2002 (for the description of FG5 instruments, see e.g. Niebauer *et al.*, 1995). Another inter-comparison was also made between the FG5-206 and FG5-209 in February-March 2002. Measurements were held at METAS, the Swiss Federal Office of Metrology and Accreditation, located in Wabern (Bern) and previously named "Swiss Federal Office of Metrology OFMET". The comparisons took place from June 19th to 23rd, 2000, from November 20th to 24th, 2000, from February 27th to March 7th and from May 27th to 31st, 2002. The measurements were made in 2000 on two points inside the METAS building, on the floor of the ZA13 hall, and in 2002, on two points inside the new "Watt Balance" laboratory.

- The first 2000 point is MH, marked by a black pipe cover (46.924667° N, 7.4631944° E, 550.958*m*).
- The second 2000 point is ZA, marked by black concentric circles (46.924639° N, 7.4632222° E, 550.958*m*).
- The first 2002 point is WAN0 (46.923778°N, 7.464722°E, 546.5m)
- The second 2002 point is WANA (46.923778°N, 7.464722°E, 546.5m)

During the June campaign, several hardware and software problems occurred. The software problems affected both the FG5-202 and 209 gravimeters and were due to the Windows 95/98 "g" software (hereafter named "gsoft"), a new release from the FG5 manufacturer Micro-g. The hardware problems affected the FG5-202 instrument and were especially due to the GT650 card, which counts the interference fringes. This card was replaced in July 2000. Another malfunction was observed on June 28 on the auxiliary parameters (laser voltage) of the FG5-202. This was solved by immediately changing the defective "digital" wire. As problems were also diagnosed on the BSI acquisition PC, it was also replaced by a rack-mount PC in July 2000. Similarly the PC of the FG5-209 was replaced in October 2000.

During the November session, a bent delta rod flexure into the FG5-202 superspring caused noisy data during 2 days (individual set scatter of ~30-40$\mu Gals$). It concerns MH measurements from November 20 to 22 in the morning. After several attempts to straighten up the rod, the problem was solved.

No problem occurred in February-March and May 2002.

The vertical gravity gradient, necessary to calculate g, was measured in June using the CG-3M Scintrex gravimeter. Due to an instrumental breakdown, it was not possible to make the measurements again in November.

Up to now no vertical gravity gradient has been measured on the WAN0 and WANA points.

Calibrations

By comparing with the METAS standards, the barometers and rubidium clocks were calibrated during the June session. The FG5-202 clock was also calibrated 5 times in May 2002.

The results are:

In 2000:

– FG5-202:
  Pressure:
  P_{corr} = 1.0727 + 0.99831*P_{meas}. At a pressure of 950*hPa*, this correction removes 0.53*hPa*.
  Clock:
  Corrected rubidium frequency = 10 000 000.0030±0.0030 *Hz* (2000);
  = 10 000 000.0034±0.0003 *Hz* (2002).

– FG5-206:
  Pressure: no correction available
  Clock:

– FG5-209:
  Pressure:
  P_{corr} = -7.4181 + 1.0072*P_{meas}. At a pressure of 950*hPa*, this correction removes 0.58*hPa*.
  Clock:
  Corrected rubidium frequency = 10 000 000.0073*Hz* (2000). In 2002, the used clock was the METAS Caesium standard

In November 2000, a short comparison was performed between the 202 and 209 Rb clocks using a two-channel oscilloscope: a difference of 1/180*Hz* = 5.5 m*Hz* was found, which is compatible with the June calibration. Moreover, further calibrations performed in December on the FG5-209 clock with METAS standard give a correction of 0.0077*Hz*, compatible with the June one.

In 2001 :

– Using BIPM Cs :
  clock (202) = 10.000.000,0029 Hz
  clock (206) = 9.999.999,99913 Hz
  clock (209) = 10.000.000,0072 Hz

  → clock (206) = clock (202) – 3.77 mHz
  → clock (209) = clock (202) + 4.3 mHz

In 2002 :

– Feb. 2002 (EOST-J9): clock (209) = clock (202) + 2.5 mHz
– March. 2002 (Membach): clock (209) = clock (202) + 0.5 mHz
– Using METAS Cs :
  clock (202) = 10.000.000,0034 ± 0.0003 Hz (5 experiments).
  clock (206) = 10.000.000.000 Hz +/- 0.0015 Hz (sign of the correction unknown)
– Using 209 Rb: clock (209) = clock (202) + 4.6 mHz

The FG5-209 laser was successfully checked using METAS (2000) and BIPM (2001) standards. The FG5-202 laser was successfully checked using BIPM (1997 & 2001) standards.

The pressure corrections applied on the FG5#202 and FG5#209 were checked using METAS standard in 2002 and BIPM standard in 2001. The FG5-202 barometer was also checked using BKG standard in May 2002. It agrees with the METAS 2000 calibration at the 0.15 hPa level.

Note that a positive correction of 0.001Hz induces a positive gravity offset of +0.2*µGal*, and a positive offset of 1*hPa* in the air pressure induces a positive offset of +0.30*µGal*.

Absolute gravity measurements

Data processing details

Used softwares:

	Acquisition Version	Processing Version
June 2000		
FG5-202	g_0622	g_2.0321
FG5-209	g_0622	g_2.0321
November 2000		
FG5-202	Olivia	g_2.0321
FG5-209	g_1106a	g_2.0321
Feb.-March 2002		
FG5-206	Olivia	g_2.0708
FG5-209	g_1.0321	g_2.0708
May 2002		
FG5-202	Olivia	g_2.0321
FG5-209	g_1.0321	g_2.0708

Details:

- Files ".ddt", which were recorded with OLIVIA, were converted into .FG5 files using the "Convert" software.
- Unless indicated in Table 6, there is one set per hour, and each set contains 100 drops.
- The established barometer and clock calibrations were taken into account.
- In June and November 2000, due to the g data acquisition software, some barometer data of the FG5-209 instrument are missing, which produces a diminution of the gravity of about 250-300$\mu Gals$. When those bad data occur, they are automatically rejected when using a rejection sigma of 3.0. However, it does not work when too many pressure data are missing, which is often the case. So, a sigma of 2.5 was chosen for all 2000 FG5-209 data sets, which gives satisfaction.
- The vertical gravity gradients are: -3.058 $\mu Gal/cm$ (MH), –3.015 $\mu Gal/cm$ (ZA) (see below for detailed results), -3.1 $\mu Gal/cm$ (assumed for WAN0 and WANA).
- The polar motion coordinates are taken from the US-Navy web site: ftp://maia.usno.navy.mil/ser7/finals.data. The coordinates used for measurements taken during several days are the average of the daily coordinates. Example: for data recorded overnight between June 27 and 28 (file OFMET_ZA_27_06_00.FG5), the polar coordinates are obtained by averaging the June 27 and 28 ones).
- For the FG5-209 November measurements, due to an unexpected modification in the gsoft 1106 release, the channel 0 to 3 multipliers have to be modified in the "IOTech A2D Setup" parameters (Table 1):

Ch0 (Thermometer)	50 (instead of 100)
Ch1 (Superspring voltage)	0.5 (instead of 1)
Ch2 (Ion pump)	0.5 (instead of 1)
Ch3 (Laser voltage)	0.5 (instead of 1)

Table 1: IOTech A2D parameters for the November FG5-209 measurements.

- During the November campaign, we noticed an insufficient hold time after lifting the mass of the FG5-209: the corner cube stayed only a split second before being dropped, which could perturb measurements. The parameter “Pulse delay” was changed on November 22 from 5 to 7s, such that the hold time was about 2 seconds. However, we did not notice any change in the gravity measurements.

Laser voltage:
The FG5-209 laser peak voltages present a strong drift, making it difficult to monitor the selected peak. For example, the original laser voltages of the file OFMET_MH_24_06_00.FG5 are:
d: 0.56, e: 0.20, f: -0.03. If we process the whole 65 sets of this file, the drift is such that the measured laser voltages are interpreted as “e” peak for the sets 48 and 60 to 65, while the actual peak is “d”. In this case, we had to split the file up, using two voltage sets:
d: 0.56, e: 0.20, f: -0.03 for the first 47 sets and for the last 18 ones, d: 0.40, e: 0.20, f: -0.03. The laser drift was such that it was not possible to select only one laser voltage set for the whole file. For other files, this was however possible (e.g.: OFMET_MH10_11_00.FG5: for the whole file the laser voltages were modified to: d: 0.72, e: 0.34, f: 0.12, otherwise gsoft considers f instead of e for sets 9 to 12).
Another solution is to suppress the auto-peak detection option, but problems appear when peak fluctuations occur, which is the case for the OFMET_MH_24_06_00.FG5 measurements. However, this option works e.g. for the OFMET_MH_26_06_00.FG5 file.

No laser problem occurred during the May 2002 measurements. This is due to the very stable temperature conditions in the Watt laboratory.

Results

All the results are detailed in Table 2. In 2000, several g values result only from one or two data sets generally made to check e.g. the clock or a new set-up. Accurate values of g are obtained only after several sets. Only such results are shown in Figure 1 and 2 where we can see a higher scattering for the FG5-209 than for the FG5-202 measurements. On the other hand, we never noticed significant differences in the individual error bars: both instruments have similar noise characteristics.

Discussion

To study the differences between measurement points and between the instruments, we averaged the different gravity values. In 2000 the averages were calculated using the results given on the Figures 1 & 2, taking the June and November 2000 data separately, as well as together. Then, we subtracted the averages in order to study the differences.

Differences between FG5-202 and FG5-209

In June 2000, November 2000 as well as May 2002, significant differences were observed between the FG5-202 and 209 instruments, as shown in Table 2. There are discrepancies between these differences according to the locations and the campaigns.
One can see on Figure 1 and 2 that the FG5-209 gravity data are more scattered than the FG5-202 ones. For example, at the MH point, the FG5-209 gravimeter presents in itself a discrepancy of 7.56*µGals* between J9 and J13 and of 6.15 between N4 and N16. This explains the variations affecting the differences observed in Table 3.
In spite of this, a systematic effect of 4 to 10 *µGals* remains. After November 2000, a grounding problem due to a temporary 209 data acquisition system was solved by installing a rack-mount PC inside the electronic rack. A difference of about 6.8 µGal remained in May 2002 between the FG5-202 and 209, but was much more constant.
Notice that the FG5-202 and 209 provided much more similar results during the 2001 BIPM campaign.
We also calculated in Table 3 the differences between the June and November campaigns. The positive difference indicates a decrease of the gravity between June and November, which is however not significant.

BIPM 202 vs. 209	**Difference at point A**	**Difference at point B**
July 2001	-1.0	+2.1
Bern 202 vs. 209	**Difference at point MH**	**Difference at point ZA**
June 2000	2.44±3.87	0.09±1.44
November 2000	6.27±2.61	3.85±1.39
Average 2000	4.84±3.95	2.80±2.41
Bern 206 vs. 209	**Difference at point WAN0**	**Difference at point WANA**
Feb.-March 2002	1.63±1.78	2.50±2.20
Bern 202 vs. 209		
May 2002	6.95±1.50	6.69±0.90

Table 2: Differences [µGals] of the averaged gravity data between the FG5-202, the FG5-206 and the FG5-209 instruments for the June 2000, the November 2000, the February-March 2002 and the May 2002 campaigns. Results are given for the MH, ZA, WAN0 and WANA points. The averages are calculated using the values indicated by double stars in Table 6.

2000	Difference Nov.-June **(202)**	Difference Nov.-June **(209)**
MH	1.02±1.97	4.85±4.24
ZA	0.39±1.22	4.16±1.59

Table 3: differences of the averaged gravity data between the June and November campaigns, for the points MH and ZA, as well as for the FG5-202 and FG5-209 instruments. The averages are calculated using the values indicated by double stars in table 6.

Differences between the MH and ZA points

The results are given in the Table 4. For the gravimeter FG5-202 , all the results lie within the error bars. This is also the case for the FG5-209, but there is a systematic difference of about 2.5 *µGal* in comparison with the FG5-202. However, if we select only the N16-N34 (MH) and the N10-N12-N31-N33 (ZA) gravity series, we obtain a difference of 18.51±1.54 *µGals*, similar to the FG5-202 values. This asks the question of the FG5-209 reliability.

A horizontal gravity transfer was also made using the Scintrex spring gravimeter, at a level of 27.9 *cm*. Using 24 data at the ZA point and 18 at the MH point, after correcting for Earth tides and linear instrumental drift, we obtain 8.90±0.57 *µGal*, more than half the FG5-202 value. This result must be considered carefully because:

1. The difference of 18.33 *µGals* reaches the Scintrex's instrumental capacities;
2. The horizontal transfer is the last measurement made by the Scintrex gravimeter before we noticed a breakdown when trying to use it later in Belgium.

A new transfer should be performed again as soon as one or more spring gravimeters will be available.

2000	**FG5-202**	**FG5-209**	**Scintrex**
June	18.33±2.18	15.98±3.51	8.90±0.57

November	17.71±0.78	15.29±2.85	
All	18.02±1.55	15.98±4.36	

Table 4: Differences [µGals] of the averaged gravity data between points MH and ZA, as observed by the FG5-202 and the FG5-209 instruments for the June and November campaigns. The averages are calculated using the values indicated by double stars in Table 6. Value measured with the Scintrex spring gravimeter must be considered carefully.

Differences between the WAN0 and WANA points

The results are given in the Table 5. The results lie within the error bars.

2002	**FG5-202**	**FG5-206**	**FG5-209**
Feb.-March	n.a.	6.57±1.65	5.70±2.30
May	6.01±1.40	n.a.	5.75±1.10

Table 5: Differences [µGals] of the averaged gravity data between points WANA and WANO, as observed by the FG5-202, 206 and 209 instruments for the 2002 campaigns. The averages are calculated using the values indicated by double stars in Table 6

Control of the FG5-202 gravimeter

With the FG5-202 we make regular measurements at a reference station in order to ensure that the instrument remains in good working conditions.

These measurements are made at the reference station Membach (eastern Belgium) where the superconducting gravimeter GWR-C021 (Warburton & Brinton, 1995) is recording the gravity continuously. This allows us to monitor the gravity changes in time, due e.g. to the Earth tides, the ocean or atmospheric loading effects, or the water table variations.

As shown in Figure 3 and 4, the FG5-202 instrument was successfully controlled in Membach before and after the campaigns in Switzerland.

Date	Day #	Sets avail.	Point	Gravimeter #	File name Identification number	g [µGal]	Polar coordinates	Comments
June 2000	**202 Vs 209**							
24-06-2000	176	47	MH	209	OFMET_MH_24_06_00.FG5 (first part) J1	**980 588 035.82±1.48** **	x: 0.108049 y: 0.288624 (average 23→26)	laser voltage: d: 0.56, e: 0.20, f: -0.03
24-06-2000	176	18	MH	209	OFMET_MH_24_06_00.FG5 (second part) J2	**980 588 036.61±1.32** **	x: 0.108049 y: 0.288624 (average 23→26)	laser voltage: d: 0.40, e: 0.20, f: -0.03 (otherwise gsoft considers e in stead of d for sets # 48 & 60→65).
26-06-2000	178	12	ZA	209	OFMET_ZA_26_06_00.FG5 J3	**980 588 018.87±0.81** **	x: 0.108774 y: 0.286007 (average 26-27)	"e" peak selected (otherwise gsoft considers f in stead of e for sets # > 7).
		8	*MH*	*202*	*TEST.FG5* J4	***980 588 038.25±0.49*** **	x: 0.108774 y: 0.286007 (average 26-27)	
27-06-2000	179	20	ZA	209	OFMET_ZA_27_06_00.FG5 J5	**980 588 018.22.±0.92** **	x: 0.109258 y: 0.284661 (average 27-28)	
		5	*MH*	*202*	*OFMETMH0627.FG5* J6	***980 588 035.35±1.49*** **	x: 0.108994 y: 0.285334 (value 27)	Test file (1 set = 10 drops).
		20	*MH*	*202*	*OFMETMH0627b.FG5* J7	***980 588 039.02±0.83*** **	x: 0.109258 y: 0.284661 (average 27-28)	
28-06-2000	180	1	MH	209	OFMET_MH_28_06_00.FG5 J8	**Nihil**	x: 0.109529 y: 0.283954 (value 28)	Corrupted test file. One existing set but not recognised by the .FG5 file.
		15	MH	209	OFMET_MH_28_06_00a.FG5 J9	**980 588 030.20±1.58** **	x: 0.109794 y: 0.283433 (average 28-29)	
		2	*ZA*	*202*	*OFMETZA0628E.FG5*	***980 588 018.50±0.35***	x: 0.109529	Only 2 first sets usable (hardware

		(on 16)			J10	**	y: 0.283954 (value 28)	problem: defective GT650 card).
29-06-2000	181	15	*ZA*	*202*	*OFMET_ZA_0629.FG5* J11	***980 588 019.92±0.79*** **	x: 0.110129 y: 0.282205 (average 29-30)	Acquisition = PC FG5-209 (OFMET).
		1	MH	209	OFMET_MH_28_06_00b.FG5 J12	**980 588 033.42±13.60**	x: 0.110065 y: 0.282865 (value 29)	
30-06-2000	182	62	MH	209	OFMET_MH_30_06_00.FG5 J13	**980 588 037.76±0.98** **	x: 0.109974 y: 0.279397 (average 30→03)	
07-07-2000	189	15	ZA	209	OFMET_ZA_07_07_00.FG5 J14	**980 588 020.26±1.50** **	x: 0.107168 y: 0.274347 (average 06-07)	
November 2000	**202 Vs 209**							
10-11-2000	315	12	MH	209	OFMET_MH10_11_00.FG5 N1	**980 588 029.82±1.34** **	x: -0.065524 y: 0.299908 (average 10-11)	! Height: 12.05 (instead of 12.50) laser voltage: d: 0.72, e: 0.34, f: 0.12 (otherwise gsoft considers f in stead of e for sets # 9→12).
13-11-2000	318	14	MH	209	OFMET_MH13_11_00.FG5 N2	**980 588 028.61±1.78** **	x: -0.066571 y: 0.303231 (value 13)	! Height: 12.05 (instead of 12.50) Day 13/11/00. “e” peak selected (otherwise gsoft considers d in stead of e for sets #1 and > 8).
		15	MH	209	OFMET_MH13_11_00a.FG5 N3	**980 588 028.75±1.35** **	x: -0.067030 y: 0.304187 (average 13-14)	! Height: 12.05 (instead of 12.50) Night 13-14/11/00. “e” peak selected (otherwise gsoft considers f in stead of e for sets # > 5).
14-11-2000	319	14 (on 15)	MH	209	OFMET_MH14_11_00.FG5 N4	**980 588 027.43±2.02** **	x: -0.068337 y: 0.306055 (average 14-15)	! Height: 12.05 (instead of 12.50) Set #6 suppressed (too much bad barometric data).
15-11-2000	320	13 (on 15)	ZA	209	OFMET_ZA15_11_00.FG5 N5	**980 588 015.80±1.14** **	x: -0.070205 y: 0.307691 (average 15-16)	Sets # 14, 15 suppressed. Cause: Mb 5.9 earthquake New Ireland.
16-11-2000	321	15	ZA	209	OFMET_ZA16_11_00.FG5	**980 588 015.70±1.10**	x: -0.072191	

					N6	**	y: 0.309099 (average 16-17)	
17-11-2000	322	30	ZA	209	OFMET_ZA17_11_00.FG5 N7	**980 588 013.48±1.34** **	x: -0.073932 y: 0.310609 (average 17-18)	Sets #7-8-17 suppressed (earthquake).
20-11-2000	325	1	*MH*	*202*	*BNMH00325.ddt* N8	***980 588 032.65 ±27.838***	x: -0.075830 y: 0.315559 (value 20)	Problem superspring.
		0	*MH*	*202*	*BNMH00325a.ddt*	**Nihil**		Corrupted test file.
		15	*MH*	*202*	*BNMH00325b.ddt* N9	***980 588 036.24±1.11*** **	x: -0.075790 y: 0.316705 (average 20-21)	Problem superspring: high sigma (~30-40*μGals*) for each individual set.
		15	ZA	209	OFMET_ZA20_11_00.FG5 N10	**980 588 016.28±1.25** **	x: -0.075790 y: 0.316705 (average 20-21)	
21-11-2000	326	18	*MH*	*202*	*BNMH00326.ddt* N11	***980 588 036.41±1.40*** **	x: -0.07578 y: 0.31897 (average 21-22)	Problem superspring: high sigma (~30-40*μGals*) for each individual set.
		17	ZA	209	OFMET_ZA21_11_00.FG5 N12	**980 588 015.17±1.37** **	x: -0.07578 y: 0.31897 (average 21-22)	
22-11-2000	327	6	*ZA*	*202*	*BNZA00327.ddt* N13	***980 588 018.32±0.96*** **	x: -0.075808 y: 0.320088 (value 22)	Superspring problem solved.
		1	*ZA*	*202*	*BNZA00327a.ddt* N14	***980 588 011.22 ±13.115***	x: -0.075808 y: 0.320088 (value 22)	Clock = 209. Frequency=10 000 000.003 Hz.
		16	*ZA*	*202*	*BNZA00327b.ddt* N15	***980 588 019.31±1.19*** **	x: -0.075933 y: 0.321133 (average 22-23)	
		15	MH	209	OFMET_MH_22_11_00c.FG5 N16	**980 588 033.58±1.21** **	x: -0.075933 y: 0.321133 (average 22-23)	
		2	MH	209	OFMET_MH_22_11_00a.FG5 N17	**980 588 028.11±0.367**	x: -0.075808 y: 0.320088 (value 22)	Test

		1	MH	209	OFMET_MH_22_11_00b.FG5 N18	**980 588 031.59 ±11.928**	x: -0.075808 y: 0.320088 (value 22)	Test
		2	MH	209	OFMET_ZA22_11_00.FG5 N19	**980 588 024.26±0.051**	x: -0.075808 y: 0.320088 (value 22)	!! Wrong file name: should be OFMET_MH in stead of OFMET_ZA.
23-11-2000	328	1	*ZA*	*202*	*BNZA00328.ddt* !! do not confuse it with BZA00328 !! N20	***980 588 014.29 ±16.204***	x: -0.076058 y: 0.322178 (value 23)	Clock = 209. Frequency=10 000 000.003 Hz.
		1	*ZA*	*202*	*BNZA00328a.fg5* N21	***980 588 015.45 ±15.484***	x: -0.076058 y: 0.322178 (value 23)	Clock = 209. Frequency=10 000 000.003 Hz. Unsuccessful test with modified frequency in FG5PARAM.DAT.
		1	*ZA*	*202*	*BNZA00328b.fg5* N22	***980 588 017.15 ±16.892***	x: -0.076058 y: 0.322178 (value 23)	Idem (but only 20 drops).
		1	*ZA*	*202*	*BNZA00328c.fg5* N23	***980 588 015.72 ±15.262***	x: -0.076058 y: 0.322178 (value 23)	50 first drops: clock 209 50 last ones: clock 202. Frequency=10 000 000.003 Hz.
		1	ZA	209	BZA00328.ddt !! do not confuse it with B*N*ZA00328 !! N24	**980 588 012.06 ±14.329**	x: -0.076058 y: 0.322178 (value 23)	Acquisition 202 on 209, clock = 209. Frequency=10 000 000.0073 Hz.
		1	*MH*	*202*	*BNMH00328.ddt* N25	***980 588 034.90 ±17.094***	x: -0.076058 y: 0.322178 (value 23)	
		1	*MH*	*202*	*BNMH00328a.ddt* *N26*	***980 588 034.13 ±11.130***	x: -0.076058 y: 0.322178 (value 23)	
		28	*MH*	*202*	*BNMH00328b.ddt* N27	***980 588 036.90±1.72*** *****	x: -0.076267 y: 0.323106 (average 23-24)	
		1	ZA	209	OFMET_ZA_23_11_00.FG5	**980 588 010.09 ±11.461**	x: -0.076058 y: 0.322178	

					N28		(value 23)	
		2	ZA	209	OFMET_ZA_23_11_00a.FG5 N29	**980 588 006.67±1.040**	x: -0.076058 y: 0.322178 (value 23)	
		1	ZA	209	OFMET_ZA_23_11_00b.FG5 N30	**980 588 007.41 ±11.475**	x: -0.076058 y: 0.322178 (value 23)	Test. Only 20 drops.
		27	ZA	209	OFMET_ZA_23_11_00c.FG5 N31	**980 588 015.16±0.98**	x: -0.076267 y: 0.323106 (average 23-24)	
24-11-2000	329	2	ZA	209	OFMET_ZA_24 drop202.FG5 N32	**980 588 016.36±1.04**	x: -0.076455 y: 0.324026 (value 24)	Dropping chamber of FG5-202 on FG5-209. Ref height: +1 mm
		25	ZA	209	OFMET_ZA_24_11_00.FG5 N33	**980 588 013.13±0.96** **	x: -0.076754 y: 0.324891 (average 24-25)	
27-11-2000	332	20	MH	209	OFMET_MH_27_11_00.FG5 N34	**980 588 033.32±1.25** **	x: -0.078715 y: 0.330411 (average 27-28)	
March 2002	**206 Vs 209**							
28-02-2002	059	13	*WANA*	*206*	*FG5_206_WANA* F1	***980 588 770.55±1.53*** **	x: -0.1272 y: +0.4718	
	059	15	WAN0	209	metas WAN0_27_02_02 F2	**980 588 773.13±1.52** **	x: -0.1272 y: +0.4718	
	059	21	*WAN0*	*206*	*2802002_206* F3	***980 588 776.68±1.01*** **	x: -0.1247 y: +0.4750	
	059	24	WANA	209	metas WANA_28_02_02 F4	**980 588 769.18±1.17** **	x: -0.1247 y: +0.4750	
02-03-2002	061	26	WANA	209	metas WANA_01_03_02	**980 588 769.67±1.52**	x: -0.1221 y: +0.4781	

					F5	**		
04-03-2002	063	14	WANA	209	metas WANA_laser146_04_03_02 F6	**980 588 768.54±1.17**	x: -0.1156 y: +0.4874	Laser 206 on 209
05-03-2002	064	17	*WAN0*	*206*	*laser159_WAN0* F7	***980 588 779.05±0.80***	x: -0.1156 y: +0.4874	Laser 209 on 206
06-03-2002	065	46	*WAN0*	*206*	*206chambre209* F8	***980 588 774.22±1.28***	x: -0.1117 y: +0.4917	Chamber 209 on 206
07-03-2002	066	15	*WAN0*	*206*	*206_cs* F9	***980 588 777.56±1.13*** **	x: -0.1072 y: +0.4957	Clock = Cs METAS
08-03-2002	067	17	WANA	209	metas WANA_07_02_02 F10	**980 588 767.91±1.54** **	x: -0.1072 y: +0.4957	Clock = Rb 209 (the +0.0077 Hz correction is taken into account)
11-03-2002	070	26	WAN0	209	metas WAN0_11_03_02 F11	**980 588 776.11±1.32** **	x: -0.0960 y: +0.5064	
May 2002	**202 Vs 209**							
28-05-2002	148	21	*WANA*	*202*	*Ba02147* M1	***980 588 774.47±1.04*** **	x: +0.1446 y: +0.5332	
	148	21	WAN0	209	metas WAN0_27_05_02 M2	**980 588 773.39±2.41** **	x: +0.1446 y: +0.5332	
29-05-2002	149	23	*WAN0*	*202*	*B002148* M3	**980 588 780.30±1.10** **	x: +0.1476 y: +0.5320	
	149	23	WANA	209	metas WANA_28_05_02 M4	**980 588 768.64±1.07** **	x: +0.1476 y: +0.5320	
	149	21	*WANA*	*202*	*BA02149*	***980 588 775.66±1.10***	x: +0.1504 y: +0.5307	

					M5	**		
	149	21	WAN0	209	metas WAN0_29_05_02 M6	**980 588 774.86±1.36** **	x: +0.1504 y: +0.5307	
30-05-2002	150	4	*WANA*	*202*	*Ba02150* *M7*	***980 588 773.03±0.79 (34/640)*** ***980 588 773.49±0.82 (30/600)***	x: +0.1519 y: +0.5300	Dropping chamber of FG5-209 on FG5-202.
	150	4	WAN0	209	metas WAN0_30_05_02 M8	**980 588 776.19±1.63 (30/600)** **980 588 777.23±2.07 (34/640)**	x: +0.1519 y: +0.5300	Dropping chamber of FG5-202 on FG5-209.
	150	17	*WAN0*	*202*	*B002150* *M9*	***980 588 781.86±0.84*** **	x: +0.1533 y: +0.5293	
31-05-2002	151	26	WANA	209	metas WANA_30_05_02 M10	**980 588 768.11±1.65** **	x: +0.1533 y: +0.5293	

Table 6: Results of the FG5-202, FG5-206 and FG5-209 measurements made at the METAS office (June and November 2000; February-March and May 2002). The double stars indicate the data used in the Table 2, 3, 4 & 5

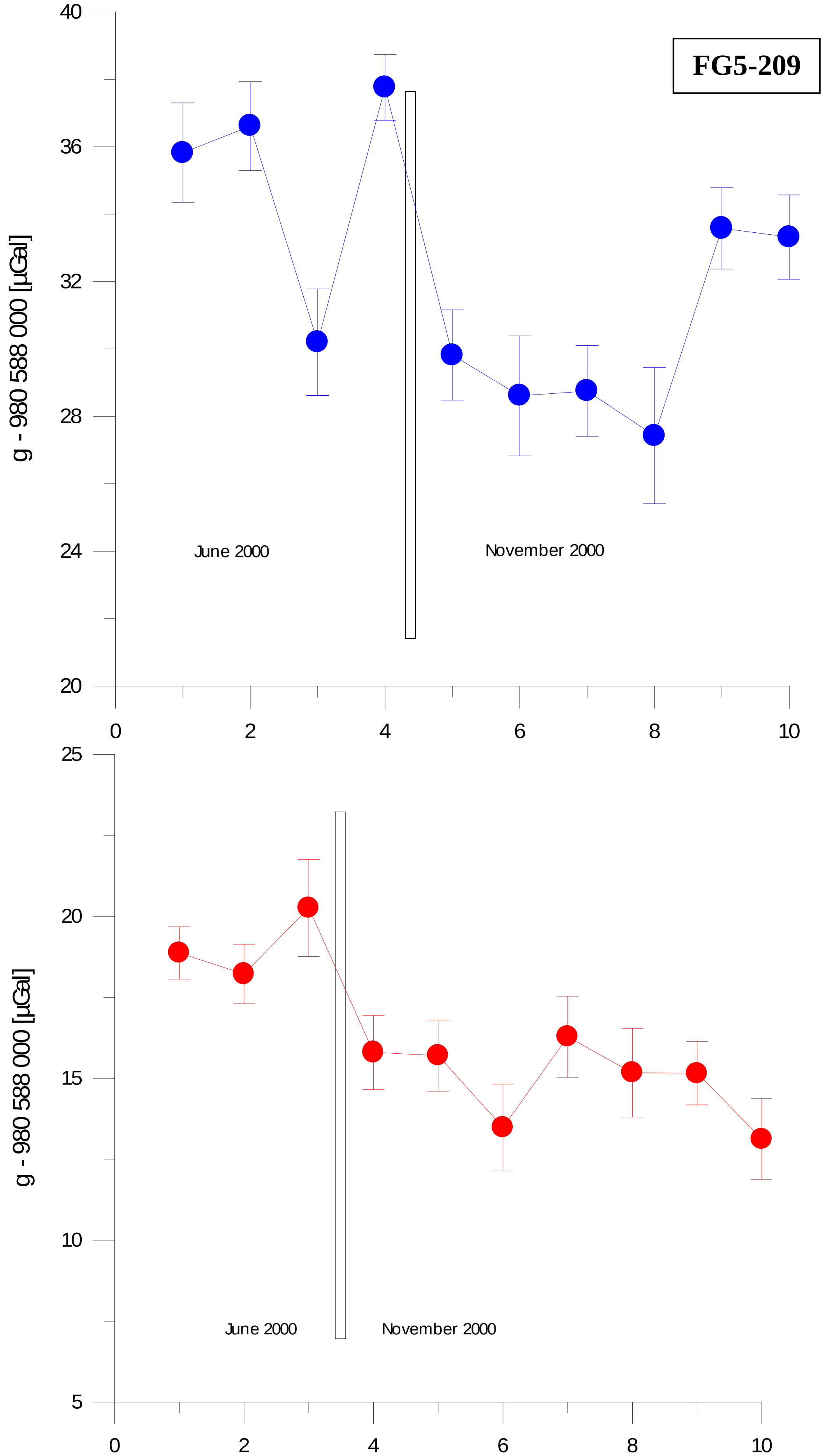

Figure 1: FG5-209 gravity measurements. Top: point MH (J1, J2, J9, J13, N1, N2, N3, N4, N16, N34); Bottom: point ZA (J3, J5, J14, N5, N6, N7, N10, N12, N31, N33).

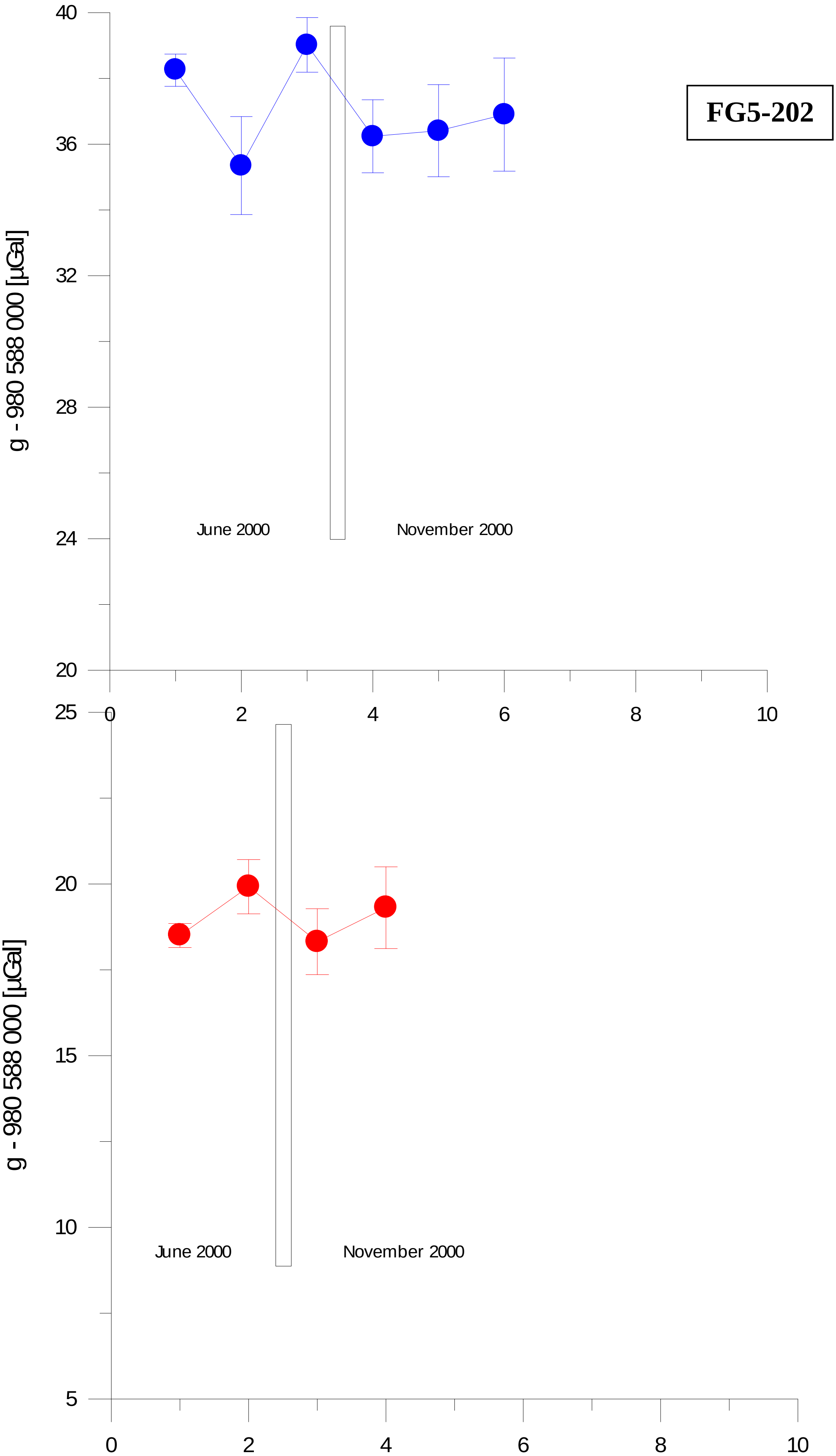

Figure 2: FG5-202 gravity measurements. Top: point MH (J4, J6, J7, N9, N11, N27); Bottom: point ZA (J10, J11, N13, N15).

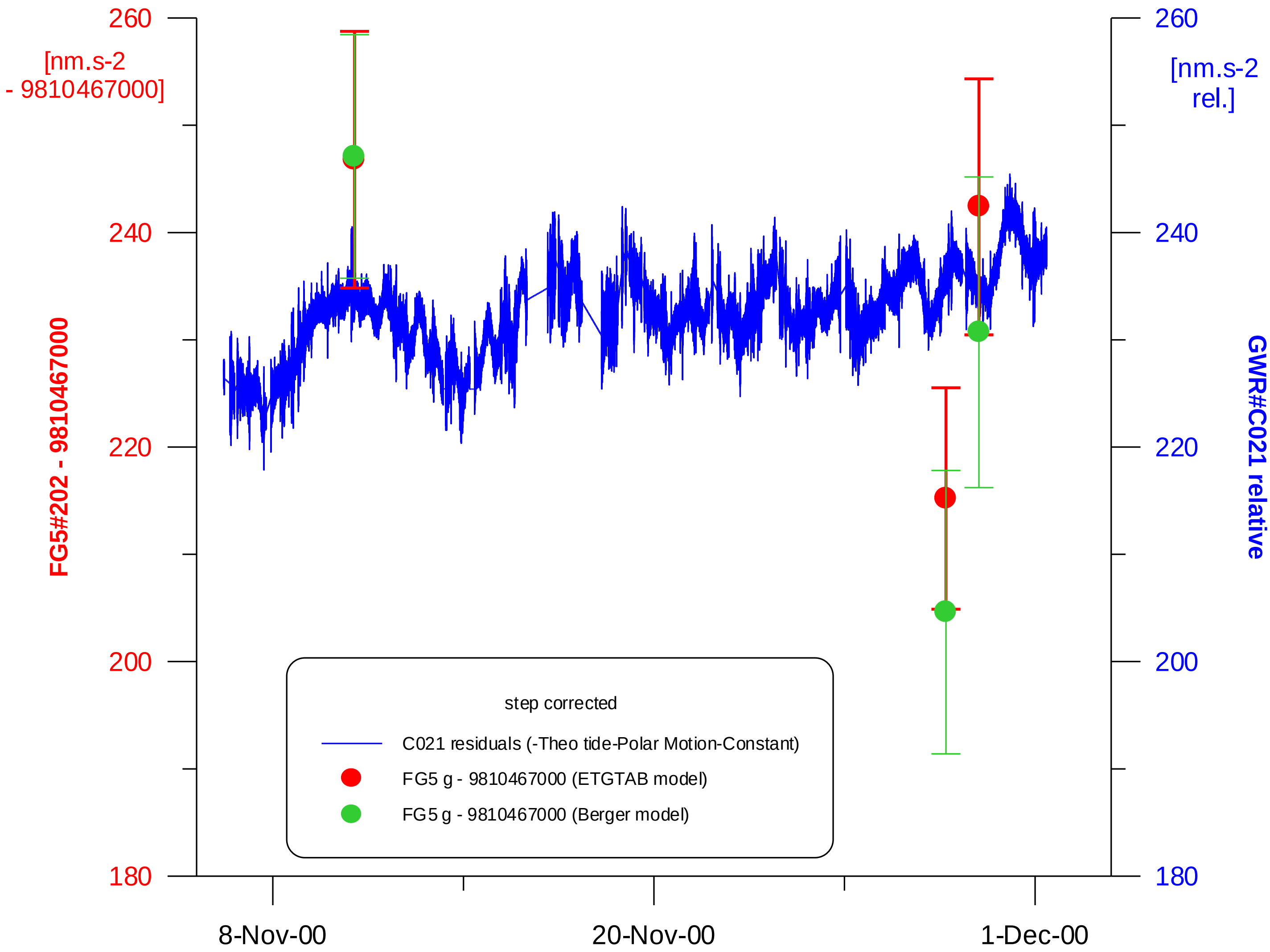

Figure 3. Comparison between the absolute FG5-202 and the superconducting (relative) GWR-C021 gravimeters at the Membach station (FG5-202 measurements from 2000-11-10 to 2000-11-11 and from 2000-11-28 to 2000-11-30). A jump on November 14, 2001, due to the helium filling of the GWR-C021 was removed. The tidal correction on the FG5 data was computed by the mean of the Berger and Tamura ("ETGTAB", with observed tidal parameters) potentials.

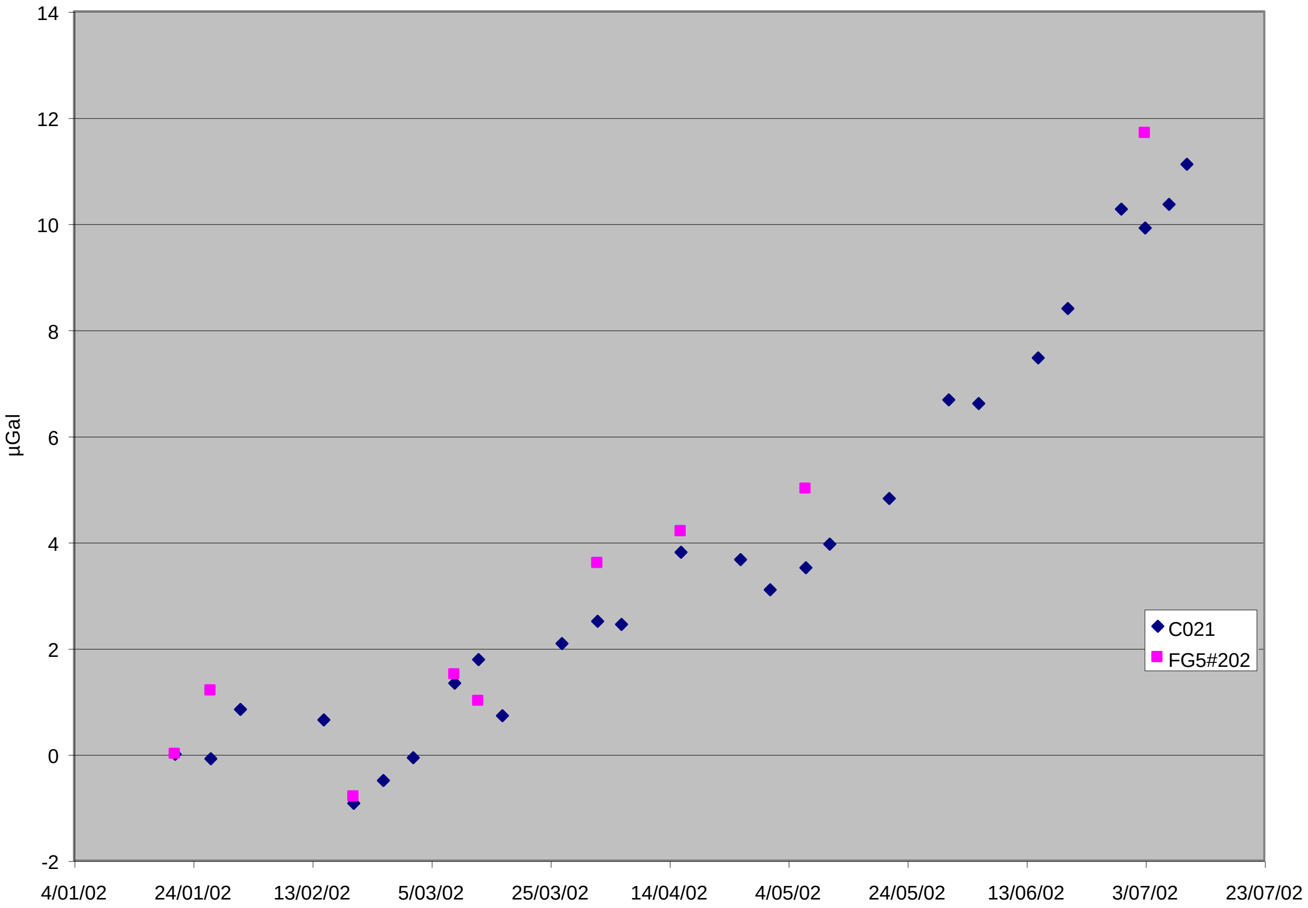

Figure 4: Comparison between the superconducting gravimeter C021 and the AG FG5#202 at the Membach station in 2002. The polar motion is not corrected. An instrumental drift of 5 µGal/year was removed from the C021 data.

The vertical gravity gradient (Bern MH & ZA)

The FG5-202 and 209 absolute gravimeters measure the fall time of a test mass on a distance of about 20cm. During the drop, the mass is subject to a variation of g of about 50$\mu Gals$. This is due to the vertical gravity gradient that must be taken into account when calculating g.
The measurements were made at METAS with the Scintrex CG-3M gravimeter #9408265, at 3 different heights (28, 90, 130 *cm*), in order to check the linearity of the gradient.
Data were post-processed using Tsoft (1.1.5 release, available on http://www.astro.oma.be/SEISMO/TSOFT/tsoft.html); which allows one to remove the Earth tides and to calculate automatically the gravity gradient.
Earth tides effects are removed using the Tamura potential (1200 waves, cf. Merriam, 1995) with the following synthetic tidal parameters (amplitudes and phases, frequencies in cycles per day):

Min. freq.	Max. freq.	Amplitude	Phase	Name
0.000000	0.002427	1.10000	0.0000	DC
0.002428	4.000000	1.16000	0.0000	all

Then, the following equation is fitted on the corrected gravity data:

$$g = x_1 h + x_2 h^2 + x_3 + x_4 t$$

where *h* is the gravimeter height and $x_4 t$, the temporal polynomial necessary to remove the instrumental drift as well as remaining tides. The height *h* is measured between the ground and the bottom of the gravimeter, but takes also into account the height between the bottom and the proof mass (9.8cm, as given by the Scintrex's user's guide).
The gravity gradient is:

$$\nabla g = h + 2x_2 h \,.$$

and the error on ∇g is[1]: $E(f) = \sqrt{E^2(x_1) + E^2(x_2)4h^2 + 4\rho h E(x_1)E(x_2)}$.
The chosen height *h* is 65*cm*, i.e. halfway between the top of the dropping chamber and the ground, chosen as a reference for g.

[1] The error on $f = ax + b$ is:

$$E(f) = \left(E^2(a)\left(\frac{df}{da}\right)^2 + E^2(b)\left(\frac{df}{db}\right) + 2E(a)E(b)\frac{df}{da}\frac{df}{db}\rho \right)^{1/2} = \left(E^2(a)4x^2 + E^2(b) + 4\rho x E(a)E(b) \right)^{1/2}$$

where $E(a)$ and $E(b)$ are the errors on *a* and *b*, respectively and ρ, the correlation coefficient between *a* and *b*.

Point MH

Note: a bad gravity value had to be removed (12h24m52s).

Height of level 1:	27.9 *cm*
Height of level 2:	91.4 *cm*
Height of level 3:	131.6 *cm*

File name: mhcorr.tsf

```
============================================
Multilinear regression
============================================
CORRELATION MATRIX :
 +1.000000 -0.987117 -0.882542 +0.160198
 -0.987117 +1.000000 +0.840210 -0.176922
 -0.882542 +0.840210 +1.000000 -0.480830
 +0.160198 -0.176922 -0.480830 +1.000000
============================================
          h |     -3.1111123     err     0.0307621
        h^2 |      0.0000407     err     0.0000199
Poly(t)  0 |   1538.8979855     err     9.9752095
Poly(t)  1 |      0.0311516     err     0.0011956
Correlation:      0.9999155
Residual standard deviation:     17.4570086
```

Gradient MH @ 65 cm (quadratic model): -3.058 +/- 0.007 *µGal/cm*

Point ZA

Height of level 1:	27.9 *cm*
Height of level 2:	91.5 *cm*
Height of level 3:	131.6 *cm*

File name: zacorr.tsf

```
============================================
Multilinear regression
============================================
CORRELATION MATRIX :
 +1.000000 -0.987153 -0.884028 +0.150039
 -0.987153 +1.000000 +0.843460 -0.170987
 -0.884028 +0.843460 +1.000000 -0.468979
 +0.150039 -0.170987 -0.468979 +1.000000
============================================
          h |     -3.0374667     err     0.0361325
        h^2 |      0.0000172     err     0.0000234
Poly(t)  0 |   1818.0849545     err    11.5838471
Poly(t)  1 |      0.0330125     err     0.0014099
Correlation:      0.9998794
Residual standard deviation:     20.5638012
```

Gradient ZA @ 65 cm (quadratic model): -3.015 +/- 0.008 *µGal/cm*

References

- Merriam, J.B., 1993. A comparison of recent tide catalogue and the consequence of catalogue error for tidal analysis. *Bull. Inf. Marées Terrestres* **115**: 8515-8526.
- Niebauer, T., Sasagawa, G., Faller, J., Hilt, R. and Klopping, F., 1995. A new generation of absolute gravimeters. *Metrologia*, **32**, 159-180.
- Warburton, R. and Brinton, E., 1995. Recent developments in GWR instruments' superconducting gravimeters. In Poitevin, C. (Ed.), *Proc. 2nd Workshop on non tidal gravity changes, cahier du Centre Européen de Géodynamique et de Seismologie*, Vol. 11.