

# Comparisons of the FG5#101, #202, #206 and #209 Absolute Gravimeters at four Different European Sites

M. Van Camp, M. Hendrickx  
Royal Observatory of Belgium, Seismology, Avenue Circulaire, 3, B-1180 Bruxelles, Belgique, [mvc@oma.be](mailto:mvc@oma.be)

P. Richard, S. Thies  
Swiss Federal Office of Metrology and Accreditation, METAS,  
Lindenweg 50, CH-3003 Bern-Wabern, Switzerland, [philippe.richard@metas.ch](mailto:philippe.richard@metas.ch)

J. Hinderer, M. Amalvict, B. Luck.  
Ecole et Observatoire des Sciences de la Terre, EOST,  
5, rue René Descartes, F-67084 Strasbourg Cedex, France, [Jacques.Hinderer@east.u-strasbg.fr](mailto:Jacques.Hinderer@east.u-strasbg.fr)

R. Falk  
Bundesamt für Kartographie und Geodäsie, BKG,  
Richard-Strauss-Allee 11, D-60598 Frankfurt am Main, Germany, [reinhard.falk@bkg.bund.de](mailto:reinhard.falk@bkg.bund.de)

**Abstract.** Between 1997 and 2002, 10 bilateral comparisons were performed involving the FG5#202 (ROB, Belgium) absolute gravimeter and the FG5#101 (BKG, Germany), the #206 (EOST, France) or the #209 (METAS, Switzerland), respectively.

We report here on the results of these comparisons and compare them with the results of the Bureau International des Poids et Mesures (BIPM) multilateral comparisons carried out in 1997 and 2001. The observed differences between the FG5#202 and the other instruments remained between 1.3 and 6.8  $\mu\text{Gal}$ . We present a description of the various tests performed on the gravimeters to lower the observed differences. The comparisons gave the opportunity to deal with instrumental problems as well as to check the barometers and the rubidium clocks regularly. We also provide some recommendations for error assessment and for future comparisons.

## 1 Introduction

International Comparisons of absolute Gravimeters (ICAG) are held at the Bureau International des Poids et Mesures (BIPM, Sèvres, France) on a 4 year basis only (Vitushkin et al. (2002)). To validate absolute gravimeters (AGs), it is necessary to perform comparisons more regularly. Therefore, 10 bilateral comparisons were performed in Europe using 4 FG5 AGs at 4 different sites. This study aimed at better determination of the uncertainty level in the absolute measurements, as the ICAGs do. Projects like the future redefinition of the kilogram, or joint gravity projects as UNIGRACE

	Membach	Bern	Strasbourg	Bad Hom- burg
#202				
01/1997	#206			
06/2000		#209		
11/2000		#209		
02/2002			#206	
03/2002	#206			
04/2002	#101			
05/2002				#101
05/2002		#209		
11/2002	#209			
#206				
03/2002		#209		

**Table 1.** Epochs and locations of the comparisons between the FG5#202, #206, #209 and #101 AGs in Europe. The FG5#202 was involved in all but one comparisons.

(Wilmes et al. (2003)) using different AGs, need a common reference given by instrumental comparisons.

We present the results from 10 comparisons performed between 1997 and 2002 involving 4 FG5 AGs models by Micro-g solutions (Niebauer et al. (1995)): the German FG5#101, the Belgian FG5#202, the French FG5#206 and the Swiss FG5#209. Places and time of comparisons are shown at Table 1.

During all the bilateral comparisons except in January 1997, the gravimeters were swapped at

least once, in order to remove possible setting up errors.

We also compared all the results from these 10 bilateral comparisons with the ICAG held in November 1997 (ICAG1997) (Robertson et al. (2001)) and July 2001 (ICAG2001) (Vitushkin et al. (2002)).

The FG5 AG operates by using the free-fall method. An object is dropped inside a vacuum chamber (called the dropping chamber). The position as a function of time of the freely falling object is monitored very accurately using a laser interferometer and an atomic clock. The #202 is provided with the bulk-type interferometer with enclosed laser. The other three AGs are now built on the fibre pattern, i.e. with an external laser connected to a smaller interferometer using an optical fibre. The fibre type AGs are lighter and easier to maintain, but the accuracy is stated to be the same as for the bulk models.

All the data were processed using the “g” software, versions 2.0128 or later, from Micro-g Solutions. Tidal effects were removed using the 1200 wave Tamura catalogue, the solid Earth tide parameters of the Wahr-Dehant model and the Ocean loading parameters of the Schwiderski model (Van Camp (this issue)). In routine operation, for all but the German campaigns, the drops were repeated each 10 s, 100 times per hour (German campaigns: 1 set = 150 drops, 1 drop/20 s). The average of 100 (or 150) drops is a “set”. Measurements consist of one set per hour during 12 to 24 hours or more. The average value of all sets provides the final “gravity value” of one experiment at a given gravity site. In this study, the error bars are based on the one sigma standard deviation, called “set scatter” in the “g” software, and not the standard deviation of the estimated mean (“Measurement precision” in “g”).

## 2 Calibration of the lasers, clocks and barometers

The optical fringes generated in the laser interferometer provide a very accurate absolute distance measurement. Very accurate and precise timing of the occurrence of these optical fringes is performed using an atomic rubidium clock as reference. The lasers and the rubidium clocks presently used in the AGs are secondary frequency standards. When ageing, clock characteristics change so that these clocks must be traceable to primary standards.

As absolute gravity values comply with a standard procedure, which refers to the normal pressure at the station height, an air pressure correction has to be determined. Therefore, AGs are also equipped with a barometer.

### 2.1 The lasers

The AGs considered in this study use an iodine-stabilised HeNe laser from Winters Electro Optics Inc. (WEO). This type of laser with an internal iodine cell could be used for the practical realisation of the meter (Quinn (1992)). During the last ICAG in 2001 at the BIPM all lasers of the participating AGs were successfully checked and certified. The least accurate laser presented an absolute accuracy still better than 30 kHz, equivalent to a 0.06  $\mu$ Gal uncertainty contribution [(30  $\pm$  7) kHz is from the #202 (WEO#136), (7.6 $\pm$ 2.8) kHz from the #206 (WEO#146), (2.5  $\pm$  2.8) kHz from the #209 (WEO#159), (-19  $\pm$  3.8) kHz from the #101 (WEO#164)].

The #209 laser was also checked in July 2000 using the METAS primary standards.

### 2.2 The clocks

From our comparisons and from the 10 years experience using AGs at BKG, it is known that the quality of absolute gravity measurements is strongly dependent on the quality of the Rb clocks. As a lead of 1 mHz around the 10 MHz reference frequency would increase the gravity by 0.2  $\mu$ Gal if no correction were applied, a continual check of the clock is necessary. Therefore, during all comparison campaigns but the 1997 one, the FG5’s Rb clocks were systematically compared and, whenever available, calibrated against Cs clocks. The frequency corrections were applied for the data reprocessing.

Rb/Rb and the Rb/Cs comparisons were found consistent at the 1 mHz level for all the FG5s with exception of the #206. For example the frequency differences between the Rb of the #202 and the #101 were: (6.3  $\pm$  0.3) mHz (April 2002) and (5.7  $\pm$  0.1) mHz (May 2002). On the other hand, taking the difference between the absolute calibrations made at METAS (#202, May 2002) and Wettzell (#101, July 2002), we obtained:

$$\begin{aligned} \nu_{101} - \nu_{202} &= 10\,000\,000.0097 - 10\,000\,000.0034 \\ &= 6.3 \text{ mHz} \end{aligned}$$

which confirms the quality of the former relative Rb/Rb comparisons. Such a reasoning is also valid for the #202 compared with the Cs from METAS, BIPM, CERGA (Centre de Recherche en Géodynamique et Astrométrie, Grasse, France) and the #209 Rubidium, but it was not the case with the #206 (see section 4).

The Rb/Rb and Rb/Cs comparisons were mostly performed using an oscilloscope, with one clock on the X-channel used for trigger, and the other one on the Y-channel. Then, the frequency differences were calculated by measuring the time the Y channel needed to shift by a complete cycle. This

method is known as phase difference method (Stein (1990)).

The ICAG2001 and Wettzell calibrations, which agree with ours, were made independently by other operators and method.

Considering the frequency differences that appeared between the clocks, it was pointless to perform comparisons at the 1  $\mu\text{Gal}$  level without correcting the clocks.

### 2.3 The barometers

A barometer reading that is 1 hPa too high would increase the air pressure correction and so the absolute gravity value by 0.3  $\mu\text{Gal}$  if no correction was applied. Since 2000, during all comparison campaigns, the barometers were systematically compared and whenever available, compared with a pressure standard. This was done calculating one or more averages of 10 pressure values taken during 100 s. The barometers of the #202 and the #209 were calibrated with the METAS pressure primary standard from 930 hPa to 980 hPa in June 2000. Another calibration of the #209 barometer, from 930 hPa to 1030 hPa, was also performed in November 2002. All calibrations and comparisons carried out on the #202 and the #209 barometers (at BKG (#202 only), METAS and BIPM) showed that their long-term stability is better than 0.2 hPa, which corresponds to a correction lower than 0.1  $\mu\text{Gal}$ .

Because no calibration was performed for the #206 barometer, no correction was applied when processing the data of the three AGs #202, #206 & #209 implied in the “French campaigns” (section 4). The consequences are negligible: by comparing the #202 and the #206 barometers in February and March 2002, we obtained, at 985 and 1002 hPa:

$$P_{206} - P_{202} = (0.65 \pm 0.04) \text{ hPa}$$

equivalent to 0.2  $\mu\text{Gal}$  (the difference between the #206 and the #209 is even smaller). As the #202 calibration provided a +0.60 hPa correction at 1000 hPa on the #202 barometer, then a +1.25 hPa correction should be applied to the #206, equivalent to +0.38  $\mu\text{Gal}$ . This should be taken into account for future comparisons when barometer correction is applied to the other AGs. For the #101 barometer, an offset less than 0.3 hPa was found so that no corrections were applied.

## 3 The Swiss campaigns: FG5#202 – #206 – #209

### 3.1 Description of the campaigns

Five campaigns took place with the #209: in June 2000, November 2000, May 2002 and November

2002 with the #202, and in March 2002 with the #206. The 2000 campaigns were performed in the METAS room ZA13, while the measurements made in March and May 2002 were done in the new air-conditioned “Watt balance” laboratory N1, where the #209 is directly connected to one of the METAS Cs clocks. The last campaign took place in Belgium at the Membach station in November 2002.

The Figure 1 presents, for each point, the differences between each observed gravity value and the average gravity value computed with all gravity values from all possible campaigns at that given point. Each AG contributes equally to the average, independently of the availability of its data on that point. If the gravimeters perfectly agreed, for a given campaign, all the data would lie on the same level on Figure 1 (a similar presentation is used for the French and German campaigns on Figure 2 and 3).

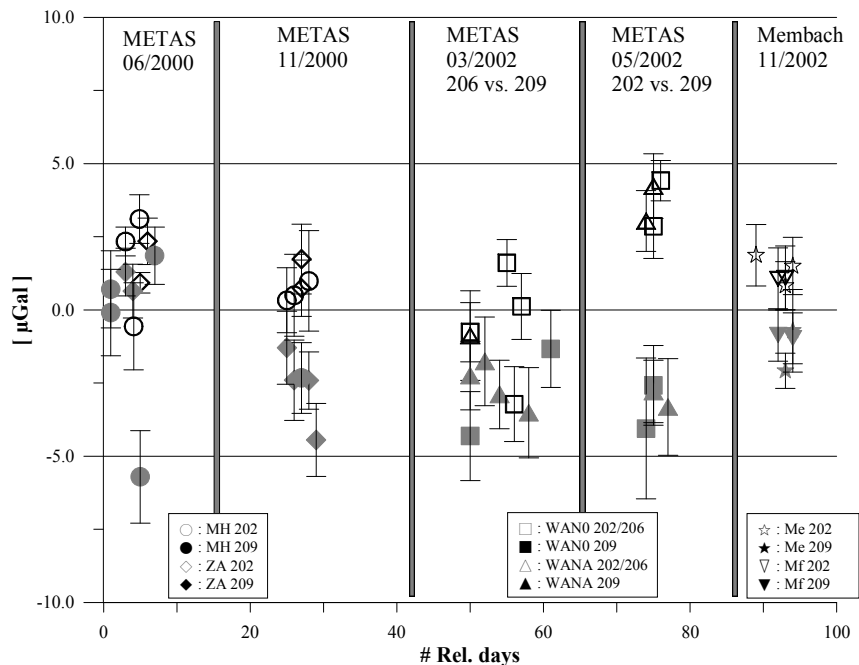
### 3.2 The 2000 campaigns: #202 and #209

The results of the first campaign agreed at the 1.6  $\mu\text{Gal}$  level for all gravity values but one of the #209 on the MH point. We do not have any explanation for this MH point, which is 5.7  $\mu\text{Gal}$  lower. One gravity value measured by the #202 on the ZA point was made using the #209 data acquisition system (desktop PC provided with A/D and Fringe cards), but no significant changes occurred.

In November 2000, the #202 and the #209 differed by  $(3.4 \pm 1.2) \mu\text{Gal}$ . Moreover, the #209 suffered from large dispersions reaching up to 4.5  $\mu\text{Gal}$  at MH. This was not due to environmental effects, as simultaneous measurements on ZA had remained more stable. The cause turned out to lie in the #209 acquisition system where parasitic ground loops were induced by a newly acquired rack-mount PC that was still working outside the electronics box. This was solved in December 2000 when that PC could be integrated inside the electronics rack. The improvement was confirmed during the ICAG2001 with an observed difference between the #202 and the #209 of  $(1.3 \pm 2.1) \mu\text{Gal}$  (Figure 4).

### 3.2 The 2002 campaigns: #202, #206 and #209

After noticing a  $(4.3 \pm 0.6) \mu\text{Gal}$  discrepancy between the #202 and the #206 in February 2002 in Strasbourg (cf. section 4), the #206 was compared to the #209 in March 2002 at METAS. There, the #206 turned out to be  $(2.7 \pm 1.6) \mu\text{Gal}$  higher than the #209, which would have meant that the #209 was 7  $\mu\text{Gal}$  lower than the #202.



**Fig 1** Results from the FG5#206 / #209 comparison (March 2002) and the 4 different FG5#202 / FG5#209 comparisons performed at METAS and at the Membach station. Each data is the difference between the observed gravity value at one point and the average gravity value computed with all gravity values from all possible campaigns at that given point. Each AG contributes equally to the average, independently of the availability of its data on that point. Most of the gravity values represents the average of more than 12 sets. For the METAS 03/2002 #206 / #209 comparison, the #206 WAN0 point, which is at  $-3.2 \mu\text{Gal}$ , was observed by installing the #209 chamber on the #206 AG. This point was not taken into account in the final numerical results. For the Membach campaign (11/2002), we show the gravity values of the FG5#209 only after focusing the fibre and stabilising the FG5#209 tripod. The error bars represent one sigma standard deviation.

To check this, we performed a new comparison at METAS in May 2002 between the #202 and the #209: we observed then the largest difference:  $(6.9 \pm 1.0) \mu\text{Gal}$ . After maintenance of #209 at Micro-g in October 2002, a new comparison was performed at the Membach station and the difference between decreased to an acceptable  $(2.4 \pm 0.8)$ .

### 3.3 Looking for solutions

To try to solve the discrepancies, we made many attempts during the 2000 campaigns and the first 2002 one. First, we checked the Olivia software versus the new g-software. Then, the dropping chambers (#202/#206/#209), the clocks and the lasers (#206/#209) were exchanged. We also found that the pulse delay on the #209 was too short. The hold time on the top of the drop was nearly 0 s. Because this could have prevented the falling mass from stabilising, we changed the pulse delay such that the hold time reached 2 s. All those attempts did not change the results significantly.

In May 2002, we did not try to solve the discrepancies between the #202 and the #209 (except an exchange of the dropping chambers during 3 hours and a regular check of the clocks and barometers), as we wanted to check the stability of the results after 4 successive settings up. Despite of the good stability and reproducibility of the results of each instrument (Figure 1), this campaign provided the largest difference at the  $6.9 \mu\text{Gal}$  level.

At the Membach station, we reached an agreement at the  $2.4 \mu\text{Gal}$  level in November 2002, with good stability. However, during the first measurements the #209 was  $(8.5 \pm 1.3) \mu\text{Gal}$  lower than the #202. On the one hand, after focusing the optical fibre, we obtained a thinner beam, allowing us to better adjust the verticality. On the other hand, reducing the laser beam diameter also introduced a systematic reduction in the measured gravity value. This is due to the inherent curvature of the wavefronts in the laser beam. A diffraction correction based on the measured beam width could be applied (van Westrum and Niebauer (2003)), but as we did not measure the beam diameter, we were not able to calculate this correction. However the #209 gravity value increased by  $(2.2 \pm 1.7) \mu\text{Gal}$  after focusing the fibre. Then the #209 was set-up twice but a difference of about  $(7.1 \pm 1.4) \mu\text{Gal}$  remained. Moreover, the #209 noise distribution was not symmetric: we observed more values below the average than above. After several tests, it turned out that the dropping chamber tripod was unstable, which did not allow us to maintain the verticality properly. This was due to the irregular concrete floor. On the Me point, we solved the problem by installing the #209 tripod exactly the same way as the #202 one (about 80 set-ups of the #202 on the Me points have proved its stability since 1996, cf. section 6). On the Mf point, we smoothed the floor. Then, the dropping chamber became stable, the noise distribution became Gaussian and we finally

obtained an acceptable difference of  $(2.4 \pm 0.8)$   $\mu\text{Gal}$  (on the Mf point only, we even reached  $(1.8 \pm 2.0)$   $\mu\text{Gal}$ ). The #202 did not suffer from this problem as its tripod was differently oriented.

As no pre-service runs were performed prior the September 2002 maintenance at Micro-g Solutions, we are not able to state the cause of the 6.9  $\mu\text{Gal}$  discrepancy observed at METAS in May 2002.

## 4 The French campaigns: FG5#202 – #206 – #209

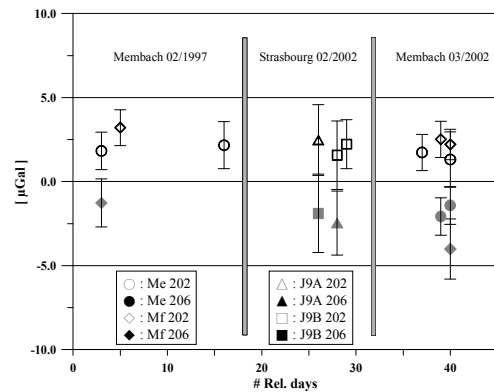
### 4.1 The 1997 campaign: #202 and #206

The results of the French campaigns are presented on Figure 2. One campaign occurred at the Membach station in January 1997 and three other ones in 2002. In January 1997, the #202 and the #206 differed by  $(3.7 \pm 1.6)$   $\mu\text{Gal}$ . This had not conflicted with the  $(3.3 \pm 2.3)$   $\mu\text{Gal}$  obtained later during the ICAG 1997 (Robertson et al. (2001)). Officially, the discrepancy was  $(7.3 \pm 2.3)$   $\mu\text{Gal}$  but a 4  $\mu\text{Gal}$  jump occurred after May 23rd, 1997. This offset was detected later on the #202 by comparison with the superconducting gravimeter at the Membach station and eventually confirmed and solved during the maintenance at the Table Mountain Gravity Observatory (TMGO) in March 1998. During the ICAG2001, the #206 was  $(5.2 \pm 2.0)$   $\mu\text{Gal}$  higher than the #202 (Figure 4). Yet, one must take into account that, due to a technical problem, the #206 gravity value was measured on only one point, instead of three for the other AGs.

### 4.2 The 2002 campaigns: #202, #206 and #209

In February 2002, the first comparison took place between the #202 and the #206 at the J9 Strasbourg station just after the upgrade of the #206. Its bulk interferometer had been changed for the fibre model and its data acquisition system, originally based on a laptop PC in a docking station and a time interval counter, had been replaced by a rack-mount PC equipped with a fringe counter card.

This first comparison showed a discrepancy of  $(4.3 \pm 0.6)$   $\mu\text{Gal}$  between the #202 and the #206. To try to clear this up, it was decided to compare the #206 with the #209 at METAS. This was carried out at the end of February/beginning of March 2002 and the #206 turned out to be  $(2.7 \pm 1.6)$   $\mu\text{Gal}$  higher than the #209. Assuming the #206 had remained stable during the transport, this result at METAS led us to suppose that the difference between the #202 and the #209 had been increasing up to  $(7.0 \pm 2.1)$   $\mu\text{Gal}$  since the last ICAG 2001. This was to be confirmed, unfortunately, during the comparison at METAS in May 2002, where a high



**Fig. 2** Results from the 3 different FG5#202 / FG5#206 comparisons performed at the Membach and Strasbourg stations. Each data is the difference between the observed gravity value at one point and the average gravity value computed with all gravity values from all possible campaigns at that given point. Each AG contributes equally to the average, independently of the availability of its data on that point. Each gravity value represents the average of at least 14 sets. The error bars represent one sigma standard deviation.

discrepancy of  $(6.9 \pm 1.0)$   $\mu\text{Gal}$  was observed, as shown in section 3.2. Finally, a last comparison between the #202 and the #206 made in Membach in March 2002 provided a difference of  $(4.5 \pm 1.4)$   $\mu\text{Gal}$ , confirming the results of February.

### 4.3 Attempts to solve the discrepancies

No attempt was undertaken to solve the difference in February 1997. In 2002, the following attempts were undertaken to solve the discrepancy: the data acquisition PCs were swapped, the tilt meters on the fibre #206 interferometer were temporarily switched off, the #206 and #209 lasers swapped, the dropping chambers exchanged; all those attempts failed to change the measurements significantly.

It is worth noting that an accidental grounding between the #202 and the #206 controllers of the supersprings caused the gravity to increase suddenly by 11  $\mu\text{Gal}$  on the #202, while the noise did not change and nothing noticeable occurred on the #206. We detected this misuse immediately, but it illustrates the danger to operate a single AG without ever comparing it with others.

The comparison made in May 2002 between the #202 and the #209 did not conflict with those made between the #202 and the #206 and between the #206 and the #209. At least, the #202/#206/#209 comparisons indicated a good stability between the different set-ups, even after travelling (see Figures 1 & 2).

Due to the observed discrepancies and to problems with the dropping chamber (too many drops were rejected due to a bad fringe detection), the #206 was sent back to Micro-g in April 2002. There, a 20 mHz discrepancy was found on the rubidium clock of the #206. Such an error reduced the observed gravity by 4  $\mu\text{Gal}$  and could have explained our observed discrepancies. However, the #202 and the #206 Rb clocks did not differ by more than 2.5 mHz in February and March 2002, and by no more than 1.5 mHz between METAS Cs and the #206 Rb in March 2002. Such results indicated a larger instability of the #206 Rb, but still at the 2 mHz level. It is too small to explain the observed discrepancies, even if this could reveal a clock malfunction. Eventually, there are no evident explanations of the discrepancies observed in 2002 between the #202, the #206 and the #209. The agreement between the #202 and the #206 is expected to be confirmed during the next comparison planned at J9 in February 2003, after the maintenance of the #202 at Micro-g Solutions at the very beginning of 2003.

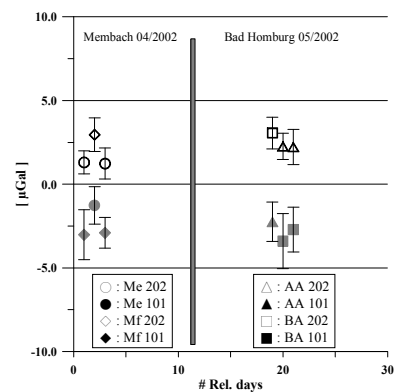
## 5 The German campaigns: FG5#101 – #202

The #202 and the #101 were compared twice in 2002. The difference between both AGs reached  $(4.2 \pm 1.4) \mu\text{Gal}$  at Membach in April 2002 and  $(5.3 \pm 0.7) \mu\text{Gal}$  at Bad Homburg in May 2002. The results are presented on Figure 3.

Looking in details at the Membach data, there was a difference of  $(2.5 \pm 1.6) \mu\text{Gal}$  between the #202 and the #101 at the point Me, and of  $(5.9 \pm 2.0) \mu\text{Gal}$  at the point Mf for all sets but one. This latter set agreed with the #202 at better than 1  $\mu\text{Gal}$ . This occurred between two settings. In fact, the #101 suffered at both stations from 3 to 5  $\mu\text{Gal}$  offsets after many settings (fringe optimising and/or vertical adjustment) which also occurred during the ICAG2001. Outliers due to some of these offsets were not included in the presented results of our two bilateral campaigns. In Bad Homburg, the #202 remained at least 3  $\mu\text{Gal}$  higher. The raw floor and induced instabilities of the dropping chamber at the Membach station can be partly responsible for the differences between the #101 and the #202. However, as differences also appeared in Bad Homburg, and considering the unexplained offsets were regularly observed after setting up the #101 elsewhere too (included the ICAG2001), another explanation must be found. Besides, an alignment of the interferometer and a focusing of the fibre could not solve this problem either. It is expected that the #101 will work stable after the next service at Micro-g solutions in early spring 2003.

## 5.1 Sensitivity of #101 to fringe parameters

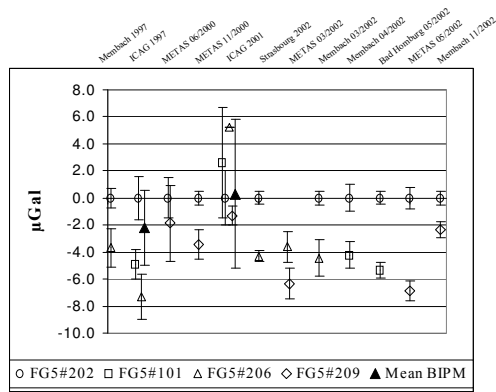
The #101 is also very sensitive to the number of processed fringes. E.g., using 34 as “fringe start” and 640 as “processed fringes” for both AGs, the difference #202-#101 at Me (resp. Mf) could be reduced to  $(-0.3 \pm 1.4) \mu\text{Gal}$  (resp.  $(4.7 \pm 2.3) \mu\text{Gal}$ ), but increased to  $(2.2 \pm 1.4) \mu\text{Gal}$  (resp.  $(5.3 \pm 2.6) \mu\text{Gal}$ ) using the parameters 30/600. These values are normally used for the #101, while the #202 defaults to the 34/640 parameters. This latter AG being relatively insensitive to the chosen parameters, the choice of the parameters is not such a limiting factor as for the #101. For the #206 and the #209 this fringe sensitivity was not investigated. Manufacturer knowledge and further user studies are necessary to get a tuning or adjustment procedure for ‘processed fringe’-independent results.



**Fig. 3** Results from the 3 different FG5#202 / FG5#101 comparisons performed at the Membach and Bad Homburg stations. Each data is the difference between the observed gravity value at one point and the average gravity value computed with all gravity values from all possible campaigns at that given point. Each AG contributes equally to the average, independently of the availability of its data on that point. Each gravity value represents the average of at least 11 sets. The error bars represent one sigma standard deviation.

## 6 Assessing precision and accuracy

The discrepancies observed during our comparisons ask the question about the best way to evaluate the precision and accuracy of a single AG. With this aim in view, we compared the AG #202 data with the superconducting gravimeter GWR#C021 operating continuously at the Membach station since 1995. Both instruments are very different in their principle of operation. The advantage of the SG is to provide continuous data in between AG measurements and to present a signal-to-noise ratio lower than the AG one by one order of magnitude (Francis et al. (1998)). The AG and SG observations (these latter corrected for the instrumental



**Fig. 4** Difference of the bilateral comparisons performed between the FG5#202 and the FG5#101, the #206 and the #209. The results obtained during the ICAG1997 and 2001 are also given. Only the June 2000, ICAG 2001 and November 2002 comparisons performed between the FG5#202 and the #209 are below the 2.5  $\mu\text{Gal}$  level. For the comparison performed in March 2002 between the FG5#206 and the #209, the reference is the FG5#202 value obtained in May 2002. The ICAG1997 and 2001 data are based on three points for all instruments but the FG5#206 in 2001: due to a technical problem, only one point was available (see Vitushkin et al. (2002)). The error bars represent one sigma standard deviation.

drift) should overlap on the same graphic. This operation does not allow us to check the accuracy of the AG as SG provides only gravity variations. At least, one can check if the AG data are consistent over time. For instance, this would allow us to detect any sudden offset, such as the 4  $\mu\text{Gal}$  jump observed between May 1997 and March 1998. Such an observation could have explained most of the discrepancies between the #202 and the other AGs, but this never happened again since 1998. Similar comparisons at the Strasbourg station between the SG#C026 operating since 1997 and the AGs seemed to confirm that the 4.3  $\mu\text{Gal}$  discrepancy observed between the #202 and #206 was due to this former.

In Membach, 82 AG values are available since 1996. After removing an instrumental linear drift from the SG#C021, both instruments proved to agree at the 1  $\mu\text{Gal}$  level (Francis et al. (2003)). In fact, considering each gravity data and its set scatter (one sigma), 46% of the gravity value agree with the SG at the  $1\sigma$  level, 83% at the  $2\sigma$  and 95% at the  $3\sigma$  one (SG and AG data being corrected for Earth tides, ocean loading, polar motion and atmospheric effects). The distribution is negatively skewed (-0.82); however, this is not so far from a normal distribution and indicates the good working of the #202. One limitation of this calculation is that the SG is supposed as noise-free.

Provided an AG works properly, this indicates that the “set scatter” parameter, i.e. the standard

deviation of the sets, gives a good idea on the instrumental precision. However, looking at the different comparisons, even when the AGs appeared to work properly, the “set scatter” did not provide a right evaluation of the accuracy. The “uncertainty”, another parameter provided by “g” soft, turns out to provide a suitable approximation for the AGs accuracy. This parameter includes the standard deviation of the estimated mean (the “measurement precision”), the uncertainties coming from the environmental corrections, the system and the set-up. Under normal conditions, using the default parameters, one obtains an uncertainty on the accuracy of about 3 – 4  $\mu\text{Gal}$ . This seems a reasonable approximation of the accuracy.

## 7 Conclusions

In this study, we summarised 10 comparisons between the FG5#101, the #202, the #206 and the #209 carried out at METAS, Membach, Strasbourg and Bad Homburg. Their results were integrated to the last two ICAG held at the BIPM in 1997 and 2001. The differences between the AGs lay between 1.3  $\mu\text{Gal}$  and 6.9  $\mu\text{Gal}$ . For all but one comparison (the ICAG2001), the #202 registered a gravity value systematically higher than the other AGs. As the #202 participated in all comparisons but one, we could use the average set scatter to evaluate the site stability during the campaigns. It was close to 1  $\mu\text{Gal}$  at all locations but Strasbourg, where it reached 1.9  $\mu\text{Gal}$ , which is still satisfactory. Besides the #202 has been proved stable during the numerous controls made at the Membach station.

Among the 12 comparisons, only three campaigns provided an agreement better than 2.5  $\mu\text{Gal}$ : The #202 and the #209 in June 2000, July 2001 and November 2002. Numerous attempts were undertaken to solve the discrepancies but remained unsuccessful, with the exception of Membach in November 2002. There, by focusing the fibre and stabilising the tripod, we were able to improve the difference between the #202 and the #209 from 8.5  $\mu\text{Gal}$  to 2.4  $\mu\text{Gal}$ .

These 10 bilateral comparisons provided opportunities to compare AGs side-by-side and to check different parts, which is not possible during ICAG due to the unavoidable strict schedule. It also allowed us to follow up AGs more regularly.

Finally, to make it easier to detect and correct unexplained discrepancies, it would be more efficient to compare more than two instruments simultaneously and to use SG measurements as it makes possible to distinguish between instrumental instabilities and 'real' gravity variations.

Bilateral comparisons give the opportunity to compare instrumental characteristics and help to

decide about manufacture maintenance. Also, adjustment and tuning of different components of the AGs are then possible. Comparisons of AGs help to detect instrumental problems, provide good training for beginners and give the possibility to increase the confidence in absolute gravity measurements up to the 1-2  $\mu\text{Gal}$  level.

## 8 Recommendations for future comparisons

Based on the experience gained during the different campaigns, we give here some recommendations for future regional comparisons:

1. The chosen site should be stable and offer room enough to allow simultaneous measurements of at least three AGs.
2. The gravity at the chosen site should be monitored regularly by a reference AG and/or SG.
3. The station shall have good electric installation to avoid e.g. grounding problems.
4. The vertical gradients of the gravity stations should be known.
5. A careful comparison campaign can require 4 to 5 days.
6. The Rubidium clocks need to be calibrated with primary standards at least twice per year and whenever possible also during the comparison. The clocks of the participating AGs can also be compared relative against each other.
7. The laser beam waist could be measured in order to apply the diffraction correction.
8. We recommend to swap the instruments and measure during 12 h minimum on each point. At least one point should be visited twice, rather both, as this helps to constrain errors due to set-up and site-related effects.
9. An agreement should be found about the number of processed fringes. Rules should be settled by the manufacture and the users.
10. We encourage independent checks of settings (reference heights, verticality, power of the fringe signal).
11. The technical protocol and the data processing method should be defined before the comparison and the same station parameters, including tidal model, should be used.

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