Results of the European Comparison of Absolute Gravimeters in Walferdange (Luxembourg) of November 2007

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Abstract. The second international comparison of absolute gravimeters was held in Walferdange, Grand Duchy of Luxembourg, in November 2007, in which twenty absolute gravimeters took part. A short description of the data processing and adjustments will be presented here and will be followed by the presentation of the results. Two different methods were applied to estimate the relative offsets between the gravimeters. We show that the results are equivalent as the uncertainties of both adjustments overlap. The absolute gravity meters agree with one another with a standard deviation of 2 μGal (1 Gal = 1 cm/s^2).

Keywords. Absolute gravimetry, gravimeter, metrology.

1 Introduction

On November 6th to November 14th 2007, Luxembourg's European Center for Geodynamics and Seismology (ECGS) hosted an international comparison of absolute gravimeters in the Underground Laboratory for Geodynamics in Walferdange (WULG). Twenty gravimeters from 15 countries (from Europe and 1 team from China) took part the comparison. Four different types of gravimeters were present: 17 FG5's, 1 Jilag, 1 IMGC and 1 prototype MPG#2 (Table 1).

In 1999, a laboratory (Figure 1) dedicated to the comparison of absolute gravimeters was built within the WULG. The laboratory lies 100 meters below the surface at a distance of 300 m from the entrance of the mine. The WULG is environmentally stable (i.e. constant temperature and humidity within the lab), and is extremely well isolated from anthropogenic noise. It has the power and space requirements to be able to accommodate up 16 instruments operating simultaneously.

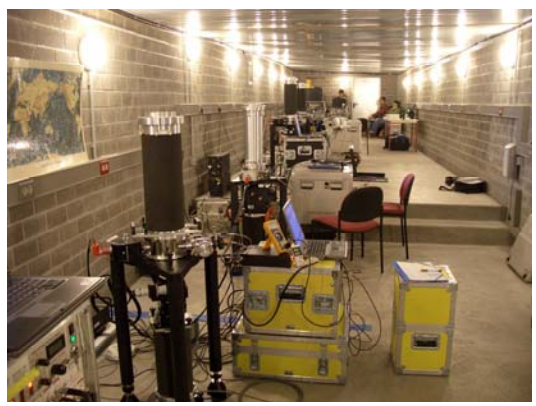

Fig. 1 Picture taken during the comparison of absolute gravimeters in the Underground Laboratory for Geodynamics in Walferdange.

Multiple absolute gravimeter comparisons are regularly carried out. Being absolute instruments, these gravimeters cannot really be calibrated. Only some of their components (such as the atomic clock and the laser) can be calibrated by comparison with known standards. The only way one currently has to verify their good working order is via a simultaneous comparison with other absolute gravimeters of the same and/or if possible even of a different model, to detect possible systematic errors.

During a comparison, we cannot estimate how accurate the meters are: in fact, as we have no way to know the true value of g, we can only investigate the relative offsets between instruments. This means that all instruments can suffer from the same unknown and undetectable systematic error. However, differences larger than the uncertainty of

Table 1. Participants in the European Comparison of Absolute Gravimeters in Walferdange – November 2007.

Country	Institution	Absolute gravimeter
Austria	Federal Office of Metrology and Surveying (BEV)	JILAg#6
Luxembourg	University of Luxembourg/ECGS	FG5#216
Belgium	Royal Observatory of Belgium	FG5#202
China	China Earthquake Administration (CEA)	FG5#232
Czech Republic	Geodetic Observatory Pecny	FG5#215
Finland	Finnish Geodetic Institute	FG5#221
France	CNRS - Géosciences Montpellier	FG5#228
	EOST, Strabourg	FG5#206
Germany	Leibniz Universität Hannover	FG5#220
	Bundesamt für Kartographie und Geodäsie	FG5#101
	University Erlangen-Nuremberg	MPG#2
Italy	Istituto Nazionale di Ricerca Metrologica (INRIM)	IMGC#02
	Italian Space Agency	FG5#218
Norway	University of Environmental and Life Sciences	FG5#226
Poland	Institute of Geodesy and Geodetic - Warsaw University of Technology	FG5#230
Spain	National Geographic Institute of Spain	FG5#211
Sweden	National Land Survey of Sweden - Geodetic Research Division	FG5#233
The Netherlands	Faculty of Aerospace Engineering DEOS/PSG	FG5#234
United Kingdom	Proudman Oceanographic Laboratory	FG5#222
	Natural Environnement Research Council	FG5#229

the measurements, is usually indicative of a possible systematic error.

For the second comparison in Walferdange, a few new procedures have been introduced. First, some of the participants accepted to take part in a European Association of National Metrology Institutes (EUROMET) Pilot Study in anticipation of the next key comparison at the BIPM in November 2009. This means that metrological rules of comparison were strictly followed. Secondly, it has been decided that the raw observations will not be processed by the same individual with the same software as in the past comparisons. Each operator had to process the data himself and present his results. This allows us to test the instruments as well as the data processing done by the operators. Third, for the first time during a comparison, a superconducting gravimeter was continuously recording the environmental gravity changes (Figure 2).

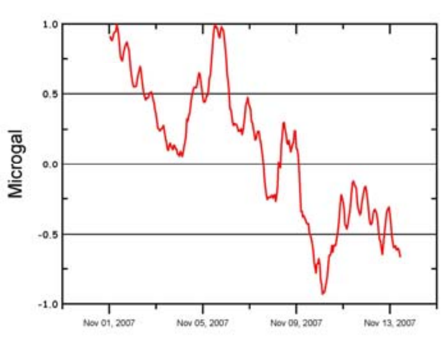

Fig. 2 Hourly record of the superconducting gravimeter CT40 in the WULG during the comparison corrected for tides and barometric effect pressure.

The observed variation is about 1 microgal. At this stage, no correction based on this data set has been applied yet. Finally, due to the large number of instruments, the comparison was split in two sessions of 3 days each.

2 Protocol

Ideally to compare gravimeters, they should measure at the same site at the same time. Obviously, this is impossible for a practical point of view. Thus, the comparison was spread over three days. The first day, each instrument was installed at one of the 16 bench marks or sites. The second day, as the WULG is composed of three different platforms, all instruments moved to another site on a different platform and again on the third day. Overall, each instrument occupied at least 3 sites one on each platform. We also planned the observations in such a way, that two different instruments which occupied the same site did not measure at another common site again. This allows us to compare each instrument to as many other instruments possible.

3 Data processing

Each operator provided the final g-values and their uncertainties for each station occupation. To process the data, they used the vertical gravity gradients and the observed tidal parameters obtained from the analysis of a 3-year record of the superconducting gravimeter in WULG. The atmospheric pressure effect was removed using a constant admittance and the polar motion effect using pole positions from IERS. The vertical gravity gradient was measured by three different operators (O. Francis, M. Van Camp and P. Richard) with two Scintrex CG3-Ms and one Scintrex CG5 before the 2003 comparison (O. Francis et al., 2006). Gradients were remeasured in 2007 by O. Francis. As no significant variations have been observed, the same values as those used in 2003 have been applied. Comparisons between the rubidium clocks and the barometers were carried out by M. Van Camp and R. Falk. The results of these calibrations were communicated to the operators who were responsible for using these calibrations or not in the data processing. We did not have any laser calibrations as the WULG is not equipped for this.

4 Adjustment of the data

Data from one instrument (MPG#2) were discarded as the instrument, being a prototype, had a significant offset that would have biased the final adjustment.

As each gravimeter measured at only 3 sites of the 16 sites, the g-values have to be adjusted to compare the results of all the gravimeters. Two different approaches for adjusting the data have been carried out.

In the first approach, O. Francis performed a least-square adjustment of the absolute gravimeters measurements using the following observation equation:

$$g_{ik} = g_k + \delta_i + \varepsilon_{ik}$$

$$\text{with the condition } \sum_i \delta_i = 0$$

where g_{ik} is the gravity value at the site k given by the instrument i, g_k is the adjusted gravity value at the site k, δ_i the offset of gravimeter i and ε_{ik} the stochastic error. The condition that the sum of the offsets should be zero is essential, otherwise the problem is ill-posed and numerically unstable. Without this condition, there is an infinite number of solutions: if one finds a solution (i.e. a set of the theoffsets of each instrument), on could find another solution simply by adding the same constant value to each offset. This expresses mathematically that one cannot estimate the true g value but only a reference value which is defined as the most likely value.

As a priori error, the mean set standard deviation as given by the operator plus a systematic error of 2 μGal has been implemented. The results are shown in Figure 3 and in Tables 2 and 3. The error bars are the a posteriori standard deviation resulting from the least-square fit.

In the second approach, A. Germak took the average value at each site and calculated the difference for each instrument with the average value. He obtained three values of the offset for each instrument corresponding to the three occupations. The mean value was then calculated as well as the standard deviation. The uncertainty assessment in this approach is much more elaborate than in the first approach. The operators were asked to provide as complete as possible a description of the stochastic and systematic errors affecting their gravimeters. The reported expanded uncertainty of measurement shown in Figure 3 for the blue results is stated as the standard uncertainty of measurement multiplied by the coverage factor $k = 2$, which for a normal distribution corresponds to a coverage probability of approximately 95%.

Table 2. Results of the adjustement of all the absolute gravity data expressed in microgal after substraction of the reference value 980 960 000 microgal for two different methods of adjustment (OF = O. Francis and AG = A. Germak).

Site	g value OF /μGal	g value AG /μGal	Difference
A1	4227.4 ±1.0	4228.2±1.0	-0.8
A2	4216.4 ± 1.0	4216.4±1.2	0.0
A3	4206.6 ± 1.2	4206.4±3.1	0.2
A4	4192.6 ± 1.1	4193.4±0.6	-0.8
A5	4184.7 ± 1.1	4184±1.1	0.7
B1	4079.3 ±1.2	4080.6±0.6	-1.3
B2	4070.6±2.1	4067.2±1.0	3.4
B3	4069.0±0.6	4069.7±0.6	-0.7
B4	4064.5±1.0	4063.2±0.8	1.3
B5	4049.9±1.0	4050.8±0.7	-0.9
C1	3951.9±0.9	3951±1.0	0.9
C2	3949.3±0.9	3949.7±1.1	-0.4
C3	3949.3±0.9	3949.5±1.0	-0.2
C4	3946.5±1.1	3946.2±1.6	0.3
C5	3943.8±1.0	3944.8±1.2	-1.0
C6	3943.9 ±1.0	3944.5±1.4	-0.6

Both approaches give equivalent results with differences less than 1 microgal except for the FG5#226. However, the estimated uncertainties are much bigger for the second approach. This could be explained partly by the coverage factor which is not applied in the first approach and by the more complete and detailed budget error used in the second approach.

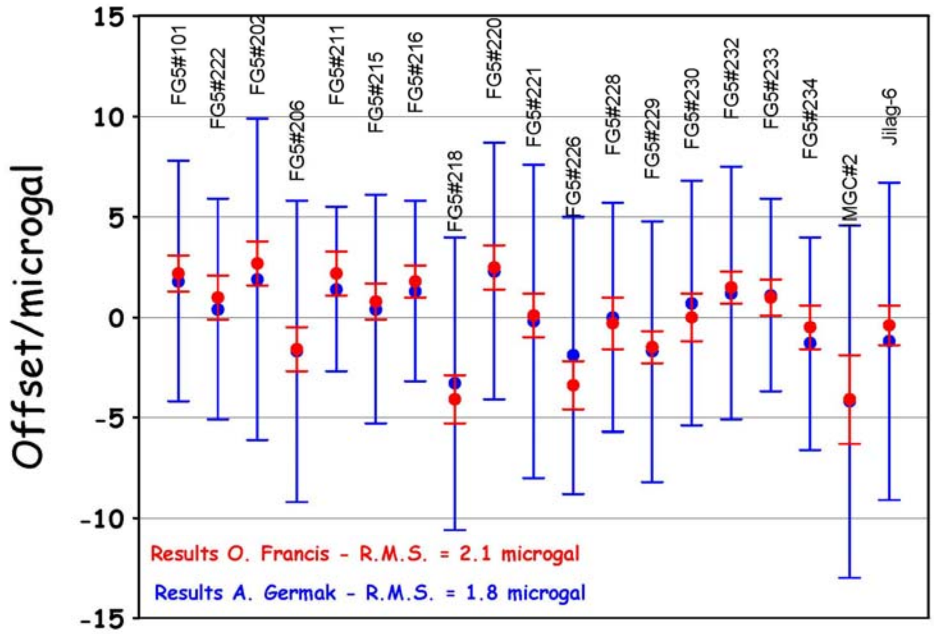

Fig. 3 Relative offsets between the gravimeters for two different methods of adjustment (O. Francis in red and A. Germak in blue).

Table 3. Relative offsets between the gravimeters for two different methods of adjustment (OF = O. Francis and AG = A. Germak).

Instrument	Offset OF /μGal	Offset AG /μGal	Difference
FG5#101	2.2 ± 0.9	1.8 ± 6.0	0,4
FG5#222	1.0 ± 1.1	0.4 ± 5.5	0,6
FG5#202	2.7 ± 1.1	1.9 ± 8.0	0,8
FG5#206	-1.6 ± 1.1	-1.7 ± 7.5	0,1
FG5#211	2.2 ± 1.1	1.4 ± 4.1	0,8
FG5#215	0.8 ± 0.9	0.4 ± 5.7	0,4
FG5#216	1.8 ± 0.8	1.3 ± 4.5	0,5
FG5#218	-4.1 ± 1.2	-3.3 ± 7.3	-0,8
FG5#220	2.5 ± 1.1	2.3 ± 6.4	0,2
FG5#221	0.1 ± 1.1	-0.2 ± 7.8	0,3
FG5#226	-3.4 ± 1.2	-1.9 ± 6.9	-1,5
FG5#228	-0.3 ± 1.3	0.0 ± 5.7	-0,3
FG5#229	-1.5 ± 0.8	-1.7 ± 6.5	0,2
FG5#230	0.0 ± 1.2	0.7 ± 6.1	-0,7
FG5#232	1.5 ± 0.8	1.2 ± 6.3	0,3
FG5#233	1.0 ± 0.9	1.1 ± 4.8	-0,1
FG5#234	-0.5 ± 1.1	-1.3 ± 5.3	0,8
IMGC#2	-4.1 ± 2.2	-4.2 ± 8.8	0,1
Jilag-6	-0.4 ± 1.0	-1.2 ± 7.9	0,8
RMS	2.1	1.8	

5 Conclusions

The second international comparison of absolute gravimeters in Walferdange shows an overall agreement between the participating gravimeters of between 1.8 to 2.1 microgal depending on the method used for the final adjustment. The minimum and maximum offsets are -4.2 and 2.7 microgal.

This result demonstrates the importance of the comparison in particular if different gravimeters are used at different epochs at the same station for monitoring long term gravity variations with a precision of a few microgal. The instrumental offsets are not a limitation if they are properly monitored during comparisons.

References

Francis, O. and T. van Dam, Analysis of results of the International Comparison of Absolute Gravimeters in Walferdange (Luxembourg) of November 2003, *Cahiers du Centre Européen de Géodynamique et de Séismologie*, vol.26, 1-23, 2006.