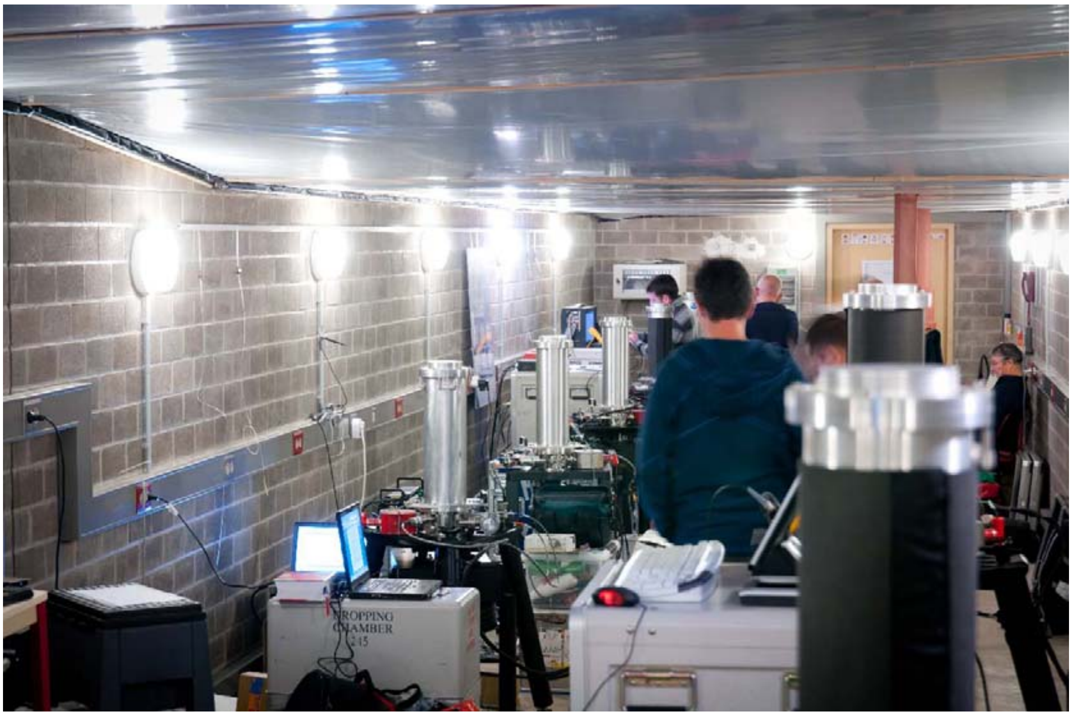
European Comparison of Absolute Gravimeters
ECAG-2011

EURAMET project 1186



Final Report of the Regional Key comparison
EURAMET.M.G-K1

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Participants

#	Country	Institution	Gravimeter	Name
1	Australia	Geoscience Australia	FG5-237	Nicolas Dando Ray Tracey
2	Austria	Federal Office of Metrology and Surveying (BEV)	FG5-242	Christian Ullrich
3	Belgium	Royal Observatory of Belgium	FG5-202	Stefaan Castelein
4	China	Tsinghua University	T1	Hu Hua Wu Kang
5	China	Institute of Seismology, China Earthquake Administration, Wuhan	FG5-232	Shen Chongyang Xuan Songbo Tan Hongbo Li Zhengyuan
6	Czech Republic	Research Institute of Geodesy, Topography and Cartography	FG5-215	Vojtech Pálinkás Jakub Kostelecký
7	Finland	Finnish Geodetic Institute	FG5-221	Jaakko Mäkinen Jyri Näränen
8	France	LNE-SYRTE	CAG-1	Sébastien Merlet Tristan Farah Christine Guerlin Franck Pereira Dos Santos
9	France	Université de Montpellier 2	FG5-228	Nicolas Le Moigne Cédric Champollion Sabrina Deville
10	Germany	Leibniz Universität Hannover	FG5-220	Ludger Timmen
11	Germany	Federal Agency for Cartography and Geodesy (BKG)	FG5-301	Reinhard Falk Herbert Wilmes
12	Italy	ASI (Agenzia Spaziale Italiana)	FG5-218	Domenico Iacovone Francesco Baccaro
13	Italy	INRIM-Istituto Nazionale di Ricerca Metrologica	IMGC-02	Alessandro Germak Emanuele Biolcati
14	Luxembourg	University of Luxembourg	FG5X-216	Olivier Francis Gilbert Klein
15	Poland	Institute of Geodesy and Cartography	A10-020	Jan Krynski Marcin Sekowski
16	Poland	Warsaw University of Technology	FG5-230	Tomasz Olszak Andrzej Pachuta
17	Sweden	Lantmäteriet – the Swedish mapping, cadastral and land registration authority	FG5-233	Jonas Agren Andreas Engfeldt
18	Switzerland	Metas	FG5-209	Henri Baumann
19	The Netherlands	Delft University of Technology	FG5-234	René Reudink Pedro Inacio
20	United Kingdom	National Oceanography Centre – Liverpool	FG5-103	Daniel McLaughlin Geoff Shannon
21	USA	National Geodetic Survey	FG5-102	Marc Eckl Tim Wilkins
22	USA	Micro-gLaCoste	FG5X-302	Derek van Westrum Ryan Billson

1. Introduction

The European Comparison of Absolute Gravimeters, ECAG 11, was held in the Underground Laboratory for Geodynamics in Walferdange, Luxembourg in November 2011. The ECAG-2011 is registered as EURAMET project 1186 as well as Key Comparison EURAMET.M.G-K1.

METAS was the Pilot Laboratory under the leadership of Dr. Henri Baumann. Prof. Dr. Olivier Francis, Dr. Christian Rothleitner and Ing. Gilbert Klein from the University of Luxembourg are the members of the local organizing committee.

Before the comparison, the Technical Protocol (TP) based on the document of the ICAG-2009 was presented to the participants. This important document includes the list of the registered participants, a description of the comparison site, the timetable of the measurements, and a standardized excel table to express the uncertainty of the gravimeters. The TP also specifies the data processing as well as the reporting of the results. The final version of the TP was approved by all the participants the 15th of September 2011.

The report is based on the EURMATE.M.GK1 Draft B report the has been approved by all participants. It includes a description of the Walferdange Underground Laboratory for Geodynamics where the comparison took place, the list of the participants, the absolute gravity measurements, the measurement strategy, a section on the self-attraction and laser beam diffraction corrections, the data processing, the results, and links with previous comparisons. In the conclusion, we also propose some recommendations for future comparisons.

2. List of participants

The list of the participants is given in Table 1. The majority of the participants are from European countries. However, the comparison was also open to non-European countries to ensure a link between other regional comparisons organized in other parts of the world. In total, 22 absolute gravimeters were compared including 6 different types of instruments. The number of FG5 free-fall gravimeters is dominant. However, one atomic gravimeter (CAG-1), one rise-and-fall gravimeter (IMGC-02) as well as a new free-fall prototype from China (T1) were present.
Overall, 6 teams from National Metrology Institutes (NMI) or Designated Institutes (DI) were participating to the ECAG11.

Table 1. Participants to ECAG-2011 (NMI = National Metrology Institutes; DI = Designated Institutes).

#	Country	Institution	Gravimeter	NMI or DI	Operator(s)
1	Australia	Geoscience Australia	FG5-237	NO	Nicolas Dando Ray Tracey
2	Austria	Federal Office of Metrology and Surveying (BEV)	FG5-242	YES	Christian Ullrich
3	Belgium	Royal Observatory of Belgium	FG5-202	NO	Stefaan Castelein
4	China	Tsinghua University	T1	NO	Hu Hua Wu Kang
5	China	Institute of Seismology, China Earthquake Administration, Wuhan	FG5-232	NO	Shen Chongyang Xuan Songbo Tan Hongbo Li Zhengyuan
6	Czech Republic	Research Institute of Geodesy, Topography and Cartography	FG5-215	YES	Vojtech Pálinkás Jakub Kostelecký
7	Finland	Finnish Geodetic Institute	FG5-221	YES	Jaakko Mäkinen Jyri Näränen
8	France	LNE-SYRTE	CAG-1	YES	Sébastien Merlet Tristan Farah Christine Guerlin Franck Pereira Dos Santos
9	France	Université de Montpellier 2	FG5-228	NO	Nicolas Le Moigne Cédric Champollion Sabrina Deville
10	Germany	Leibniz Universität Hannover	FG5-220	NO	Ludger Timmen
11	Germany	Federal Agency for Cartography and Geodesy (BKG)	FG5-301	NO	Reinhard Falk Herbert Wilmes
12	Italy	ASI (Agenzia Spaziale Italiana)	FG5-218	NO	Domenico Iacovone Francesco Baccaro
13	Italy	INRIM-Istituto Nazionale di Ricerca Metrologica	IMGC-02	YES	Alessandro Germak Emanuele Biolcati
14	Luxembourg	University of Luxembourg	FG5X-216	NO	Olivier Francis Gilbert Klein
15	Poland	Institute of Geodesy and Cartography	A10-020	NO	Jan Krynski Marcin Sekowski
16	Poland	Warsaw University of Technology	FG5-230	NO	Tomasz Olszak Andrzej Pachuta
17	Sweden	Lantmäteriet – the Swedish mapping, cadastral and land registration authority	FG5-233	NO	Jonas Agren Andreas Engfeldt
18	Switzerland	Metas	FG5-209	YES	Henri Baumann
19	The Netherlands	Delft University of Technology	FG5-234	NO	René Reudink Pedro Inacio
20	United Kingdom	National Oceanography Centre – Liverpool	FG5-103	NO	Daniel McLaughlin Geoff Shannon
21	USA	National Geodetic Survey	FG5-102	NO	Marc Eckl Tim Wilkins
22	USA	Micro-gLaCoste	FG5X-302	NO	Derek van Westrum Ryan Billson

3. Site description

The comparison was held in the Underground Laboratory for Geodynamics in Walferdange. This specially designed laboratory, dedicated to the comparison of absolute gravimeters, was built in 1999. The laboratory lies 100 meters below the surface at a distance of 300 m from the entrance to an abandoned mine. To transport the 350 kilograms of equipment (the typical weight of an absolute gravimeter and its peripherals) over the 300 meters to the laboratory, electric golf carts were used. The carts travel on a smooth concrete surface to avoid vibrations.

The WULG is environmentally stable (i.e. constant temperature and humidity within the laboratory), and is extremely well isolated from anthropogenic noise. It has the power and space requirements able to accommodate 15 instruments operating simultaneously (Figure 1). In addition, the mine is equipped with the Superconducting Gravimeter OSG-CT040 which continuously measures the variations of the acceleration due to gravity with a precision of 5 $(nm/s^2)^2/Hz$.

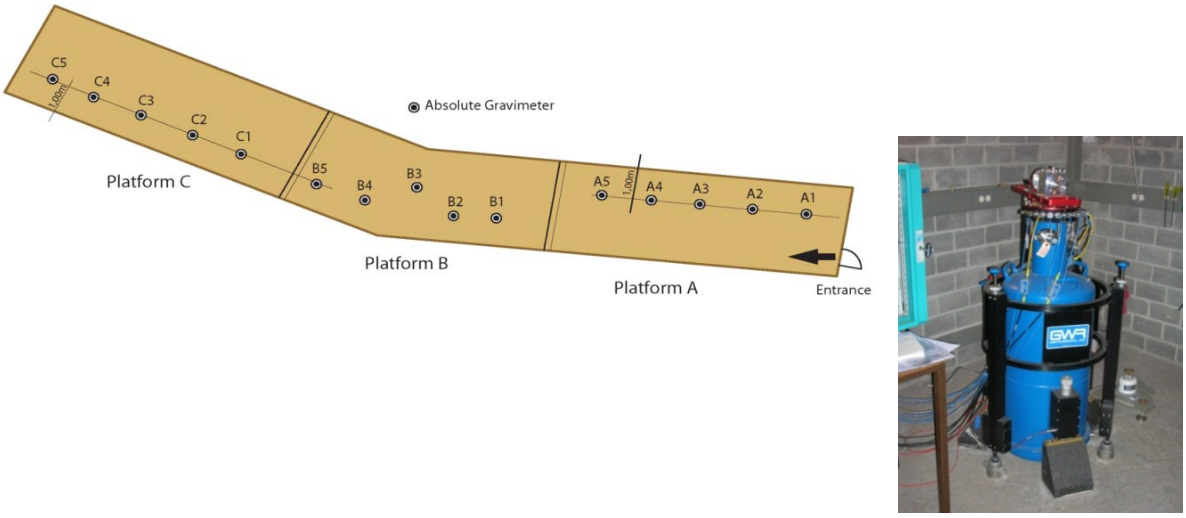

Figure 1: Sketch of the underground laboratory allowing for the simultaneous set up of 15 gravimeters (40 m length and 3.6 m wide) and the superconducting gravimeter OSG-CT040.

The vertical gravity gradients were measured with Scintrex spring relative gravimeters at each site for the previous comparisons, ECAG-2003 (Francis and van Dam, 2006) and ECAG-2007 (Francis et al., 2010). A month before ECAG-2011, Tomas Volarik re-measured the gradients at 3 sites. As the new results were consistent with the old ones (the errors bars overlapped), we did not re-measure the 12 other sites. The values of the vertical gravity gradients of the previous comparisons (Table 1) were re-used.
The observed tidal parameters (Table 2) were estimated from 4 years of continuous measurements of the superconducting gravimeter OSG-CT040 installed in a room next to the comparison site (at less than 20 meters). It was calibrated with an uncertainty of 10-4 using an absolute gravimeter.
The OSG-CT040 also provided continuous observations of the time changes of the acceleration due to gravity. It is used to monitor geophysical gravity changes that could happen during the comparison. It also allowed us to link the measurements performed a few weeks or even months after the official time schedule of the comparison.

Table 1: Vertical gravity gradients at the 15 gravity stations inside the WULG (taken from Francis and van Dam, 2006).

Site	Vertical gravity gradient/ μGal/m
A1	-289.7±2.0
A2	-271.5±1.9
A3	-262.0±2.0
A4	-267.7±2.3
A5	-262.9±2.3
B1	-288.1±1.9
B2	-277.6±2.0
B3	-274.6±1.8
B4	-264.5±2.0
B5	-267.7±2.0
C1	-275.7±1.9
C2	-273.0±1.7
C3	-271.9±1.0
C4	-261.6±1.0
C5	-264.2±1.0

Table 2: Observed tidal parameters for the Walferdange Underground Laboratory for Geodynamics from 4 years of continuous observations with the superconducting gravimeter OSG-CT040.

Wave	Start frequency/ cpd	End frequency/ cpd	Amplitude Factor	Phase Lead/ degree
DC	0.000000	0.000001	1.00000	0.0000
Long Period	0.000002	0.249951	1.16000	0.0000
Q_1	0.721500	0.906315	1.14218	-1.4047
O_1	0.921941	0.940487	1.15001	0.1310
M_1	0.958085	0.974188	1.16448	1.1522
K_1	0.989049	1.011099	1.13628	0.3612
J_1	1.013689	1.044800	1.17370	0.8380
OO_1	1.064841	1.216397	1.17638	4.7836
$2N_2$	1.719381	1.872142	1.12839	3.3773
N_2	1.888387	1.906462	1.18419	3.5318
M_2	1.923766	1.942754	1.19031	2.5519
L_2	1.958233	1.976926	1.19620	2.7367
S_2	1.991787	2.182843	1.19406	1.1885
M_3	2.753244	3.081254	1.05599	0.0000
M_4	3.791964	3.937897	1.05000	0.0000

4. Raw absolute gravity measurements

The raw Absolute Gravity (AG) measurement is the mean free-fall acceleration at the reference height corrected for:

- the gravimetric Earth tides including the oceanic attraction and loading effects. The corrections are made according to Resolution 16 of the 18th General Assembly of the IAG 1983 to obtain "zero-tide” values for gravity (IERS, 2003);
- the atmospheric attraction and loading effects using an admittance factor of -0.3 µgal/hPa on the difference between atmospheric pressure of a standard model and the local air pressure measurement;
- the polar motion effects estimated from the pole position as published by the Earth Rotation and Reference Systems Service (IERS).

The operators were responsible for processing their own gravity data. They submitted the final g-values for all the measured sites at 1.3 m above the benchmark, their associated mean set standard deviations, and their uncertainties which contain all the known instrumental uncertainties plus the site dependent uncertainty. The reported time of the measurement is the average of the times of the observations contributing to the measurement.

A detailed form for describing the uncertainty budget of an absolute gravimeter was provided to each of the participating groups in the TP. The form was prepared for the ICAG-2009 (CCM Working Group on Gravity and IAG Study Group on Comparison of Absolute Gravimeters, 2009) and described the “unified” uncertainty budget of absolute gravimeters.

The 65 AG measurements from the 22 absolute gravimeters over the 15 stations are listed in Table 3. In addition to the g-values, their associated mean set standard deviation and combined uncertainty were requested. The first one is computed directly from the observations. It is the standard deviation of the averaged set-values. The second one, the combined uncertainty, is estimated by each operator according to the instructions of the TP approved by all the participants before the comparison.

Table 3: List of all the raw AG measurements (uncorrected for the self-attraction and diffraction corrections): σ is the mean set standard deviation and u is the uncertainty declared by the participants. The gravity change as measured by the Superconducting Gravimeter (SG) is given in the last column. This value has been calculated by averaging the SG observations over the same time window as each AG measurement session.

Date	Time	Gravimeter	Site	#Sets/ #Drops	g @1.30 m /µGal	σ /µGal	u /µGal	SG data /µGal
2-3 Nov.	19:14 - 7:19	A10-020	C4	26/120	980963953.3	2.2	10.5	-0.9
3-4 Nov.	18:01 - 7:06	A10-020	B1	28/120	980964064.9	1.7	10.5	-1.0
5 Nov.	7:09 - 7:32	A10-020	C3	8/120	980963955.6	2.4	10.5	-0.2
28-31 Oct.	17:46 - 7:01	CAG-01	C2	1/282000	980963961.2	0.2	4.8	-0.2
1-2 Nov.	18:36 - 7:33	CAG-01	A5	1/104000	980964195.7	0.3	4.9	-0.4
2-3 Nov.	18:27 - 7:15	CAG-01	A2	1/102400	980964225.3	0.4	5.0	-0.9
8-9 Nov.	17:00 - 7:16	FG5-102	A1	15/100	980964229.9	0.3	1.8	0.1
9-10 Nov.	12:00 - 8:08	FG5-102	B1	21/100	980964076.5	0.2	1.8	0.2
10-11 Nov.	16:00 - 8:08	FG5-102	C1	17/100	980963951.8	0.2	1.8	0.6
8-9 Nov.	17:00 - 8:33	FG5-103	A2	16/200	980964223.8	0.8	1.8	0.1
9-10 Nov.	12:00 - 7:33	FG5-103	B2	20/200	980964076.3	1.0	1.8	0.2
10-11 Nov.	11:00 - 9:00	FG5-103	C2	22/200	980963954.4	1.3	1.8	0.5

8-9 Nov.	16:30 - 7:30	FG5-202	A3	16/100	980964217.0	1.3	2.1	0.1
9-10 Nov.	15:00 - 7:00	FG5-202	B3	17/100	980964077.5	1.3	2.1	0.2
7-8 Nov.	20:00 - 9:00	FG5-202	C3	13/100	980963956.4	1.2	2.1	0.4
8-9 Nov.	9:34 - 6:44	FG5-209	B1	28/100	980964082.9	0.5	1.9	0.2
9-10 Nov.	9:52 - 6:53	FG5-209	C5	28/100	980963945.6	0.5	1.9	0.2
10 Nov.	9:47 - 16:46	FG5-209	A2	15/100	980964221.6	0.5	1.9	0.4
8-9 Nov.	10:59 - 7:25	FG5-215	A5	21/150	980964191.0	0.2	2.3	0.2
9-10 Nov.	11:00 - 7:25	FG5-215	B5	21/150	980964055.2	0.2	2.3	0.2
10-11 Nov.	10:00 - 9:30	FG5-215	C5	15/150	980963949.3	0.1	2.3	0.5
8-9 Nov.	18:24 - 5:34	FG5-218	B4	12/120	980964069.2	1.3	1.8	0.1
9-10 Nov.	18:30 - 5:40	FG5-218	C3	12/120	980963952.5	1.4	1.9	0.2
10-11 Nov.	17:42 - 4:52	FG5-218	A5	12/120	980964187.8	1.9	1.9	0.5
2-3 Nov.	19:00 - 6:38	FG5-220	B2	24/50	980964075.8	1.4	2.1	-0.9
3-4 Nov.	19:00 - 14:14	FG5-220	C2	12/100	980963954.5	2.4	2.1	-1.0
4-5 Nov.	18:52 - 6:30	FG5-220	A5	24/50	980964189.7	1.9	2.1	-0.5
8-9 Nov.	16:20 - 7:58	FG5-221	A4	32/50	980964198.6	0.2	2.6	0.1
9-10 Nov.	18:02 - 7:40	FG5-221	B4	28/50	980964070.2	0.2	2.6	0.3
10-11 Nov.	17:33 - 8:11	FG5-221	C4	30/50	980963954.1	0.3	2.6	0.6
8-9 Nov.	13:35 - 8:05	FG5-228	C1	38/120	980963958.3	0.7	1.9	0.2
9-10 Nov.	10:28 - 5:58	FG5-228	A2	40/120	980964221.6	0.9	1.9	0.2
10-11 Nov.	9:55 - 7:25	FG5-228	B5	43/120	980964055.6	1.0	1.9	0.5
8-9 Nov.	18:30 - 7:50	FG5-230	B2	14/125	980964064.5	1.9	1.9	0.1
9-10 Nov.	18:10 - 7:30	FG5-230	C1	14/125	980963945.2	1.3	1.9	0.3
10-11 Nov.	17:40 - 7:00	FG5-230	A3	14/125	980964201.8	1.6	1.9	0.5
9-10 Nov.	18:59 - 2:04	FG5-232	A4	15/100	980964199.3	0.6	2.0	0.2
10 Nov.	10:42 - 16:58	FG5-232	B2	13/100	980964073.8	0.6	2.0	0.4
10-11 Nov.	19:01 - 06:46	FG5-232	C3	24/100	980963950.3	0.5	1.9	0.6
8-9 Nov.	16:37 - 7:45	FG5-233	C4	31/50	980963958.5	0.3	2.4	0.1
9-10 Nov.	13:37 - 7:45	FG5-233	A5	36/50	980964193.5	0.3	2.4	0.2
10-11 Nov.	12:37 - 7:45	FG5-233	B3	39/50	980964081.2	0.2	2.4	0.5
1-2 Dec.	20:30 - 3:39	FG5-234	A1	15/100	980964233.2	1.1	2.0	0.1
29-30 Nov.	21:30 - 4:47	FG5-234	C4	15/100	980963954.5	1.6	2.0	0.0
30 Nov -1Dec.	21:30 - 4:39	FG5-234	B5	15/100	980964055.3	1.1	2.0	-0.2
2-3 Nov.	19:00 - 7:00	FG5-237	B3	24/100	980964074.6	2.4	1.9	-0.9
3-4 Nov.	19:00 - 7:00	FG5-237	C1	24/100	980963956.6	1.6	1.8	-1.0
4 Nov.	13:30 - 20:00	FG5-237	C5	13/100	980963947.2	1.2	1.8	-0.9
30 Oct - 1 Nov.	14:33 - 8:15	FG5-242	B5	45/100	980964053.9	1.3	2.7	-0.6
1-2 Nov.	11:07 - 8:07	FG5-242	B4	43/100	980964067.7	1.2	2.6	-0.5
2-3 Nov.	16:32 - 8:32	FG5-242	A3	33/100	980964215.5	1.5	2.8	-0.9
2-3 Nov.	18:37 - 13:49	FG5-301	B4	23/150	980964064.5	0.5	2.1	-0.9
3-4 Nov.	15:03 - 8:27	FG5-301	B3	20/150	980964070.8	1.2	2.1	-1.0
4-5 Nov.	13:28 - 7:47	FG5-301	A2	22/150	980964219.9	0.8	2.1	-0.6
9-10 Nov.	17:44 - 4:44	FG5X-216	A3	12/200	980964215.3	1.0	2.0	0.2
10-11 Nov.	16:17 - 3:18	FG5X-216	B1	12/200	980964088.1	0.9	2.0	0.5
8-9 Nov.	19:08 - 6:08	FG5X-216	C2	12/200	980963954.7	1.6	2.0	0.1
9-10 Nov.	12:00 - 6:00	FG5X-302	A1	36/100	980964231.9	0.2	2.1	0.2
10-11 Nov.	12:00 - 6:00	FG5X-302	B4	36/100	980964064.9	0.4	2.1	0.5
6-7 Nov.	12:00 - 6:00	FG5X-302	C5	70/100	980963946.2	0.3	2.1	0.4

3 Nov.	11:32 - 15:59	IMGC02	C5	1/252	980963940.7	1.7	4.3	-1.0
3-4 Nov.	18:49 - 8:35	IMGC02	C4	1/754	980963944.9	0.9	4.1	-1.0
31 Oct - 1 Nov.	17:00 - 1:30	T-1	C2	18/16	980963955.4	0.7	5.9	-0.7
1-2 Nov.	20:45 - 8:45	T-1	B5	25/16	980964056.8	1.2	6.0	-0.4
5-6 Nov.	19:15 - 5:45	T-1	C3	22/16	980963957.6	0.9	6.0	0.1

5. Measurement strategy

All 15 gravity sites (5 on 3 different platforms) were used during the comparison. Each gravimeter measured at three sites. However, the data for the B2 site from the IMGC-02 were removed from the comparison as the operators detected a problem during the data processing causing a systematic error.
The schedule was arranged in such a way that two instruments did not measure twice at the same site. In addition, the program has been optimized in such a way that each station was measured by 2 to 5 gravimeters. Each gravimeter occupied the same stations as at least 8 other gravimeters.
The comparison was organized in two consecutive sessions. The first one took place between the 2nd to the 5th of November 2011 with 9 gravimeters. This first group includes the atomic gravimeter (CAG-1) as it needs more room and time to operate. In fact, the CAG-1 started the measurements as earlier as the 28th of October 2011. The second session with 13 gravimeters started the 8th of November 2011 and finished the 11th of November 2011.

6. Self attraction and beam diffraction correction

In the TP, the participants were asked to provide the g-values and their associated uncertainties without applying corrections for the self-attraction of the gravimeter and for the diffraction of the laser beam. The operators were also asked to submit an estimate for these two corrections. Only 8 teams - including all the KC participants – provided this information (Table 4). For those (all FG5s and A-10) who did not give an estimate, the corrections provided by the manufacturer were adopted (van Westrum and Niebauer, 2003).
It is interesting to note that these two effects almost cancel each other. For most of the gravimeters, the sum is insignificant as its uncertainty if bigger than the effects. However, for a few instruments, this is not the case. It is of the upmost importance to apply these corrections for two reasons: 1. when comparing different types of gravimeters for which the combination of these two corrections is significant (like for the CAG-1, IMGC-02 and T-1); 2. it is better to remove any known systematic error and include its uncertainty in the combined uncertainty.

Table 4: Corrections for the effects of the self-attraction of the gravimeters and of the diffraction of the laser beam.

Gravimeter	Self-attraction correction /µGal	Diffraction correction /µGal	Total correction /µGal
CAG-01	-1.3 ± 0.1	-0.05 ± 0.02	-1.3 ± 0.1
FG5-209	-1.3 ± 1.0	+2.5 ± 1.0	+1.2 ± 1.4
FG5-215	-1.8 ± 0.3	+1.6 ± 0.7	-0.2 ± 0.8
FG5-221	-1.1 ± 0.2	+1.4 ± 0.3	+0.3 ± 0.4
FG5-242	-1.3 ± 0.1	+1.0 ± 0.1	-0.3± 0.1
FG5X-302	-1.4 ± 0.5	+1.2 ± 0.5	-0.2 ± 0.7
IMGC-02	+0.6±0.1	+5.2±0.5	+5.8±0.5
T-1	-2.0 ± 0.5	+4.2 ± 0.8	+2.2 ± 0.9
A-10 and FG5s	-1.4 ± 0.5	+1.2 ± 0.5	-0.2 ± 0.7

7. Data processing

As each gravimeter measured at only three of the 15 sites, the g-values cannot be directly compared. For ECAG-2011, the procedure used in the 2007 comparison in Walferdange (Francis et al., 2010) and in the NACAG-2010 (Schmerge et al., 2011) was adopted. A global weighted least-square adjustment is performed using as input the g-values given by the operators and the associated expanded uncertainties. The associated expanded uncertainty is the combination of the experimental standard deviation with the combined instrumental and site uncertainties multiplied by the coverage factor k=2 (Guide to the Expression of Uncertainty in Measurement, 1995). These are the weights (strictly speaking the inverse square of the uncertainties) of the gravity observations in the least-square adjustment. The outputs are the g-value at each site and the bias (or Degree of Equivalence (DoE)) for each instrument including their expanded uncertainties U. The following observation equation was formed:

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

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 or the site dependent Comparison Reference Value (CRV), δ_i the systematic error or the bias (i.e. DoE) of gravimeter i (which is assumed to be constant during the comparison) and ε_{ik} the stochastic error. The additional condition insures that the problem is well posed and numerically stable. It is worth noting that there would be infinite sets of solutions without this condition. Indeed, adding the same constant to each bias would also provide a solution.

8. Results

The results presented in this section include all the gravimeters (except the FG5-230) that participated in the comparison. All the g-values from the KC gravimeters were corrected for the self-attraction and laser beam diffraction corrections as well as for the observed geophysical gravity changes with the SG. In order to constrain the KC solution, the gravity differences between the sites measured by all gravimeters were introduced. Each gravimeter measured at three sites. For each gravimeter, two new observations are formed by taking the gravity differences between the g-value at the first occupied station (referred below as the reference station for that specific gravimeter) and the g-values at the two other stations occupied by the same gravimeter. This procedure eliminates the assumed (by definition) "constant offsets" of the gravimeters. The variances of these new observations are obtained by summing up the variances of g-value at the reference station and of the g-values at the paired station. This simple mathematical operation induces a correlation between the two newly formed observations as the g-value of the reference station is the common reference. As it can be proved easily, the covariance is simply the variance of the g-value at the reference station. The results are presented in Tables 5 and 6 and Figure 2.

Table 5: Reference g-values at the all the sites occupied by the gravimeters participating in the KC using the gravity differences between the sites from all gravimeters. The KCRVs are the g-values minus the constant value 98096000.0 μGal, U is the expanded uncertainty.

Site	Official Key Comparison Results *Raw data corrected for self-attraction, diffraction effects and SG observations*	
	KCRVs /μGal	U /μGal
A1	4235.6	3.5
A2	4223.1	3.1
A3	4214.5	3.8
A4	4200.8	4.5
A5	4189.4	3.1
B1	4084.4	3.7
B2	4075.4	4.0
B3	4076.1	3.5
B4	4069.6	2.9
B5	4055.5	3.2
C1	3958.4	3.7
C2	3953.9	3.7
C3	3952.8	3.7
C4	3955.1	3.5
C5	3948.6	2.9

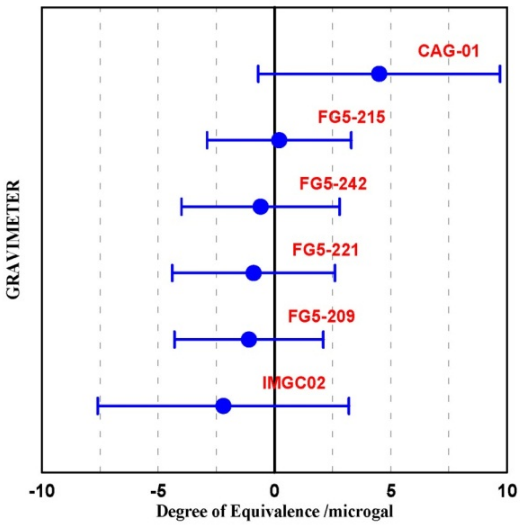

Figure 2: Degrees of Equivalence (DoE) of the gravimeters participating in the KC using the gravity differences between the sites from all gravimeters. Absolute measurements corrected for the self-attraction, laser beam diffraction effects and geophysical gravity changes observed with the SG.

Table 6: Degrees of Equivalence (DoE) of the gravimeters participating in the KC.

Gravimeter	Official Key Comparison Results *Raw data corrected for self-attraction, diffraction and SG observations*	
	DoE /μGal	U /μGal
CAG-01	+4.5	5.2
FG5-209	-1.1	3.2
FG5-215	+0.2	3.1
FG5-221	-0.9	3.5
FG5-242	-0.6	3.4
IMGC02	-2.2	5.4
Std Dev	+2.3	1.0

9. Links to previous comparisons

In order to link ECAG-2011 to earlier comparisons, the degrees of equivalence for the gravimeters that took part in the three last comparisons ECAG-2007 (Francis et al., 2010), ICAG-2009 (Arias et al., 2012) and NACAG-2010 (Schmerge et al., 2012) were compared in figure 3 and resumed in table 6.

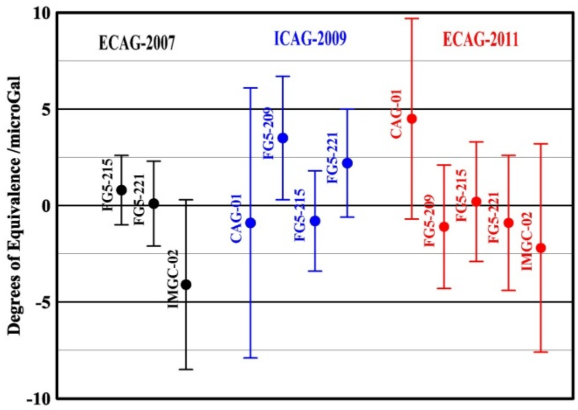

Figure 3: Degrees of Equivalence for the KC gravimeters which participated in ECAG-2007, ICAG-2009 and ECAG-2011.

Table 6: Comparison between the Degrees of Equivalence for the ECAG-2007, ICAG-2009, NACAG-2010 and ECAG-2011. The KC gravimeters are in red.

Gravimeter	ECAG-2007		ICAG-2009		ECAG-2011	
	DoE/ µGal	U/ µGal	DoE/ µGal	U/ µGal	DoE/ µGal	U/ µGal
CAG-01			-0.9	7.0	+4.5	5.2
FG5-209			+3.5	3.2	-1.1	3.2
FG5-215	+0.8	1.8	-0.8	2.6	+0.2	3.1
FG5-221	+0.1	2.2	+2.2	2.8	-0.9	3.5
IMGC-02	-4.1	4.4			-2.2	5.4

10. Conclusion

In the framework of the European key comparison of absolute gravimeters EURAMET.M.G-K1, six gravimeters from different NMI's and DI have been compared in accordance of the technical protocol established and accepted by all participants. The results of the comparison shows that all six instruments are in accord to each other within a few µGal. A comparison of the respective DoE estimated during ECAG-2011 to does estimated for the same gravimeters during earlier comparisons, ICAG-2009 and ECAG-2007, shows a good agreement.