CCM.G-K2 key comparison

Original

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Final report

INTERNATIONAL COMPARISON OF ABSOLUTE GRAVIMETERS

CCM.G-K2 Key Comparison

Olivier Francis[1], Henri Baumann[2] and all the participants

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[2] *Federal Institute of Metrology METAS (Pilot)*

November 2014

Participants of the CCM.G-K2 Key Comparison and Pilot Study

#	Country or Province	Institution	Operator(s)
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2	Belgium	Royal Observatory of Belgium	Michel Van Camp Stefaan Castelein
3	Brazil	Observatório Nacional	Mauro Andrade de Sousa Rodrigo Lima Melhorato
4	China	National Institute of Metrology	Shuqing Wu Chunjian Li Jinyi Xu Duowu Su
5	China	Tsinghua University	Hua Hu, Kang Wu Gang Li Zhe Li
6	Chinese Taipei	Industrial Technology Research Institute	Wen-Chi Hsieh
7	Czech Republic	RIGTC/VUGTK Geodetic Observatory Pecný	Vojtech Pálinkás Jakub Kostelecký
8	Finland	Finnish Geodetic Institute	Jaakko Mäkinen Jyri Näränen
9	France	LNE-SYRTE	Sébastien Merlet Franck Pereira Dos Santos Pierre Gillot
10	France	Institut de Physique du Globe de Strasbourg	Jacques Hinderer Jean-Daniel Bernard
11	France	Géosciences Montpellier – CNRS -Université de Montpellier 2	Nicolas Le Moigne Benjamin Fores
12	Germany	Leibniz Universität Hannover	Olga Gitlein Manuel Schilling
13	Germany	Federal Agency for Cartography and Geodesy	Reinhard Falk Herbert Wilmes
14	Italy	INRIM-Istituto Nazionale di Ricerca Metrologica	Alessandro Germak Emanuele Biolcati Claudio Origlia
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20	Spain	Instituto Geográfico Nacional	Ana Borreguero Sergio Sainz-Maza Marta Calvo
21	Sweden	Lantmäteriet – the Swedish mapping, cadastral and land registration authority	Andreas Engfeldt Jonas Agren
22	Switzerland	Federal Institute of Metrology - Metas	Henri Baumann
23	The Netherlands	Delft University of Technology	René Reudink
24	USA	National Geodetic Survey	Mark Eckl
25	USA	Micro-g LaCoste Inc.	Derek van Westrum Ryan Billson Brian Ellis

Participants for the relative measurements

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Arnaud Watlet, Observatoire royal de Belgique, Bruxelles, Belgium.

This report is dedicated to the memory of Mark Eckl
who passed away in August 2014

1. Introduction

The International Comparison of Absolute Gravimeters (ICAG-2013) was held in the Underground Laboratory for Geodynamics in Walferdange, Luxembourg in November 2013. The ICAG-2013 is registered as the CCM.G-K2 Key Comparison and Pilot Study. This is the first time that a Key Comparison is organized outside the walls of the BIPM [2]. This comparison is also the largest ever organized with the participation of 25 gravimeters. The comparison lasted only 6 days, 2 sessions of 3 days a week apart if we exclude the two teams that participated one week before and 3 months after the “official” sessions schedule.

Prof. Dr. Olivier Francis from the University of Luxembourg is in charge of the local organization of the comparison and of the elaboration of the results. METAS is the Pilot Laboratory under the leadership of Dr. Henri Baumann.

The Technical Protocol approved by the participants prior to the comparison is available at http://kcdb.bipm.org/appendixB/appbresults/CCM.G-K2/CCM.G-K2_Technical_Protocol.pdf. This mandatory 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. It also specifies the data processing as well as the reporting of the results.

In this report, we give the list of the participants who actually performed measurements during the comparison. The data (raw absolute gravity measurements and their uncertainties) submitted by the operators as well as the corrections due to the vertical gravity gradient applied before the data adjustment are provided. The measurement strategy is briefly discussed as well as the data elaboration which did not differ significantly from the methodology used in previous comparisons. Finally, the results of the data adjustment are presented including the degrees of equivalence of the gravimeters and the key comparison reference values. For the final and official solution, we removed the absolute gravity data from gravimeters for which their observations were not compatible with a first solution including all the measurements. Overall, the measurements are all consistent given the declared uncertainties.

2. List of participants

The list of the participants is given in Table 1. In total, 25 absolute gravimeters were compared including 7 different types of instruments. The number of FG5 free-fall gravimeters is dominant. However, one atomic gravimeter (CAG-01), one rise-and-fall gravimeter (IMGC-02) as well as two new free-fall prototypes from China (NIM-3A and T-2) were present.

Overall, 10 teams from National Metrology Institutes (NMI) or Designated Institutes (DI) participated to the ICAG-2013.

Table 1. Participants to ICAG-2013 (NMI = National Metrology Institutes; DI = Designated Institutes). The metrological institutes are marked in blue.

#	**Country or Province**	Institution	**NMI or DI**	**Gravimeter**	**Operator(s)**
1	Austria	Bundesamt für Eich- und Vermessungswesen *Austria* (BEV)	YES	FG5-242	Christian Ullrich
2	Belgium	**Royal** Observatory of Belgium	NO	FG5-202	Michel Van Camp Stefaan Castelein
3	Brazil	Observatório Nacional	NO	FG5-223	Mauro Andrade de Sousa Rodrigo Lima Melhorato
4	China	National Institute of Metrology *China* (NIM)	YES	NIM-3A	Shuqing Wu, Chunjian Li, Jinyi Xu. Duowu Su
5	China	Tsinghua University	NO	T-2	Hua Hu, Kang Wu, Gang Li, Zhe Li
6	Chinese Taipei	ITRI Center for Measurement Standards *Chinese Taipei* (CMS)	YES	FG5-231	Wen-Chi Hsieh
7	Czech Republic	Research Institute of Geodesy, Topography and Cartography *Czech Republic* (VUGTK/RIGTC)	YES	FG5-215	Vojtech Pálinkás Jakub Kostelecký
8	Finland	Finnish Geodetic Institute *Finland* (FGI)	YES	FG5X-221	Jaakko Mäkinen Jyri Näränen
9	France	Observatoire de Paris / Systèmes de Référence Temps-Espace *France* (LNE-SYRTE)	YES	CAG-01	Sébastien Merlet Franck Pereira Dos Santos Pierre Gillot
10	France	Institut de Physique du Globe de Strasbourg	NO	FG5-206	Jacques Hinderer Jean-Daniel Bernard
11	France	Géosciences Montpellier – CNRS -Université de Montpellier 2	NO	FG5-228	Nicolas Le Moigne Benjamin Fores
12	Germany	Leibniz Universität Hannover	NO	FG5X-220	Olga Gitlein Manuel Schilling
13	Germany	Federal Agency for Cartography and Geodesy	NO	FG5-301	Reinhard Falk Herbert Wilmes
14	Italy	Istituto Nazionale di Ricerca Metrologica *Italy* (INRIM)	YES	IMGC-02	Alessandro Germak Emanuele Biolcati Claudio Origlia
15	Italy	ASI (Agenzia Spaziale Italiana)	NO	FG5-218	Francesco Schiavone Domenico Iacovone
16	Japan	National Metrology Institute of Japan *Japan* (NMIJ)	YES	FG5-213	Shigeki Mizushima
17	Luxembourg	University of Luxembourg	NO	FG5X-216	Olivier Francis Raphaël de Plaen Gilbert Klein Marc Seil Remi Radinovic
18	Poland	Institute of Geodesy and Cartography	NO	A10-020	Marcin Sękowski Przemysław Dykowski
19	Republic of Korea	Korea Research Institute of Standards and Science *Korea, Republic of* (KRISS)	YES	FG5X-104	In-Mook Choi Min-Seok Kim
20	Spain	Instituto Geográfico Nacional	NO	A10-006	Ana Borreguero Sergio Sainz-Maza Marta Calvo
21	Sweden	Lantmäteriet – the Swedish mapping, cadastral and land registration authority	NO	FG5-233	Andreas Engfeldt Jonas Agren
22	Switzerland	Federal Institute of Metrology, *Switzerland* (METAS)	YES	FG5X-209	Henri Baumann
23	The Netherlands	Delft University of Technology	NO	FG5-234	René Reudink
24	USA	National Geodetic Survey	NO	FG5-102	Mark Eckl
25	USA	Micro-g LaCoste Inc.	NO	FG5X-302	Derek van Westrum Ryan Billson Brian Ellis

3. Absolute gravity measurements

3.1 Data presented by the operators

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;
- 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 measurement [7] and the local air pressure according to the IAG 1984 Resolution 9 (1984);
- the polar motion effects estimated from the pole position as published by the Earth Rotation and Reference Systems Service (IERS);
- the vertical gravity gradient;
- and all known instrumental effects (e.g. self-attraction, laser beam diffraction corrections, etc…).

The corrections for tides, polar motion and atmospheric mass redistributions are in compliance with the International Earth Rotation and Reference Systems Service (IERS) conventions 2010 [5] and IAGBN (International Absolute Gravity Base- station Network) processing standards [1]

The operators were responsible for processing their gravity data. They submitted the final g-values for all the measured sites at their own favorite height above the benchmark, the standard deviations of the set mean values, and the uncertainties. These latter ones contain all the known instrumental contributions to 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.

3.2 Vertical gravity gradient and transfer to the comparison reference height

As the data presented by the operators were not given at the same common height, some additional work needed to be performed before comparing the observations.

First, all the g-values were transferred to the reference height specific to each type of gravimeters [6] using the vertical gravity gradients provided in the Protocol. The reference height and the effective measurement height [4] are referring to the same position: one is given with respect to the ground level whereas the other one is taken from the start of the drop. At that specific height, the g-value is invariant to the vertical gravity gradient. It has been recognized as a good choice when the vertical gravity gradient is poorly or not known at all. The reference height is instrument dependent: around 1.21 m, 1.25 m and 0.68 m for the FG5s, FG5Xs, A-10s, respectively.

In a second step, the new determinations of the vertical gravity gradient (see Annex A) are used to transfer the g-values from the instrumental reference heights for the FG5s and A-10s to the comparison reference height of 1.3 m. For the other types of gravimeters, their g-values were transferred from the given height to 1.3 m.

This procedure insures the optimum consistent treatment of the vertical gravity gradient for all the data.

3.3 Final data

The 73 AG measurements from the 25 absolute gravimeters over the 15 stations are listed in Table 2. In addition, the gravity changes observed with the OSG-CT040 are provided in the last column of the same table. The SG observations are corrected using the same tides prediction and atmospheric admittance factor as for the absolute gravity measurements. As the instrumental drift of the OSG-CT040 is less than 1 μgal/year, no drift correction is applied. The SG values have been calculated by averaging the SG observations over the same time window as each AG measurement sessions. This correction implies that one needs to define a mean official comparison time which is November 9, 2013. In other words, all the observations have been transfer to this time for which the SG correction is zero.

According to the protocol, each gravimeter should have measured at least at three gravity stations. However, the FG5-242 could only provide the gravity value at one station: the gravimeter was seriously damaged during the comparison and it was not possible to fix it.

Table 2. List of all the raw AG measurements corrected for all the known geophysical (tides, atmospheric pressure and polar motion effects, vertical gravity gradient) and instrumental effects (speed-of light correction, laser beam diffraction, self-attraction): σ_{mes} is the standard deviation of the set mean values, u_{decl} is the uncertainty declared by the participants, VGG is the Vertical Gravity Gradient, and u is the uncertainty including the contribution of the uncertainty in the vertical gravity gradient transfer from the measurement or the instrumental reference height to the comparison reference height of 1.30 m. The gravity change as measured by the Superconducting Gravimeter (SG) is given in the last column (all the observations are "transported" in time to November 9, 2013 for which the SG data is zero). The constant value 980 960 000.0 µGal has been subtracted from the gravity measurements. k is the coverage factor.

Date	**Time**	**Gravimeter**	**Site**	**Measurement height** /cm	***g* at measurement height** /µGal	**σ_{meas}** /µGal	**u_{decl} (k=68%)** /µGal	**VGG from the Protocol** /µGal/cm	**Instrumental reference height** /cm	***g* at effective height** /µGal	***g* transfer to 1.30m** /µGal	**u_{trans}** /µGal	***g* at 1.3 m** /µGal	***u* (k=68%)** /µGal	**SG data** /µGal
11-12 Nov.	19:00-08:00	A10-006	A2	130.00	4206.2	3.7	10.6	-2.715	68	4374.5	-168.4	1.1	4206.1	10.7	0.3
12-13 Nov.	17:00-08:00	A10-006	B3	130.00	4061.2	1.7	10.6	-2.746	68	4231.5	-166.0	1.1	4065.5	10.7	0.6
13-14 Nov.	17:00-08:00	A10-006	A1	130.00	4217.7	1.3	10.6	-2.897	68	4397.3	-163.8	1.2	4233.5	10.7	0.2
11-12 Nov.	17:31-08:10	A10-020	C4	71.20	4092.5	1.8	5.1	-2.616	68	4100.9	-161.2	1.1	3939.7	5.2	0.3
12-13 Nov.	13:01-08:04	A10-020	A2	71.10	4372.2	1.3	5.3	-2.715	68	4380.6	-168.4	1.1	4212.2	5.4	0.6
13-14 Nov.	15:09-08:04	A10-020	B4	71.15	4213.7	1.5	5.4	-2.645	68	4222.0	-161.4	0.9	4060.6	5.5	0.3
24 Oct.	14:04-19:41	CAG-01	B3	83.30	4206.4	0.1	5.2	-2.746			-124.3	1.0	4082.1	5.3	1.3
26-27 Oct.	18:16-07:32	CAG-01	A4	83.20	4316.0	0.1	5.2	-2.677			-122.2	0.9	4193.8	5.3	0.6
28 Oct.	11:12-13:31	CAG-01	A2	83.25	4346.5	0.3	5.3	-2.715			-127.0	1.0	4219.5	5.4	0.4
11-12 Nov.	17:16-08:16	FG5-102	A4	130.00	4181.8	1.8	2.1	-2.677	121	4205.9	-23.3	0.3	4182.6	2.1	0.3
14 Nov.	10:35-18:05	FG5-102	B5	130.00	4042.8	1.6	2.1	-2.677	121	4066.9	-22.3	0.3	4044.6	2.1	0.4
15-16 Nov.	20:15-07:45	FG5-102	A3	130.00	4202.4	1.8	2.1	-2.620	121	4226.0	-23.4	0.4	4202.6	2.1	0.6
4-5 Nov.	17:01-08:34	FG5-202	A4	130.00	4191.6	1.6	2.1	-2.677	121	4215.7	-23.3	0.3	4192.4	2.1	-0.7
5-6 Nov.	16:54-07:54	FG5-202	B3	130.00	4068.7	1.1	2.1	-2.746	121	4093.4	-23.6	0.3	4069.8	2.1	-0.5
6-7 Nov.	14:58-07:58	FG5-202	C2	130.00	3949.3	0.9	2.1	-2.730	121	3973.9	-25.3	0.3	3948.6	2.1	-0.1
11-12 Nov.	19:08-07:08	FG5-206	A3	130.00	4201.8	2.1	2.4	-2.620	121	4225.4	-23.4	0.4	4202.0	2.4	0.3
12-13 Nov.	17:10-05:10	FG5-206	B4	130.00	4060.7	1.6	2.4	-2.645	121	4084.5	-23.2	0.3	4061.3	2.4	0.6

13-14 Nov.	17:38-04:48	FG5-206	A2	130.00	4214.4	1.5	2.4	-2.715	121	4238.8	-24.4	0.3	4214.4	2.4	0.2
5-6 Nov.	14:00-08:00	FG5-213	C1	120.50	3974.3	0.3	2.5	-2.757	121	3972.9	-23.5	0.3	3949.4	2.5	-0.6
6-7 Nov.	14:30-08:00	FG5-213	A2	120.60	4238.3	0.3	2.5	-2.715	121	4237.2	-24.4	0.3	4212.8	2.5	-0.1
7-8 Nov.	12:30-08:00	FG5-213	B5	120.55	4067.3	0.3	2.5	-2.677	121	4066.1	-22.3	0.3	4043.8	2.5	0.3
5 Nov.	10:41-21:14	FG5-215	B2	122.08	4090.8	0.2	2.3	-2.776	121	4093.8	-22.7	0.2	4071.1	2.3	-0.7
6-7 Nov.	10:13-00:28	FG5-215	C1	122.16	3972.2	0.2	2.3	-2.757	121	3975.4	-23.5	0.3	3951.9	2.3	-0.2
7-8 Nov.	10:54-00:32	FG5-215	A3	122.00	4228.6	0.2	2.3	-2.620	121	4231.2	-23.4	0.4	4207.8	2.3	0.3
11-12 Nov.	18:00-06:00	FG5-218	B3	130.00	4068.9	0.9	1.8	-2.746	121	4093.6	-23.6	0.3	4070.0	1.8	0.3
12-13 Nov.	19:00-07:00	FG5-218	C5	130.00	3942.8	0.7	1.8	-2.642	121	3966.6	-21.7	0.3	3944.9	1.8	0.6
13-14 Nov.	19:00-07:00	FG5-218	C1	130.00	3950.0	0.8	1.8	-2.757	121	3974.8	-23.5	0.3	3951.3	1.8	0.2
2-3 Feb.	10:38-08:38	FG5-223	C5	130.00	3943.2	0.9	2.1	-2.642	121	3967.0	-21.7	0.3	3945.3	2.1	-0.5
3-4 Feb.	18:28-08:18	FG5-223	A1	130.00	4227.0	0.9	2.1	-2.897	121	4253.1	-23.3	0.3	4229.8	2.1	-0.6
4-5 Feb.	12:34-03:34	FG5-223	B4	130.00	4062.3	1.3	2.1	-2.645	121	4086.1	-23.2	0.3	4062.9	2.1	-0.7
5-6 Nov.	10:50-10:28	FG5-228	C3	130.00	3941.9	1.2	1.9	-2.719	121	3966.4	-23.1	0.3	3943.3	1.9	-0.6
6-7 Nov.	14:19-08:17	FG5-228	A4	130.00	4185.7	0.7	1.9	-2.677	121	4209.8	-23.3	0.3	4186.5	1.9	-0.1
7-8 Nov.	10:53-07:28	FG5-228	B2	130.00	4067.4	1.0	1.9	-2.776	121	4092.4	-22.7	0.2	4069.7	1.9	0.2
9-10 Nov.	10:40-11:40	FG5-231	A4	130.00	4188.9	0.6	2.1	-2.677	121	4213.0	-23.3	0.3	4189.7	2.1	-0.1
11-12 Nov.	06:00-07:00	FG5-231	A5	130.00	4180.2	0.7	2.1	-2.629	121	4203.9	-23.0	0.3	4180.9	2.1	0.1
12-13 Nov.	10:30-09:00	FG5-231	B1	130.00	4073.7	0.6	2.1	-2.881	121	4099.6	-24.1	0.3	4075.5	2.1	0.6
5-6 Nov.	17:35-09:39	FG5-233	A1	130.00	4227.7	0.3	2.4	-2.897	121	4253.8	-23.3	0.3	4230.5	2.4	-0.5
6-7 Nov.	11:50-08:06	FG5-233	B1	130.00	4078.2	0.1	2.4	-2.881	121	4104.1	-24.1	0.3	4080.0	2.4	-0.1
7-8 Nov.	09:56-08:04	FG5-233	C1	130.00	3951.3	0.1	2.4	-2.757	121	3976.1	-23.5	0.3	3952.6	2.4	0.2
11-12 Nov.	20:00-06:00	FG5-234	B2	130.00	4072.4	2.6	2.1	-2.776	121	4097.4	-22.7	0.2	4074.7	2.1	0.3
12-13 Nov.	20:00-06:00	FG5-234	C4	130.00	3947.7	0.9	2.1	-2.616	121	3971.2	-22.8	0.3	3948.4	2.1	0.6
13-14 Nov.	20:00-06:00	FG5-234	C5	130.00	3941.5	0.6	2.1	-2.642	121	3965.3	-21.7	0.3	3943.6	2.1	0.2
9-10 Nov.	16:09-06:09	FG5-242	B1	130.00	4076.5	1.9	2.6	-2.881	121	4102.4	-24.1	0.3	4078.3	2.6	-0.1
11-12 Nov.	18:13-07:30	FG5-301	C1	130.00	3949.8	0.7	2.1	-2.757	121	3974.6	-23.5	0.3	3951.1	2.1	0.3
12-13 Nov.	15:58-09:29	FG5-301	A4	130.00	4188.6	1.1	2.1	-2.677	121	4212.7	-23.3	0.3	4189.4	2.1	0.6
13-14 Nov.	16:20-07:36	FG5-301	B2	130.00	4066.2	0.7	2.1	-2.776	121	4091.2	-22.7	0.2	4068.5	2.1	0.2

4-5 Nov.	09:00-11:00	FG5X-104	B4	130.00	4061.1	1.5	2.0	-2.645	125	4074.3	-12.9	0.2	4061.4	2.0	-0.6
6-7 Nov.	16:40-08:10	FG5X-104	C3	130.00	3946.5	1.5	2.0	-2.719	125	3960.1	-12.8	0.2	3947.3	2.0	-0.1
7-8 Nov.	10:00-08:00	FG5X-104	A5	130.00	4182.9	1.5	2.0	-2.629	125	4196.0	-12.8	0.2	4183.2	2.0	0.2
5-6 Nov.	16:17-03:17	FG5X-209	A3	130.00	4204.2	1.0	2.1	-2.620	125	4217.3	-13.0	0.2	4204.3	2.1	-0.6
6-7 Nov.	16:30-07:30	FG5X-209	B3	130.00	4066.2	0.9	2.1	-2.746	125	4079.9	-13.1	0.2	4066.8	2.1	-0.1
7-8 Nov.	15:51-02:51	FG5X-209	C3	130.00	3946.2	0.7	2.1	-2.719	125	3959.8	-12.8	0.2	3947.0	2.1	0.4
5-6 Nov.	18:08-08:08	FG5X-216	A5	130.00	4182.7	1.7	2.1	-2.629	125	4195.8	-12.8	0.2	4183.0	2.1	-0.5
6-7 Nov.	16:38-08:38	FG5X-216	B5	130.00	4048.9	1.1	2.1	-2.677	125	4062.3	-12.4	0.2	4049.9	2.1	-0.1
7-8 Nov.	18:08-17:38	FG5X-216	C5	130.00	3939.1	0.9	2.1	-2.642	125	3952.3	-12.0	0.2	3940.3	2.1	0.2
11-12 Nov.	18:22-06:52	FG5X-220	B1	125.00	4092.7	1.2	2.1	-2.881	125	4092.7	-13.3	0.2	4079.4	2.1	0.3
12-13 Nov.	17:02-08:02	FG5X-220	C3	125.00	3964.4	0.8	2.1	-2.719	125	3964.4	-12.8	0.2	3951.6	2.1	0.6
13-14 Nov.	16:16-06:46	FG5X-220	C4	125.00	3960.5	0.7	2.1	-2.616	125	3960.5	-12.7	0.2	3947.8	2.1	0.2
5-6 Nov.	16:34-08:27	FG5X-221	A2	126.40	4226.6	0.2	2.3	-2.715	125	4230.4	-13.6	0.2	4216.8	2.3	-0.5
6-7 Nov.	15:25-07:18	FG5X-221	B2	126.30	4082.1	0.2	2.3	-2.776	125	4085.7	-12.6	0.1	4073.1	2.3	-0.1
7-8 Nov.	14:45-06:38	FG5X-221	C2	126.20	3958.7	0.1	2.3	-2.730	125	3962.0	-14.1	0.2	3947.9	2.3	0.3
4-5 Nov.	12:00-06:00	FG5X-302	B5	130.00	4048.0	0.2	2.1	-2.677	125	4061.4	-12.4	0.2	4049.0	2.1	-0.6
6-7 Nov.	12:00-06:00	FG5X-302	C4	130.00	3946.7	0.4	2.1	-2.616	125	3959.8	-12.7	0.2	3947.1	2.1	-0.1
7-8 Nov.	12:00-06:00	FG5X-302	A1	130.00	4227.1	0.3	2.1	-2.897	125	4241.6	-12.9	0.2	4228.7	2.1	0.3
11-12 Nov.	17:05-09:06	IMGC02	B5	47.09	4256.1	0.9	5.2	-2.677			-212.4	1.0	4043.7	5.3	0.3
13 Nov.	08:09-13:20	IMGC02	C2	48.22	4168.3	1.4	5.2	-2.730			-228.3	1.1	3940.0	5.3	0.4
13-14 Nov.	17:27-07:58	IMGC02	C3	48.05	4171.3	0.8	5.2	-2.719			-216.0	0.9	3955.3	5.3	0.2
8-9 Nov.	21:00-06:09	NIM-3A	A3	103.80	4273.9	3.6	5.1	-2.620			-68.4	0.9	4205.5	5.2	0
9-10 Nov.	21:00-06:09	NIM-3A	C2	103.80	4017.7	3.2	4.8	-2.730			-73.6	0.8	3944.1	4.9	-0.1
10-11 Nov.	21:00-06:09	NIM-3A	B5	103.80	4120.6	3.6	5.1	-2.677			-65.4	0.7	4055.2	5.1	-0.1
3 Nov.	12:28-21:28	T-2	C4	119.50	3984.8	0.9	5.0	-2.616			-26.6	0.3	3958.2	5.0	-0.1
3-4 Nov.	23:15-08:15	T-2	A5	119.50	4214.9	0.7	5.0	-2.629			-26.8	0.3	4188.1	5.0	-0.1
4 Nov.	10:08-18:38	T-2	B3	119.50	4104.5	1.1	5.0	-2.746			-27.6	0.4	4076.9	5.0	-0.5

4. Measurement strategy

All 15 gravity sites of the Underground Laboratory for Geodynamics in Walferdange (5 on 3 different platforms) were used during the comparison. Each gravimeter measured on the three platforms insofar possible. The schedule was arranged in such a way that two instruments did not measure twice at the same site. There are some exceptions due to glitches in the measurements schedule. In addition, the program has been optimized in such a way that each station was measured by 4 to 6 gravimeters (Table 3). Each gravimeter has a direct link (i.e. measured at the same stations) to at least 8 other gravimeters.

Table 3. Site occupation for each gravimeter.

	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	C5
A10-006	X	X						X							
A10-020		X							X					X	
CAG-01		X		X				X							
FG5-102			X	X						X					
FG5-202				X				X				X			
FG5-206		X	X						X						
FG5-213		X								X	X				
FG5-215			X				X				X				
FG5-218								X			X				X
FG5-223	X								X						X
FG5-228				X			X						X		
FG5-231				X	X	X									
FG5-233	X					X					X				
FG5-234							X							X	X
FG5-242						X									
FG5-301				X			X				X				
FG5X-104					X				X				X		
FG5X-209			X					X					X		
FG5X-216					X					X					X
FG5X-220						X							X	X	
FG5X-221		X					X					X			
FG5X-302	X									X				X	
IMGC02										X		X	X		
NIM-3A			X							X		X			
T-2					X			X						X	
TOTAL	4	6	5	6	4	4	5	6	4	6	5	4	5	5	4

The comparison was organized in two consecutive sessions (Figure 1). The first one took place from the 5th to the 7th of November 2013 with 11 gravimeters. The second session with 12 gravimeters started the 12th of November 2013 and finished the 14th of November 2013. The atomic gravimeter (CAG-01) measured prior the official dates as it needs more room. The FG5-223 measured in February 2014 as it was not ready in November 2013. The geophysical gravity variations being monitored with the SG are taking into account.

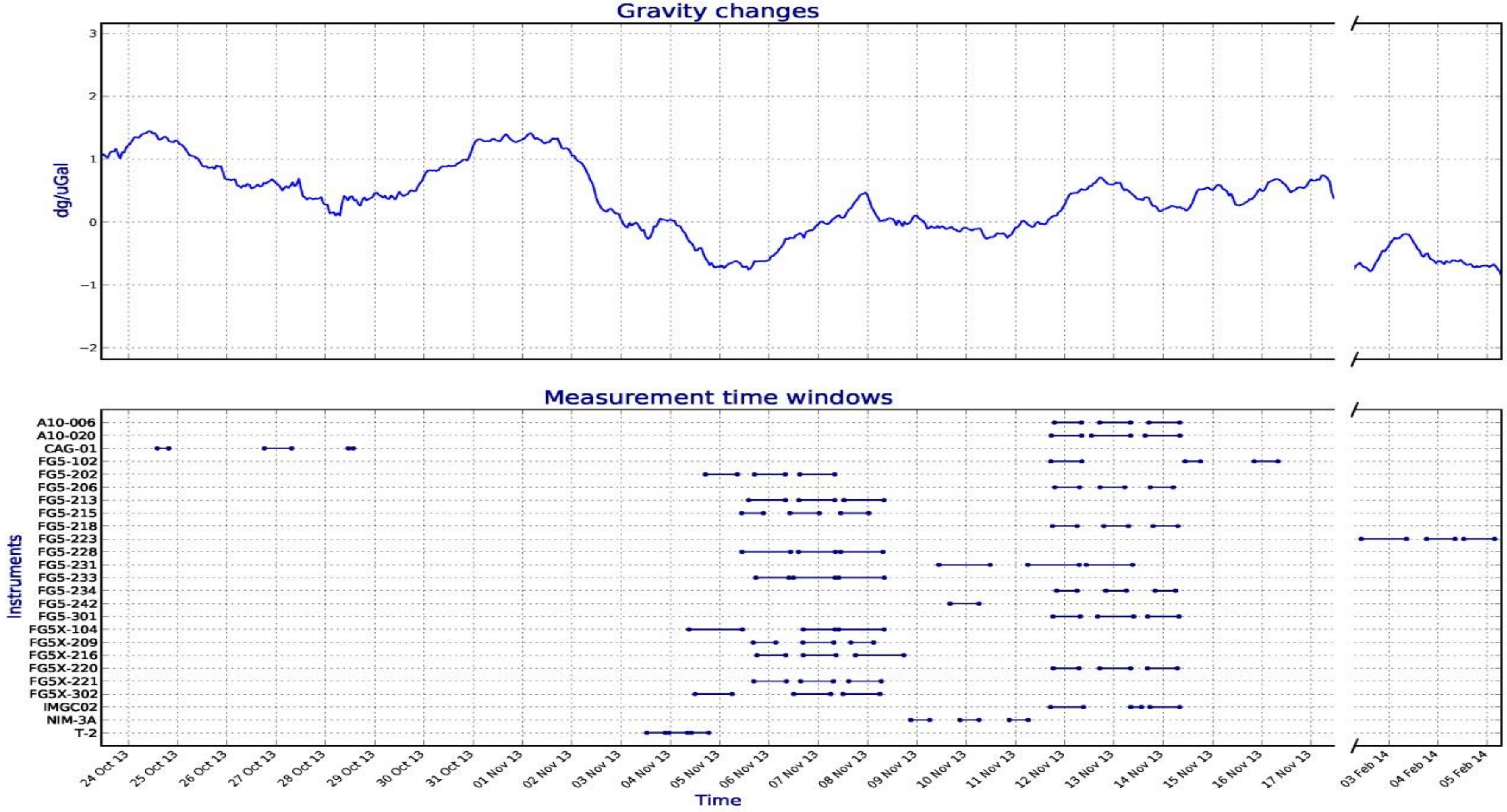

Figure 1. The gravity variations as observed with the superconducting gravimeter OSG-CT040 during the ICAG-2013 are displayed on top of the measurement time windows of the absolute gravimeters (bold blue lines).

5. Data elaboration

As each gravimeter measured at only three of the 15 sites, the g-values cannot be directly compared. The same procedure used in the ECAG-2011 comparison in Walferdange [3] was adopted.

A global weighted least-square adjustment is performed using as inputs the g-values given by the operators and their associated uncertainties. The uncertainties (strictly speaking the inverse square of the uncertainties: $1/u^2$) are used to weight 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 uncertainties multiplied by the coverage factor k=2. The observation equation is:

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

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 Key Comparison Reference Value (KCRV), 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 random error. This additional condition allows us regularizing the ill-posed problem. Without it, there would be indeed an infinite number of solutions by adding the same constant at all the biases.

The final adjustment includes the data of all the gravimeters that participated in the Key Comparison (KC). All the g-values are corrected for the observed geophysical gravity changes with the SG. In order to constrain the KC solution, the gravity differences between the sites measured by the other 15 gravimeters belonging neither to NMI nor DI were included in the adjustment. Each of those gravimeters measured at three sites: 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.

6. Results

6.1 First solution

For the first solution, all the measurements presented by the operators were included in the weighted least-square adjustment. The References Values (RVs) and the Degrees of Equivalence (DoEs) are presented in Tables 4 and 5 and Figure 2.

Table 4. Reference Values (RVs) of g using all the absolute observations from the NMI/DIs and gravity differences measured by the non-NMI/DIs. The constant value 980 960 000.0 µGal is subtracted from the RVs, U is the expanded uncertainty at 95% confidence.

Site	**RVs /µGal**	***U* (k=95%) /µGal**
A1	4228.7	3.9
A2	4216.5	3.3
A3	4206.6	2.9
A4	4190.0	2.6
A5	4183.4	3.2
B1	4077.0	3.3
B2	4072.3	2.8
B3	4069.1	3.1
B4	4063.0	3.5
B5	4049.5	2.9
C1	3952.3	2.8
C2	3945.2	3.7
C3	3948.3	2.7
C4	3946.4	3.5
C5	3942.9	3.2

Table 5. Degrees of Equivalence (DoE) of the gravimeters participating in the KC. The uncertainty U represents the expanded uncertainties of the DoE at 95% confidence.

Gravimeter	**Key Comparison Results first adjustment**	
	DoE /**µGal**	***U* (k=95%)** /**µGal**
CAG-01	+5.9	5.8
FG5-213	-4.0	3.3
FG5-215	+0.1	3.1
FG5-231	-1.6	3.0
FG5-242	+1.4	5.7
FG5X-104	-0.8	3.0
FG5X-209	-1.9	2.9
FG5X-221	+1.3	3.2
IMGC02	-1.6	5.8
NIM-3A	+1.2	5.6
RMS	2.7	4.3

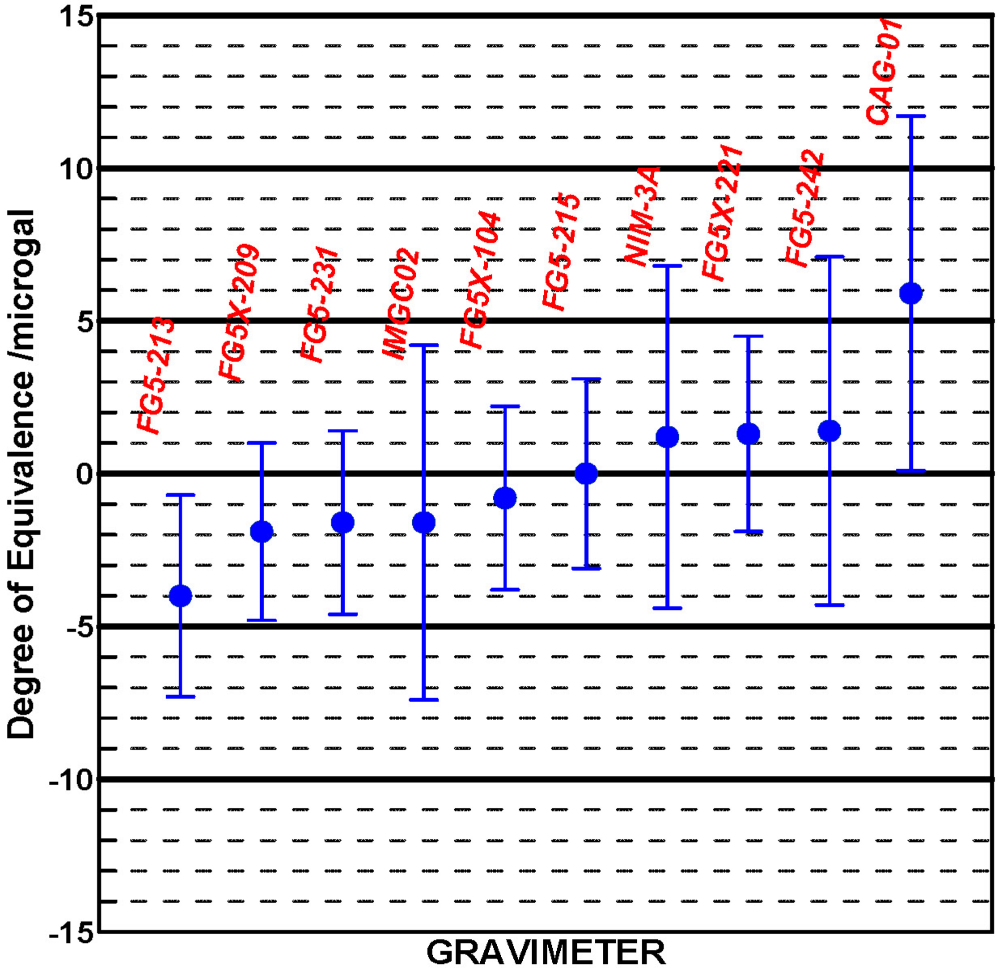

Figure 2. Degrees of Equivalence (DoE) of the gravimeters participating in the KC using the gravity differences between the sites from all gravimeters which do not belong to a NMI/DI. The error bars represent the expanded uncertainties (U) at 95% confidence.

In Table 6, the g-values of the NMI/DIs' gravimeters are compared to the RVs. The differences between the gravimeters measurements and the corresponding RVs are calculated along their uncertainties. Those are given by the square root of the sum of the square of the expanded uncertainty (k=95%) of the g-value and of the RV. In addition, we also calculated the compatibility index E_n defined by:

$$E_n = \frac{|x_i - x_j|}{\sqrt{U^2(x_i) + U^2(x_j)}}$$

In other words, this is the ratio between the difference of two estimated values and the expanded uncertainty (k=95%) of the difference. An E_n factor lager than 1 indicates that the two values are incompatible as their difference cannot be covered by their uncertainties. It means that either one of the two values is corrupted or the declared uncertainties are too small. For the NMI/DI gravimeters, the index factor (Table 6) of only one measurement marked in red is higher than 1. For the non-NMI/DI gravimeters, the gravity differences (Table 7) are all compatible with the differences of the RVs.

Table 6. Comparison between the NMI/DI's gravimeter measurements and the Reference Values (RVs). E_n is the compatibility index (see text for details). The uncertainty U represents the expanded uncertainties at 95% confidence.

Gravimeter	**Site**	**Gravimeter *g*-value /µGal**	***U* (k=95%) /µGal**	**KCRV /µGal**	***U* (k=95%) /µGal**	**Difference /µGal**	***U* (k=95%) /µGal**	**E_n**
CAG-01	A2	4219.1	10.8	4216.5	3.3	2.6	11.3	**0.2**
CAG-01	A4	4193.2	10.6	4190.0	2.6	3.2	10.9	**0.3**
CAG-01	B3	4080.8	10.6	4069.1	3.1	11.7	11.0	**1.1**
FG5-213	A2	4212.9	5.0	4216.5	3.3	-3.6	6.0	**0.6**
FG5-213	B5	4043.5	5.0	4049.5	2.9	-6.0	5.8	**1.0**
FG5-213	C1	3950.0	5.0	3952.3	2.8	-2.3	5.7	**0.4**
FG5-215	A3	4207.5	4.6	4206.6	2.9	0.9	5.4	**0.2**
FG5-215	B2	4071.8	4.6	4072.3	2.8	-0.5	5.4	**0.1**
FG5-215	C1	3952.1	4.6	3952.3	2.8	-0.2	5.4	**0.0**
FG5-231	A4	4189.8	4.2	4190.0	2.6	-0.2	4.9	**0.0**
FG5-231	A5	4180.8	4.2	4183.4	3.2	-2.6	5.3	**0.5**
FG5-231	B1	4074.9	4.2	4077.0	3.3	-2.1	5.3	**0.4**
FG5-242	B1	4078.4	5.2	4077.0	3.3	1.4	6.2	**0.2**
FG5X-104	A5	4183.0	4.0	4183.4	3.2	-0.4	5.1	**0.1**
FG5X-104	B4	4062.0	4.0	4063.0	3.5	-1.0	5.3	**0.2**
FG5X-104	C3	3947.4	4.0	3948.3	2.7	-0.9	4.8	**0.2**
FG5X-209	A3	4204.9	4.2	4206.6	2.9	-1.7	5.1	**0.3**
FG5X-209	B3	4066.9	4.2	4069.1	3.1	-2.2	5.2	**0.4**
FG5X-209	C3	3946.6	4.2	3948.3	2.7	-1.7	5.0	**0.3**
FG5X-221	A2	4217.3	4.6	4216.5	3.3	0.8	5.7	**0.1**
FG5X-221	B2	4073.2	4.6	4072.3	2.8	0.9	5.4	**0.2**
FG5X-221	C2	3947.6	4.6	3945.2	3.7	2.4	5.9	**0.4**
IMGC02	B5	4043.4	10.6	4049.5	2.9	-6.1	11.0	**0.6**

IMGC02	C2	3939.6	10.6	3945.2	3.7	-5.6	11.2	**0.5**
IMGC02	C3	3955.1	10.6	3948.3	2.7	6.8	10.9	**0.6**
NIM-3A	A3	4205.5	10.4	4206.8	2.9	-1.1	10.8	**0.1**
NIM-3A	B5	4055.3	10.2	4049.5	2.9	5.8	10.6	**0.5**
NIM-3A	C2	3944.2	9.8	3945.2	3.7	-1.0	10.5	**0.1**

Table 7. Comparison between the gravity differences between sites as measured by the non-NMI/DI's gravimeters and the differences of the Reference Values (RVs) for the same sites. E_n is the compatibility index (see text for details). The uncertainty U represents the expanded uncertainties at 95% confidence.

Gravimeter	**Sites**	***Δg*** **measured by the gravimeter /µGal**	***U*** **(k=95%) /µGal**	***Δg*** **of the RVs /µGal**	***U*** **(k=95%) /µGal**	**E_n**
A10-006	B3-A2	-140.9	30.3	-147.4	4.5	0.2
A10-006	A1-A2	27.5	30.3	12.2	5.1	0.5
A10-020	A2-C4	272.2	15.0	270.1	4.8	0.1
A10-020	B4-C4	120.9	15.1	116.6	4.9	0.3
FG5-102	B5-A4	-138.1	5.9	-140.5	3.9	0.4
FG5-102	A3-A4	19.7	5.9	16.6	3.9	0.5
FG5-202	B3-A4	-122.8	5.9	-120.9	4.0	0.3
FG5-202	C2-A4	-244.4	5.9	-244.8	4.5	0.1
FG5-206	B4-A3	-141.0	6.8	-143.6	4.5	0.4
FG5-206	A2-A3	12.5	6.8	9.9	4.4	0.4
FG5-218	C5-B3	-125.4	5.1	-126.2	4.5	0.2
FG5-218	C1-B3	-118.6	5.1	-116.8	4.2	0.3
FG5-223	A1-C5	285.6	5.9	285.8	5.0	0.2
FG5-223	B4-C5	117.8	5.9	120.1	4.7	0.3
FG5-228	A4-C3	242.7	5.4	241.7	3.7	0.2
FG5-228	B2-C3	125.6	5.4	124.0	3.9	0.3
FG5-233	B1-A1	-150.9	6.8	-151.7	5.1	0.1
FG5-233	C1-A1	-278.6	6.8	-276.4	4.8	0.3
FG5-234	C4-B2	-126.6	5.9	-125.9	4.5	0.1
FG5-234	C5-B2	-131.0	5.9	-129.4	4.3	0.2
FG5-301	A4-C1	238.0	5.9	237.7	3.8	0.1
FG5-301	B2-C1	117.5	5.9	120.0	4.0	0.4
FG5X-216	B5-A5	-133.5	5.9	-133.9	4.3	0.1
FG5X-216	C5-A5	-243.4	5.9	-240.5	4.5	0.4
FG5X-220	C3-B1	-128.1	5.9	-128.7	4.3	0.1
FG5X-220	C4-B1	-131.5	5.9	-130.6	4.8	0.1
FG5X-302	C4-B5	-102.4	5.9	-103.1	4.5	0.1
FG5X-302	A1-B5	178.8	5.9	179.2	4.9	0.1
T-2	A5-C4	229.9	14.1	237.0	4.7	0.5
T-2	B3-C4	119.1	14.1	122.7	4.7	0.2

6.2 Second and final solution

6.2.1. Key Comparison

A new adjustment is performed excluding the measurement for which the compatibility index is higher than 1: CAG-01 at B3. This procedure allows us to exclude outliers in order to obtain the best estimates for the KCRVs. However, the excluded measurements will be considered when computing the final and official DoEs.

The results of the adjustment without the excluded measurement are presented in Tables 8 and 9 and in Figure 3. The compatibility indexes of the NMI/DI gravimeters are not presented here as they are all smaller than 1.

Table 8. Key Comparison Reference Values (KCRVs) of g using only the absolute observations from the NMI/DIs which are "compatible" and gravity differences measured by the non-NMI/DIs. The constant value 980 960 000.0 µGal is subtracted from the KCRVs, U is the expanded uncertainty at 95% confidence.

Site	**Official Key Comparison Results**	
	KCRVs /µGal	***U* (k=95%) /µGal**
A1	4228.4	3.9
A2	4216.5	3.3
A3	4206.3	2.9
A4	4189.7	2.6
A5	4183.1	3.2
B1	4076.7	3.4
B2	4072.0	2.8
B3	4068.4	3.2
B4	4062.6	3.5
B5	4049.2	3.0
C1	3951.9	2.9
C2	3945.0	3.7
C3	3948.0	2.8
C4	3946.1	3.6
C5	3942.5	3.3

Table 9. Degrees of Equivalence (DoE) of the gravimeters participating in the KC as estimated in the weighted least-square adjustment (see Annex B). The uncertainty U represents the expanded uncertainties of the DoE at 95% confidence.

Gravimeter	**Key Comparison Results: A**	
	DoE **/µGal**	***U* (k=95%)** **/µGal**
CAG-01	+3.1	7.1
FG5-213	-3.7	3.3
FG5-215	+0.4	3.1
FG5-231	-1.3	3.0
FG5-242	+1.7	5.7
FG5X-104	-0.4	3.1
FG5X-209	-1.4	3.0
FG5X-221	+1.5	3.2
IMGC02	-1.3	5.8
NIM-3A	+1.5	5.6
RMS	2.0	4.5

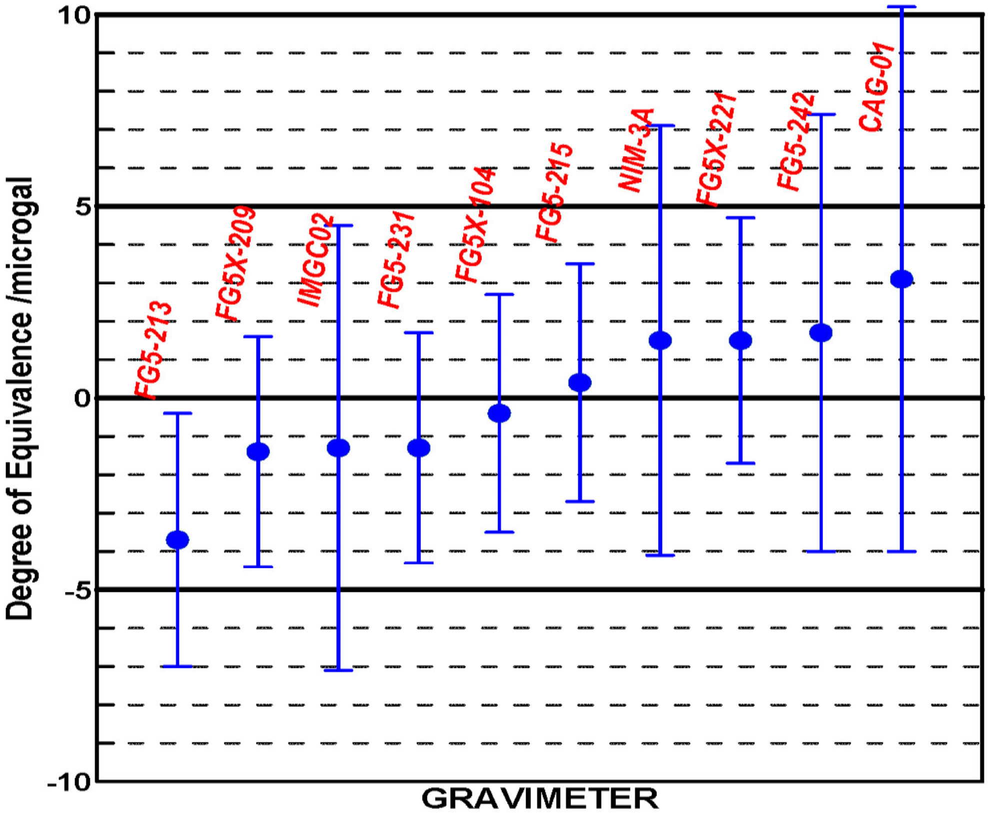

Figure 3. Degrees of Equivalence (DoE) of the gravimeters participating in the KC using the gravity differences between the sites from all gravimeters, which do not belong to a NMI/DI from the weighted least-square adjustment. The error bars represent the expanded uncertainties (U) of the DoE at 95% confidence.

The DoEs of the CAG-01 are not the same in Table 9 and Tables 10 and 11 because the measurement of the CAG-01 at B3 was excluded to produce the results presented in Table 9 whereas this measurement was taken into account in Tables 10 and 11. There are other differences mainly on the uncertainties of the DoE which are higher in Table 10 than in Table 9: 5% on average and maximum 10%. The reason is that the covariance between the measured gravity and the KCRV is not considered to produce the results in Table 10. As the uncertainties are only slightly higher, additional complications by taking the covariance into account seems pointless.

Table 10. Degrees of Equivalence (DoE) of the gravimeters participating in the KC calculated from the difference between the gravimeter measurements and the KCRVs. The uncertainty U represents the expanded uncertainties of the DoE at 95% confidence.

Gravimeter	**Key Comparison Results: B**	
	DoE /µGal	***U* (k=95%) /µGal**
CAG-01	+6.2	6.4
FG5-213	-3.7	3.4
FG5-215	+0.4	3.1
FG5-231	-1.3	3.0
FG5-242	+1.7	6.2
FG5X-104	-0.4	3.0
FG5X-209	-1.4	3.0
FG5X-221	+1.5	3.3
IMGC02	-1.4	6.4
NIM-3A	+1.5	6.1
RMS	2.7	4.7

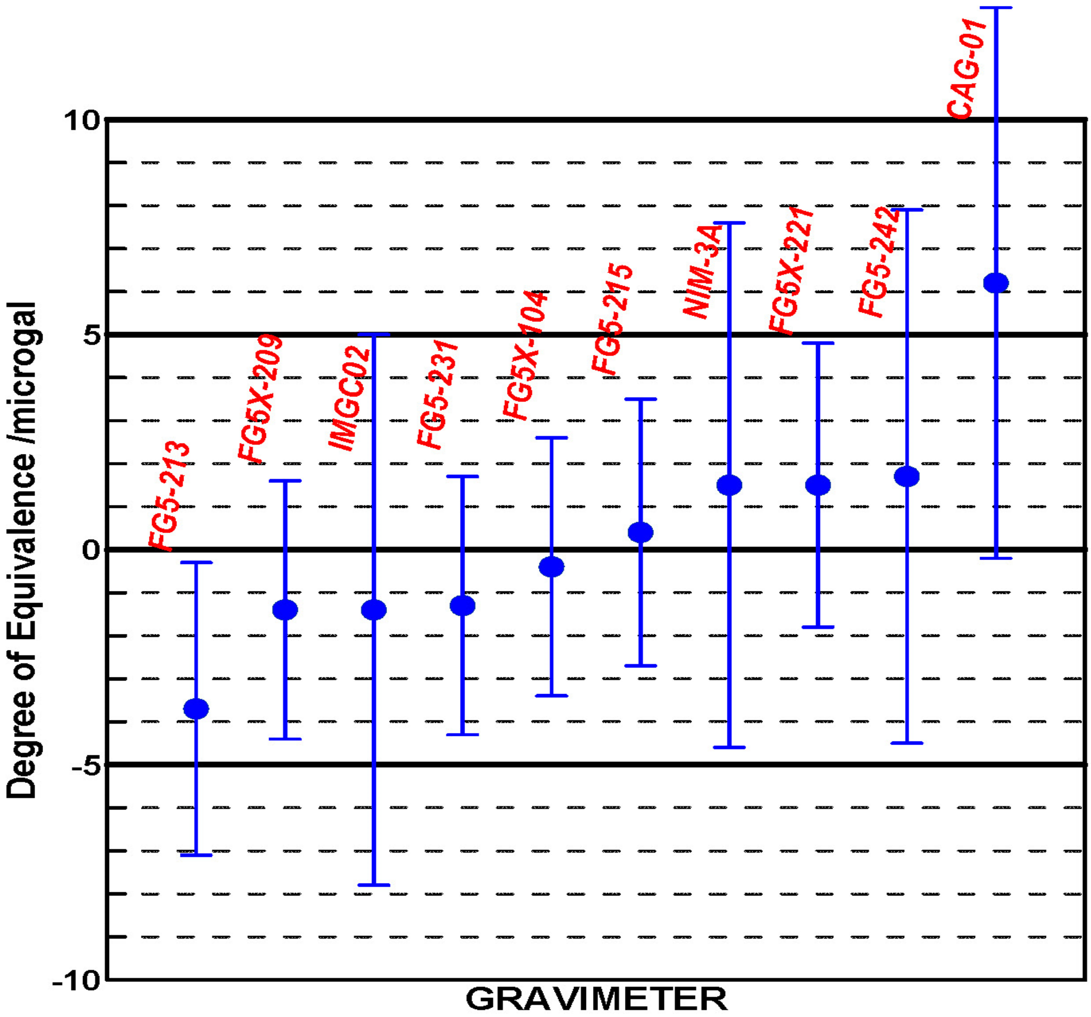

Figure 4. Degrees of Equivalence (DoE) of the gravimeters participating in the KC calculated from the difference between the gravimeter measurements and the KCRVs. The error bars represent the expanded uncertainties (U) of the DoE at 95% confidence.

In Tables 5, 9, and 10 the uncertainty U represents the uncertainty of the DoE as determined in the comparison. This uncertainty depends on the declared uncertainty of gravimeter in question and on the observation structure of the comparison, above all on the number of station occupations by the gravimeter (typically N=3). It can be shown that with increasing N the uncertainty of the DoE determined in this way decreases approximately in proportion to $1/\sqrt{N}$. Thus this uncertainty is not appropriate for assessing the compatibility of the DoE with the declared uncertainty of the gravimeter. Using it effectively implies an uncertainty model where with increasing N the DoE of a gravimeter should converge towards zero for the gravimeter to stay in equivalence.

For assessing equivalence (Table 11 and Figure 5) we therefore couple the DoE with the RMS of the uncertainties (last column of Annex B, above the lines) of the 1–3 differences between the gravimeter measurements and the KCRV that go into the determination of the DoE of the gravimeter. This RMS uncertainty is presented at the 95% level. All the gravimeters in the KC are in equivalence.

Table 11. Official Key Comparison results. Degrees of Equivalence (DoE) of the gravimeters participating in the KC. The DoE is calculated from the difference between the gravimeter measurements and the KCRVs as in Table 10. The uncertainty U, is the RMS uncertainty of the 1–3 differences. It represents the expanded uncertainty at 95% confidence.

Gravimeter	**Official Key Comparison Results**	
	DoE /µGal	***U* (k=95%) /µGal**
CAG-01	+6.2	11.1
FG5-213	-3.7	5.9
FG5-215	+0.4	5.4
FG5-231	-1.3	5.2
FG5-242	+1.7	6.2
FG5X-104	-0.4	5.1
FG5X-209	-1.4	5.1
FG5X-221	+1.5	5.7
IMGC02	-1.4	11.1
NIM-3A	+1.5	10.6
RMS	2.7	7.6

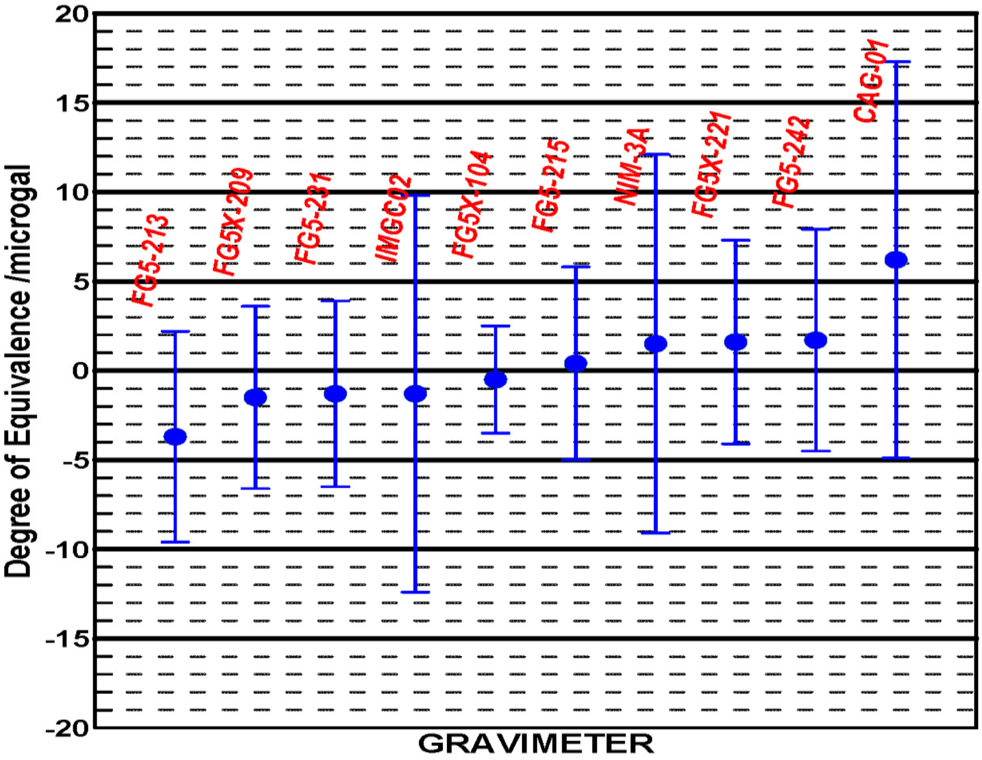

Figure 5. Official Key Comparison results from Table 11. Degrees of Equivalence (DoE) of the gravimeters participating in the KC calculated from the difference between the gravimeter measurements and the KCRVs. The error bars represent the expanded uncertainties (U) at 95% confidence.

7. Conclusions

In the framework of the International CCM.G-K2 Key Comparison of absolute gravimeters, 10 gravimeters from different NMIs and DIs were compared in accordance of the technical protocol established and accepted by all participants.

The gravity differences between sites measured by gravimeters of 15 non-metrological institutes were included in the final adjustment. The procedure eliminates the biases of the non-NMI/DI's gravimeters providing a better estimate of the gravity ties between the 15 sites used during the comparison.

The KCRVs and DoEs have been estimated by a weighted least-square adjustment of the g-values of the NMI/DI's gravimeters and the gravity differences measured by the non-NMI/DI's gravimeters. The weights are computed from the uncertainties provided by the operators and the uncertainties in the g transfer to the comparison reference height of 1.3 m. One measurement from a NMI gravimeter was found to be not in equivalence based on the compatibility index E_n. The observation was discarded to estimate the KCRVs but reintroduced to calculate the DoE of the gravimeter.

In conclusion, the DoEs of the 10 NMI and DI gravimeters are comprised between -3.7 and +6.2 µGal with a RMS of 2.7 µGal. They are all in equivalence. For the PS, 1 of the 15 gravimeters is not in equivalence (ANNEX C).

8. References

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ANNEX A: Vertical gravity gradient

In November 2013, one week after the comparison, Dr. Filippo Greco and Arnaud Watlet performed relative gravity measurements with the Scintrex CG5#008 from the University of Luxembourg and Scintrex CG5#542 from the Royal Observatory of Belgium, respectively. They measured at three different heights (0.26 m, 0.86 m and 1.27 m) at all the 15 sites in less than a week.

The vertical gravity is parameterized as function of the height z by a second degree polynomial:

$$g(z) = a\,z^2 + b\,z + c$$

A least-squares fit provides with the coefficients a, b and c as well as σ_a, σ_b and σ_{ab} (standard deviation and covariance). The data processing was done by O. Francis. The results are presented in Table A1. The coefficient c is omitted as it is of no use.

Table A1. Parameters and associated uncertainties of the second degree polynomial for the vertical gravity gradient measured in November 2013.

Site	a /μGal m^{-2}	σ_a /μGal m^{-2}	b /μGal m^{-1}	σ_b /μGal m^{-1}	σ_{ab} /μGal^2 m^{-3}
A1	9.6	3.4	-283.2	4.9	-16.6
A2	0.5	3.1	-272.6	4.7	-14.6
A3	8.3	4.2	-280.3	6.4	-26.4
A4	4.7	2.7	-271.1	4.2	-11.2
A5	4.0	3.0	-265.2	4.6	-13.9
B1	12.8	3.1	-299.5	4.6	-14.0
B2	20.0	2.4	-301.9	3.4	-7.8
B3	9.8	3.3	-287.2	5.0	-16.3
B4	5.5	3.0	-271.2	4.5	-13.4
B5	11.4	3.0	-276.4	4.4	-13.0
C1	17.2	3.2	-304.6	4.7	-14.7
C2	-3.0	3.4	-273.7	4.9	-16.3
C3	9.9	2.8	-281.1	4.2	-11.7
C4	12.2	3.3	-284.1	5.0	-16.0
C5	23.2	3.0	-299.3	4.6	-13.6

The gravity difference between height z_1 and z_2 is given by:

$$\Delta g(z_1 - z_2) = g(z_2) - g(z_1) = a \times (z_2^2 - z_1^2) + b \times (z_2 - z_1)$$

and the associated uncertainty

$$\sigma_{\Delta g}^2 = (z_2^2 - z_1^2)^2 \times \sigma_a^2 + (z_2 - z_1)^2 \times \sigma_b^2 + 2 \times (z_2^2 - z_1^2) \times (z_2 - z_1) \times \sigma_{ab}^2$$

These are the two formulas used in this report to transfer the gravity values along the vertical from any height to the instrumental reference height defined for the comparison of 1.30 m.

ANNEX B: Comparison between the gravity measurements and the KCRVs.

The differences between the gravimeter measurement and the KCVR are calculated for each gravimeter at each occupied site. The associated variances (U^2) are computed by summing up the variances of different constituents. The DoEs are then obtained by averaging these differences and the variances are calculated by summing up the different constituents divide by the number of constituent. The uncertainty U represents the expanded uncertainties at 95% confidence.

Gravimeter	Site	Gravimeter *g*-values /µGal	*U* (k=95%) /µGal	KCRVs /µGal	*U* (k=95%) /µGal	Differences DoEs /µGal	*U* (k=95%) /µGal
						Average /µGal	U(k=95%) /µGal
A10-006	A1	4233.3	21.4	4228.4	3.9	4.9	21.8
A10-006	A2	4205.8	21.4	4216.5	3.3	-10.7	21.7
A10-006	B3	4064.9	21.4	4068.4	3.2	-3.5	21.6
A10-006						**-3.1**	**12.5**
A10-020	A2	4211.6	10.8	4216.5	3.3	-4.9	11.3
A10-020	B4	4060.3	11.0	4062.6	3.5	-2.3	11.5
A10-020	C4	3939.4	10.4	3946.1	3.6	-6.7	11.0
A10-020						**-4.6**	**6.5**
CAG-01	A2	4219.1	10.8	4216.5	3.3	2.6	11.3
CAG-01	A4	4193.2	10.6	4189.7	2.6	3.5	10.9
CAG-01	B3	4080.8	10.6	4068.4	3.2	12.4	11.1
CAG-01						**6.2**	**6.4**
FG5-102	A3	4202.0	4.2	4206.3	2.9	-4.3	5.1
FG5-102	A4	4182.3	4.2	4189.7	2.6	-7.4	4.9
FG5-102	B5	4044.2	4.2	4049.2	3.0	-5.0	5.2
FG5-102						**-5.6**	**2.9**
FG5-202	A4	4193.1	4.2	4189.7	2.6	3.4	4.9
FG5-202	B3	4070.3	4.2	4068.4	3.2	1.9	5.3
FG5-202	C2	3948.7	4.2	3945.0	3.7	3.7	5.6
FG5-202						**3.0**	**3.0**
FG5-206	A2	4214.2	4.8	4216.5	3.3	-2.3	5.8
FG5-206	A3	4201.7	4.8	4206.3	2.9	-4.6	5.6
FG5-206	B4	4060.7	4.8	4062.6	3.5	-1.9	5.9
FG5-206						**-2.9**	**3.3**

FG5-213	A2	4212.9	5.0	4216.5	3.3	-3.6	6.0
FG5-213	B5	4043.5	5.0	4049.2	3.0	-5.7	5.8
FG5-213	C1	3950.0	5.0	3951.9	2.9	-1.9	5.8
FG5-213						**-3.7**	**3.4**
FG5-215	A3	4207.5	4.6	4206.3	2.9	1.2	5.4
FG5-215	B2	4071.8	4.6	4072.0	2.8	-0.2	5.4
FG5-215	C1	3952.1	4.6	3951.9	2.9	0.2	5.4
FG5-215						**0.4**	**3.1**
FG5-218	B3	4069.7	3.6	4068.4	3.2	1.3	4.8
FG5-218	C1	3951.1	3.6	3951.9	2.9	-0.8	4.6
FG5-218	C5	3944.3	3.6	3942.5	3.3	1.8	4.9
FG5-218						**0.8**	**2.8**
FG5-223	A1	4230.4	4.2	4228.4	3.9	2.0	5.7
FG5-223	B4	4063.6	4.2	4062.6	3.5	1.0	5.5
FG5-223	C5	3945.8	4.2	3942.5	3.3	3.3	5.3
FG5-223						**2.1**	**3.2**
FG5-228	A4	4186.6	3.8	4189.7	2.6	-3.1	4.6
FG5-228	B2	4069.5	3.8	4072.0	2.8	-2.5	4.7
FG5-228	C3	3943.9	3.8	3948.0	2.8	-4.1	4.7
FG5-228						**-3.2**	**2.7**
FG5-231	A4	4189.8	4.2	4189.7	2.6	0.1	4.9
FG5-231	A5	4180.8	4.2	4183.1	3.2	-2.3	5.3
FG5-231	B1	4074.9	4.2	4076.7	3.4	-1.8	5.4
FG5-231						**-1.3**	**3.0**
FG5-233	A1	4231.0	4.8	4228.4	3.9	2.6	6.2
FG5-233	B1	4080.1	4.8	4076.7	3.4	3.4	5.9
FG5-233	C1	3952.4	4.8	3951.9	2.9	0.5	5.6
FG5-233						**2.2**	**3.4**
FG5-234	B2	4074.4	4.2	4072.0	2.8	2.4	5.0
FG5-234	C4	3947.8	4.2	3946.1	3.6	1.7	5.5
FG5-234	C5	3943.4	4.2	3942.5	3.3	0.9	5.3
FG5-234						**1.7**	**3.1**

FG5-301	A4	4188.8	4.2	4189.7	2.6	-0.9	4.9
FG5-301	B2	4068.3	4.2	4072.0	2.8	-3.7	5.0
FG5-301	C1	3950.8	4.2	3951.9	2.9	-1.1	5.1
FG5-301						**-1.9**	**2.9**
FG5X-104	A5	4183.0	4.0	4183.1	3.2	-0.1	5.1
FG5X-104	B4	4062.0	4.0	4062.6	3.5	-0.6	5.3
FG5X-104	C3	3947.4	4.0	3948.0	2.8	-0.6	4.9
FG5X-104						**-0.4**	**3.0**
FG5X-209	A3	4204.9	4.2	4206.3	2.9	-1.4	5.1
FG5X-209	B3	4066.9	4.2	4068.4	3.2	-1.5	5.3
FG5X-209	C3	3946.6	4.2	3948.0	2.8	-1.4	5.0
FG5X-209						**-1.4**	**3.0**
FG5X-216	A5	4183.5	4.2	4183.1	3.2	0.4	5.3
FG5X-216	B5	4050.0	4.2	4049.2	3.0	0.8	5.2
FG5X-216	C5	3940.1	4.2	3942.5	3.3	-2.4	5.3
FG5X-216						**-0.4**	**3.0**
FG5X-220	B1	4079.1	4.2	4076.7	3.4	2.4	5.4
FG5X-220	C3	3951.0	4.2	3948.0	2.8	3.0	5.0
FG5X-220	C4	3947.6	4.2	3946.1	3.6	1.5	5.5
FG5X-220						**2.3**	**3.1**
FG5X-221	A2	4217.3	4.6	4216.5	3.3	0.8	5.7
FG5X-221	B2	4073.2	4.6	4072.0	2.8	1.2	5.4
FG5X-221	C2	3947.6	4.6	3945.0	3.7	2.6	5.9
FG5X-221						**1.5**	**3.3**
FG5X-302	A1	4228.4	4.2	4228.4	3.9	0.0	5.7
FG5X-302	B5	4049.6	4.2	4049.2	3.0	0.4	5.2
FG5X-302	C4	3947.2	4.2	3946.1	3.6	1.1	5.5
FG5X-302						**0.5**	**3.2**
IMGC02	B5	4043.4	10.6	4049.2	3.0	-5.8	11.0
IMGC02	C2	3939.6	10.6	3945.0	3.7	-5.4	11.2
IMGC02	C3	3955.1	10.6	3948.0	2.8	7.1	11.0
IMGC02						**-1.4**	**6.4**

NIM-3A	A3	4205.5	10.4	4206.3	2.9	-0.8	10.8
NIM-3A	B5	4055.3	10.2	4049.2	3.0	6.1	10.6
NIM-3A	C2	3944.2	9.8	3945.0	3.7	-0.8	10.5
NIM-3A						**1.5**	**6.1**
T-2	A5	4188.2	10.0	4183.1	3.2	5.1	10.5
T-2	B3	4077.4	10.0	4068.4	3.2	9.0	10.5
T-2	C4	3958.3	10.0	3946.1	3.6	12.2	10.6
T-2						**8.8**	**6.1**
FG5-242	B1	4078.4	5.2	4076.7	3.4	**1.7**	**6.2**

ANNEX C: Pilot study solution

In Table C1 we present the DoEs and their uncertainties for the PS, calculated from the differences between gravimeter measurements and the KCRVs in the same way as in Table 10 for the KC. Figure C1 combines the KC and PS gravimeters. Table C2 shows the final PS results where the DoEs are coupled with the uncertainties that must be used to assess equivalence. These uncertainties are calculated in the same way as in Table 11 of the KC, i.e., as the RMS of the uncertainties (last column of Annex B, above the lines) of the 1–3 differences between the gravimeter and the KCRV going into the determination of the DoE of the gravimeter. Figure C2 then combines the final KC and PS results. One gravimeter in the PS is not in equivalence: FG5-102.

Table C1. Degrees of Equivalence (DoE) of the gravimeters participating in the PS calculated from the difference between the gravimeter measurements and the KCRVs. The uncertainty U represents the expanded uncertainties of the DoE at 95% confidence.

Gravimeter	**PS Comparison Results**	
	DoE /µGal	***U* (k=95%) /µGal**
A10-006	-3.1	12.5
A10-020	-4.6	6.5
FG5-102	-5.6	2.9
FG5-202	+3.0	3.0
FG5-206	-2.9	3.3
FG5-218	+0.8	2.8
FG5-223	+2.1	3.2
FG5-228	-3.2	2.7
FG5-233	+2.2	3.4
FG5-234	+1.7	3.1
FG5-301	-1.9	2.9
FG5X-216	-0.4	3.0
FG5X-220	+2.3	3.1
FG5X-302	+0.5	3.2
T-2	+8.8	6.1
RMS	3.8	4.8

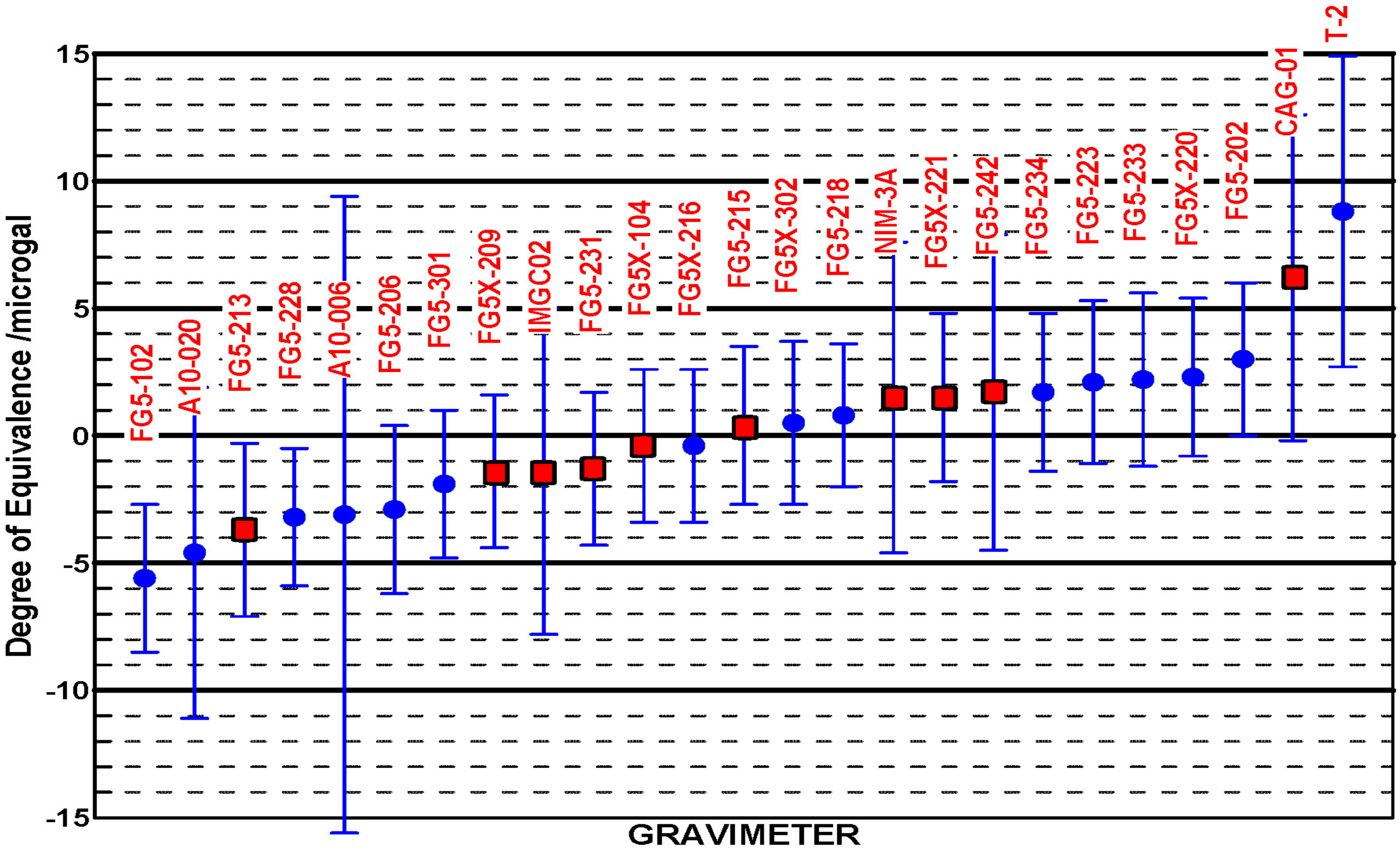

Figure C1. Degrees of Equivalence (DoE) of the all the gravimeters participating in the KC and PS calculated from the difference between the gravimeter measurements and the KCRVs. The gravimeters participating in the KC are surrounded by a red box. The error bars represent the expanded uncertainties (U) of the DoEs at 95% confidence.

Table C2. Final PS comparison results. Degrees of Equivalence (DoE) of the gravimeters participating in the PS are calculated from the differences between the gravimeter measurements and the KCRVs. The uncertainty U is the RMS uncertainty of the 1–3 differences. It represents the expanded uncertainty at 95% confidence.

Gravimeter	**Final PS Comparison Results**	
	DoE /µGal	***U* (k=95%) /µGal**
A10-006	-3.1	21.7
A10-020	-4.6	11.3
FG5-102	-5.6	5.1
FG5-202	+3.0	5.3
FG5-206	-2.9	5.8
FG5-218	+0.8	4.8
FG5-223	+2.1	5.5
FG5-228	-3.2	4.7
FG5-233	+2.2	5.9
FG5-234	+1.7	5.3
FG5-301	-1.9	5.0
FG5X-216	-0.4	5.3
FG5X-220	+2.3	5.3
FG5X-302	+0.5	5.5
T-2	+8.8	10.5
RMS	3.8	8.4

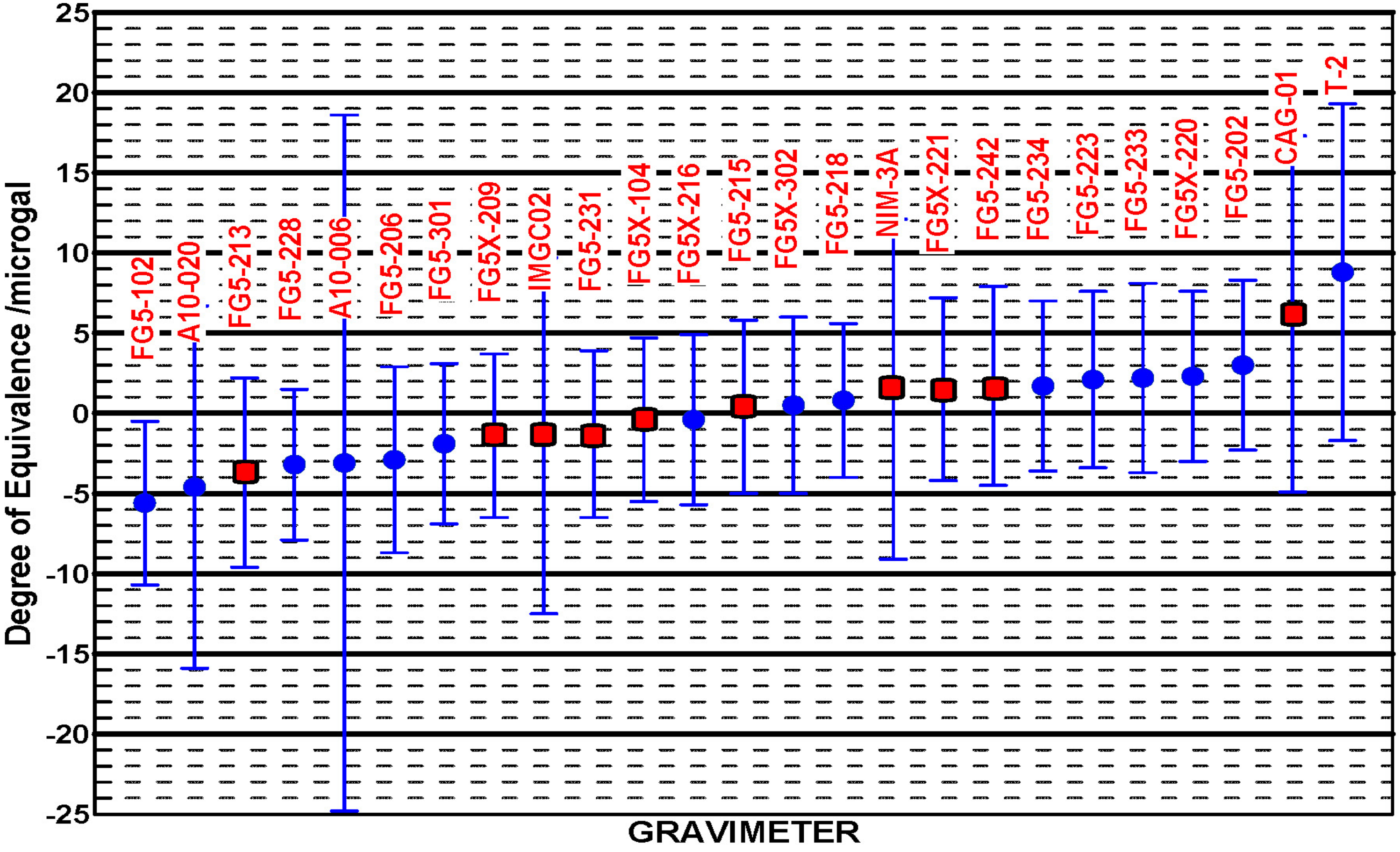

Figure C2. Final Degrees of Equivalence (DoE) of the all the gravimeters participating in the KC and PS calculated from the differences between the gravimeter measurements and the KCRVs. The gravimeters participating in the KC are surrounded by a red box. The error bars represent the final uncertainty U, calculated as the RMS uncertainty of the 1–3 differences. It represents the expanded uncertainty at 95% confidence.