REGIONAL COMPARISON OF ABSOLUTE GRAVIMETERS

EURAMET.M.G-K2 Key Comparison

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

#	Country	Institution	Operator(s)
1	Belgium	Royal Observatory of Belgium	Michel Van Camp Stefaan Castelein
2	Czech Republic	VÚGTK/ RIGTC, Geodetic Observatory Pecný	Vojtech Pálinkáš Jakub Kostelecký
3	Finland	Finnish Geospatial Research Institute (FGI), National Land Survey of Finland	Mirjam Bilker-Koivula Jyri Näränen
4	Germany	Bundesamt für Kartographie und Geodäsie	Alexander Lothhammer Reinhard Falk
5	Germany	Leibniz Universität Hannover	Manuel Schilling Ludger Timmen
6	Italy	ASI (Agenzia Spaziale Italiana)	Domenico Iacovone Francesco Baccaro
7	Italy	Istituto nazionale di Ricerca Metrologica	Alessandro Germak Emanuele Biolcati Claudio Origlia
8	Italy	Istituto Nazionale di Geofisica e Vulcanologia, Smart Measurement Solutions Srl	Filippo Greco Antonio Pistorio
9	Luxembourg	University of Luxembourg	Olivier Francis Raphaël De Plaen Gilbert Klein Marc Seil Remi Radinovic
10	Netherlands	Technical University of Delft	René Reudink
11	Poland	Institute of Geodesy and Cartography	Przemysław Dykowski Marcin Sękowski
12	Poland	Faculty of Geodesy and Cartography Warsaw University of Technology	Dominik Próchniewicz, Ryszard Szpunar
13	Slovakia	Slovak University of Technology in Bratislava	Marcel Mojzeš Juraj Janák Juraj Papčo
14	Sweden	Lantmäteriet	Andreas Engfeldt Per-Anders Olsson
15	United Kingdom	NERC / Space Geodesy Facility	Vicky Smith
16	USA	National Geodetic Survey - NOAA	Derek van Westrum
17	USA	Micro-g LaCoste	Brian Ellis Brice Lucero

Participants for the relative measurements

Olivier Francis, Raphaël De Plaen, Gilbert Klein, University of Luxembourg

Vojtech Pálinkáš, Research Institute of Geodesy, Topography and Cartography, Czech Republic

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1. Introduction

The Regional Key Comparison of Absolute Gravimeters, EURAMET.M.G-K2 and Pilot Study, was held at the new campus of the University of Luxembourg in Belval during the first two weeks of November 2015. All the measurements have been collected during 11 days from the 3rd to the 13th November 2015.

Before the comparison, the Technical Protocol (TP) was approved by participants and CCM-WGG. The TP includes the list of the registered participants, a description of the comparison site, the timetable of the measurements and standardized table to express the uncertainty of the gravimeters. It also specifies the data processing as well as the reporting of the results.

The schedule of absolute measurements has followed the TP. Nevertheless, due to the fact that one registered absolute gravimeter was not able to participate, three absolute gravimeters (FG5-215, FG5X-220, FG5X-302) measured more sites (4-5) to obtain an optimal distribution of measurements at 9 stations used for the comparison.

VÚGTK/RIGTC (Research Institute of Geodesy, Topography and Cartography) was the Pilot Laboratory under the leadership of Dr. Vojtech Pálinkáš. Prof. Dr. Olivier Francis and Ir. Gilbert Klein of the University of Luxembourg were in charge of the local organization of the comparison. The EURAMET.M.G-K2 and Pilot Study is registered as EURAMET project 1368. The comparison was organized in accordance with the CIPM MRA-D-05 of the Consultative Committee on Mass and Related Quantities (CCM). It is linked to the results of the CCM.G-K2 comparison (Francis et al. 2015) by means of four absolute gravimeters that have participated to both comparisons.

Here, 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 results of the vertical gravity gradient at the comparison sites. The measurement strategy is briefly discussed and the data elaboration is presented. Finally, the results of the data adjustment are presented including the degrees of equivalence (DoE) of the gravimeters and the key comparison reference values (KCRV). For the final and official solution of KCRVs, we removed the contribution of absolute gravity data non-compatible at the 95% confidence level. Overall, the official DoEs are all consistent given the declared uncertainties.

Four pilot solutions were computed and compared with the official key comparison results (see Annex B). In these solutions the gravimeters are not divided to NMI/DIs and non-NMI/DIs and they are treated as equivalent in terms of their contribution to the definition of RVs. These solutions are used for comparing the method of adjustment depending on the definition of the constraint 1) by imposing zero mean of biases or by minimizing the L1 norm of the biases, 2) by weighting or non-weighting biases in the constraint.

In this report, the microgal (μGal) is used as a unit of acceleration, 1 μGal is equal to $1 \cdot 10^{-8}$ m/s^2.

2. List of participants

The list of the participants is given in table 1. In total, 17 absolute gravimeters were compared including 4 different types of instruments. In case of FG5 gravimeters, the FG5-202 and FG5-215 are equipped by a bulk type of interferometer. Overall, 4 teams from National Metrology Institutes (NMIs) or Designated Institutes (DIs) participated to the comparison.

Table 1. Participants of the comparison (NMI = National Metrology Institute; DI = Designated Institute). The metrological institutes are in yellow field.

#	Country	Institution	Gravimeter	NMI or DI	Operator(s)
1	Belgium	Royal Observatory of Belgium	FG5-202	NO	Michel Van Camp Stefaan Castelein
2	Czech Republic	VÚGTK/ RIGTC, Geodetic Observatory Pecný	FG5-215	YES	Vojtech Pálinkáš Jakub Kostelecký
3	Finland	Finnish Geospatial Research Institute, National Land Survey of Finland	FG5X-221	YES	Mirjam Bilker-Koivula Jyri Näränen
4	Germany	Bundesamt für Kartographie und Geodäsie	FG5-301	NO	Alexander Lothhammer Reinhard Falk
5	Germany	Leibniz Universität Hannover	FG5X-220	NO	Manuel Schilling Ludger Timmen
6	Italy	ASI (Agenzia Spaziale Italiana)	FG5-218	NO	Domenico Iacovone Francesco Baccaro
7	Italy	Istituto nazionale di Ricerca Metrologica	IMGC-02	YES	Alessandro Germak Emanuele Biolcati Claudio Origlia
8	Italy	Instituto Nazionale di Geofisica e Vulcanologia	FG5-238	NO	Filippo Greco Antonio Pistorio
9	Luxembourg	University of Luxembourg	FG5X-216	YES	Olivier Francis Raphaël De Plaen Gilbert Klein Marc Seil Remi Radinovic
10	Netherlands	Technical University of Delft	FG5-234	NO	René Reudink
11	Poland	Institute of Geodesy and Cartography	A10-020	NO	Przemysław Dykowski Marcin Sękowski
12	Poland	Faculty of Geodesy and Cartography Warsaw University of Technology	FG5-230	NO	Dominik Próchniewicz, Ryszard Szpunar
13	Slovakia	Slovak University of Technology in Bratislava	FG5X-247	NO	Marcel Mojzeš Juraj Janák Juraj Papčo
14	Sweden	Lantmäteriet	FG5-233	NO	Andreas Engfeldt Per-Anders Olsson
15	United Kingdom	NERC / Space Geodesy Facility	FG5X-229	NO	Vicky Smith
16	USA	National Geodetic Survey - NOAA	FG5X-102	NO	Derek van Westrum
17	USA	Micro-g LaCoste	FG5X-302	NO	Brian Ellis Brice Lucero

3. Site description and relative gravity measurements

The comparison was held in the “Halle d’Essais” of the Engineering department on the Belval Campus of the University of Luxembourg in the south of Luxembourg. The laboratory is located close to sources of anthropogenic noise (traffic, construction works around). All the 9 measured stations have been located on a pillar with size of 10 m x 15 m x 1 m so –called “spannfeld”. Nevertheless, the pillar was not founded directly on the subsoil but it is supported by three 3 m high and 10 m long girder grounded on the building foundation. All these conditions are not ideal and affected especially the drop-to-drop scatter of measurements; on the other hand it gives the possibility to test the quality of gravimeters/comparisons on sites under high anthropogenic noise conditions.

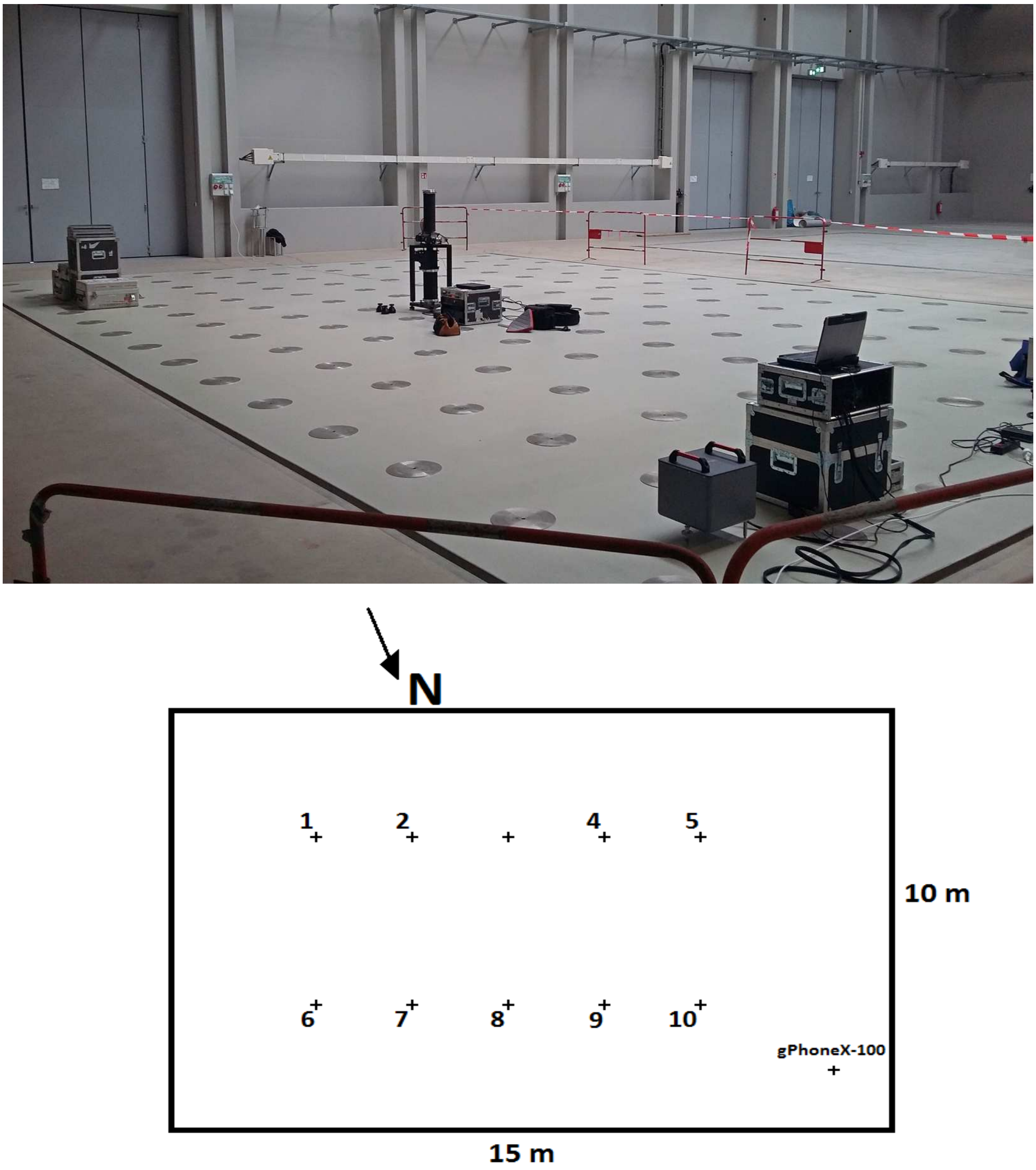

Figure 1. Photo and sketch of the comparison location in the “Halle d’Essais” of the new campus of the University of Luxembourg in Belval. It consists of a large pillar “spannfeld” where 9 sites were selected for all the measurements. On the foreground the gPhone gravimeter.

Vertical gravity gradients (VGGs) were measured with a Scintrex CG-5 and a ZLS Burris gravimeters at least at 3 different vertical levels above the sites. According to the results obtained with the Burris B-20 gravimeter (see Annex A), it was decided to approximate the VGGs by constant gradients (linear gravity change with height) at all the sites. The precision of all the measured gradients was better than 1 µGal/m and the differences between estimates from two gravimeters (see table 2) reach a standard deviation of 1.2 µGal/m. The final VGGs were obtained by arithmetic mean of individual results at the given sites. The uncertainty of the VGGs was estimated to be 2 µGal/m, which includes the uncertainty contribution due to the approximation of the VGGs by constant values at each site.

The observed tidal parameters (table 3) were estimated from 4 years of continuous measurements of the superconducting gravimeter OSG-CT040 installed in the Walferdange Underground Laboratory for Geodynamics (WULG), 25 km North of the Belval comparison.

Table 2. Vertical gravity gradients at the 9 sites used for the comparison.

Site	Gravimeter	VGG /μGal·m^{-1}	Differences /μGal·m^{-1}	Average VGG /μGal·m^{-1}
1	Scintrex-08 Burris B-20	-300.7 -298.4	2.3	**-299.6**
2	Scintrex-08 Burris B-20	-301.5 -301.6	-0.1	**-301.6**
4	Scintrex-08 Scintrex-10 Burris B-20	-302.2 -302.3 -300.7	-0.1 1.5	**-301.7**
5	Scintrex-08 Burris B-20	-305.3 -303.6	1.7	**-304.5**
6	Scintrex-10 Burris B-20	-296.2 -296.7	-0.5	**-296.5**
7	Scintrex-10 Burris B-20	-295.3 -296.2	-0.9	**-295.8**
8	Scintrex-10 Burris B-20	-298.0 -298.7	-0.7	**-298.4**
9	Scintrex-10 Burris B-20	-298.6 -299.4	-0.8	**-299.0**
10	Scintrex-10 Burris B-20	-301.3 -300.4	0.9	**-300.9**
			σ = 1.2 μGal/m	

Table 3. Observed tidal parameters for the Walferdange Underground Laboratory for Geodynamics from 4 years of continuous observations with the superconducting gravimeter OSG-CT040.

Wave	Start freq. /cpd	End freq. /cpd	Amplitude factor	Phase lag /deg
M0+S0	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

Gravity variations during the comparison were measured with the spring gravimeter gPhoneX-100, see figures 1 and 2. An instrumental drift has been removed from the 37-day data time series using a 2nd order polynomial fit. As it can be seen from figure 2, the gravity residuals variations reach up to 4 µGal during the comparison. At the nearby WULG station, the gravity variations reach 1.5 µGal during the same time-span. Such a variations are mainly caused by imperfect removal of atmospheric effects using the single admittance approach and partly also by possible hydrological effects. Uncertainty contribution of the single admittance approach is included in the error budget of absolute measurements. The hydrological effects cannot be reliably determined since the local hydrological effects are highly station-dependent. Considering that neither extreme local meteorological event (strong rain, snowmelting) during the comparison nor gravity changes larger than 1 µGal was observed at the WULG station, no additional correction for gravity variations during the comparison was applied. Nevertheless, we will include a contribution of 0.5 µGal to the uncertainties of gravity values to reflect the non-applied gravity variations, that were observed within the range of 2 µGal and 4 µGal (cf. figure 2) at Walferdange and Belval station, respectively.

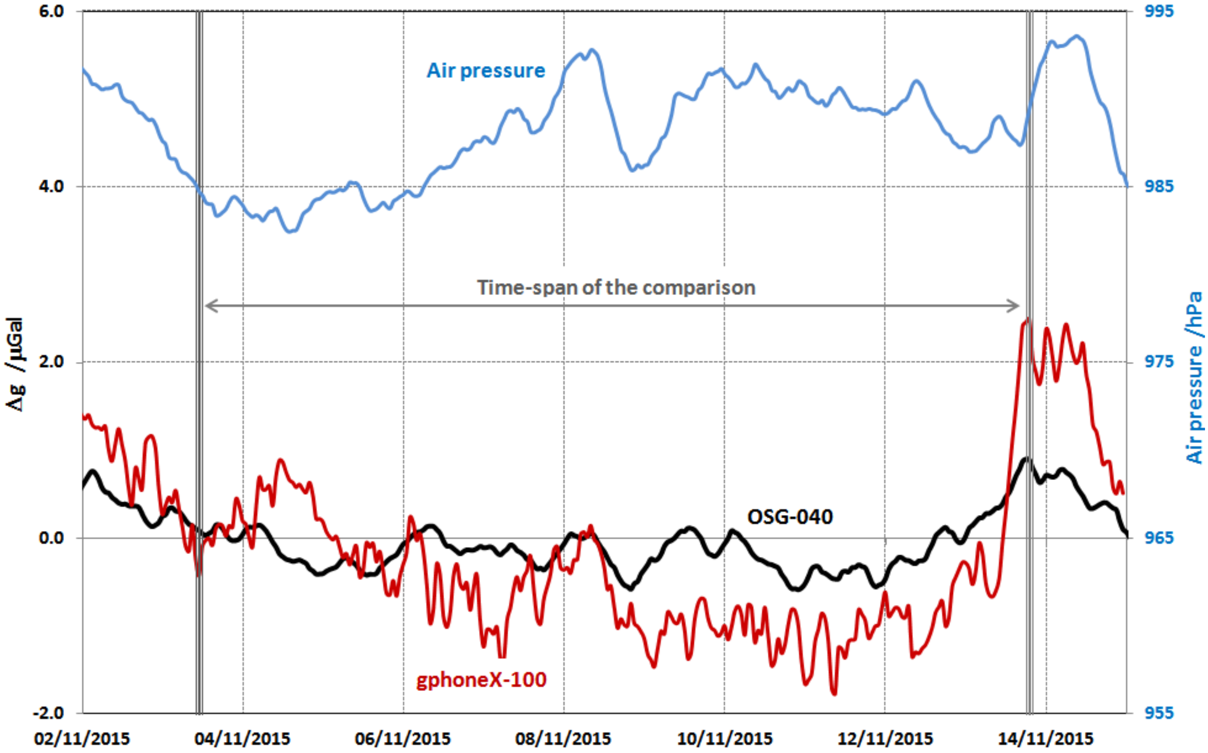

Figure 2. The gravity and air pressure variations observed during the comparison with 1) gPhoneX-100 spring gravimeter at the comparison location, 2) air pressure sensor at the comparison location, 3) the superconducting gravimeter OSG-CT040 in Walferdange.

4. Absolute gravity measurements

The raw absolute gravity measurement is the mean free-fall acceleration at the measurement height corrected for:

- the gravimetric Earth tides to obtain "zero-tide" values for gravity,
- the effect of atmospheric mass variations using the admittance factor of -0.3 µGal/hPa and difference between the normal air pressure (U. S. Standard Atmosphere, 1976) and measured air pressure at the station,
- the polar motion effect, estimated from the coordinates of the Celestial Ephemeris Pole relative to the IERS Reference Pole,
- the vertical gravity gradient to obtain gravity at the specified measurement height,
- 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 (Petit and Luzum, 2010) and IAGBN (International Absolute Gravity Base- station Network) processing standards (Boedecker, 1988).

The operators were responsible for processing their gravity data. They submitted the final g-values and uncertainties for all the measured sites at the instrument's reference height (distance between a benchmark and the effective position of free-fall), see Timmen (2003) and Pálinkáš et al. (2011), where g is invariant of the VGG used in the equation of motion. The 55 AG measurements from the 17 absolute gravimeters over the 9 sites are listed in table 4. Each gravimeter measured at least at three gravity sites. The reported time of the measurement is the average of the times of the observations contributing to the measurement. We used the final VGGs given in table 2 for transferring g from the reference height to the comparison height, which was chosen to be at 125 cm to minimize the contribution of uncertainty from VGGs to the uncertainty of KCRV. The g-values at the comparison height together with associated uncertainties ($\boldsymbol{g}$, $\boldsymbol{u}$) are listed in table 4.

Table 4. List of all the absolute gravity measurements (NMI/DIs are in yellow field). The constant value 980 949 000.0 µGal is subtracted from the gravity measurements.

g_{raw}: raw gravity data with standard uncertainty u_{raw} declared by the participants, g_{raw} are 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 **DC**, self-attraction **SAC**, etc.), g_{raw} were reported at the reference height H above the pillar using gradient $\mathbf{VGG_1}$

g: gravity values transferred to the reference height of the comparison (125 cm) using final gradients $\mathbf{VGG_2}$.

u: the standard uncertainty of g computed as root mean square of three components: u_{raw}, transfer error to the reference height of the comparison and 0.5 µGal due to unmodelled environmental effects.

u_{har}: harmonized standard uncertainties (see Section 7.1), computed as u but the contribution from u_{raw} of non NMI/DIs which are below 2.1 µGal (the best uncertainty declared by NMI/DI gravimeter) were changed to 2.1 µGal.

Gravimeter	Site	Average Time	#Drops	H /cm	VGG_1 /µGal·m^{-1}	g_{raw} /µGal	u_{raw} /µGal	SAC /µGal	DC /µGal	VGG_2 /µGal·m^{-1}	g /µGal	u /µGal	u_{har} /µGal
FG5X-221	7	10/11/2015 22:19	1846	126.80	-295.8	54.80	2.30	-1.20	1.40	-295.8	60.12	2.35	2.35
FG5X-221	6	11/11/2015 21:02	2143	126.90	-296.5	57.10	2.30	-1.20	1.40	-296.5	62.73	2.35	2.35
FG5X-221	9	12/11/2015 20:49	2149	126.90	-299.0	47.40	2.30	-1.20	1.40	-299.0	53.08	2.35	2.35
FG5-215	5	08/11/2015 13:57	1600	122.60	-304.5	38.57	2.34	-1.73	1.80	-304.5	31.26	2.39	2.39
FG5-215	8	09/11/2015 00:45	2600	122.58	-298.4	69.96	2.34	-1.73	1.80	-298.4	62.74	2.39	2.39
FG5-215	7	09/11/2015 12:06	2400	122.50	-295.8	74.06	2.34	-1.73	1.80	-295.8	66.67	2.39	2.39
FG5-215	1	10/11/2015 01:05	3000	122.56	-299.6	58.88	2.34	-1.73	1.80	-299.6	51.57	2.39	2.39
IMGC-02	10	10/11/2015 14:27	410	48.70	-300.0	296.20	8.20	0.70	5.20	-300.9	66.61	8.36	8.36
IMGC-02	4	11/11/2015 22:35	828	48.80	-300.0	280.40	8.10	0.70	5.20	-301.7	50.50	8.26	8.26
IMGC-02	7	13/11/2015 04:38	512	48.90	-300.0	297.30	8.20	0.70	5.20	-295.8	72.20	8.36	8.36
FG5X-216	1	08/11/2015 01:07	3400	127.00	-299.6	40.04	2.10	-1.40	1.20	-299.6	46.03	2.16	2.16
FG5X-216	2	06/11/2015 00:07	3600	127.00	-301.6	37.17	2.10	-1.40	1.20	-301.6	43.20	2.16	2.16
FG5X-216	7	12/11/2015 22:37	4800	127.00	-295.8	54.12	2.10	-1.40	1.20	-295.8	60.04	2.16	2.16
FG5X-102	5	03/11/2015 21:07	3700	128.40	-300.0	18.90	1.86	-1.20	1.05	-304.5	29.25	1.93	2.16
FG5X-102	10	04/11/2015 20:17	4800	128.40	-300.0	36.50	1.85	-1.20	1.05	-300.9	46.73	1.92	2.16
FG5X-102	9	05/11/2015 20:55	4600	128.40	-300.0	45.00	1.85	-1.20	1.05	-299.0	55.17	1.92	2.16
FG5-202	8	10/11/2015 23:13	3769	121.00	-298.4	75.21	2.10	-1.70	1.30	-298.4	63.27	2.16	2.16
FG5-202	9	11/11/2015 20:40	4179	121.00	-299.0	71.68	2.10	-1.70	1.30	-299.0	59.72	2.16	2.16
FG5-202	2	12/11/2015 20:54	4189	121.00	-301.6	60.83	2.10	-1.70	1.30	-301.6	48.77	2.16	2.16
FG5-218	5	11/11/2015 01:00	1440	121.00	-304.5	40.60	1.86	-1.36	1.20	-304.5	28.42	1.93	2.16
FG5-218	1	12/11/2015 01:00	1440	121.00	-299.6	60.62	1.89	-1.36	1.20	-299.6	48.64	1.96	2.16
FG5-218	6	13/11/2015 01:00	1440	121.00	-296.5	77.22	1.83	-1.36	1.20	-296.5	65.36	1.90	2.16
FG5X-220	2	10/11/2015 00:45	1200	127.00	-301.6	42.39	2.40	-1.20	1.00	-301.6	48.42	2.45	2.45
FG5X-220	1	10/11/2015 23:00	1400	127.00	-299.6	47.19	2.40	-1.20	1.00	-299.6	53.18	2.45	2.45
FG5X-220	10	11/11/2015 23:00	1400	127.00	-300.9	45.66	2.40	-1.20	1.00	-300.9	51.68	2.45	2.45
FG5X-220	8	12/11/2015 23:15	1400	127.00	-298.4	59.15	2.40	-1.20	1.00	-298.4	65.12	2.45	2.45

FG5X-229	4	03/11/2015 23:55	1700	127.20	-301.7	27.61	1.86	-1.20	1.10	-301.7	34.25	1.93	2.16
FG5X-229	2	04/11/2015 20:13	2300	127.20	-301.6	36.35	1.86	-1.20	1.10	-301.6	42.99	1.93	2.16
FG5X-229	5	05/11/2015 20:04	2300	127.20	-304.5	23.04	1.86	-1.20	1.10	-304.5	29.74	1.93	2.16
FG5-230	9	11/11/2015 00:15	2800	121.50	-299.8	63.41	1.89	-1.21	1.20	-299.0	52.95	1.96	2.16
FG5-230	5	12/11/2015 00:37	2900	121.50	-309.6	34.35	1.89	-1.21	1.20	-304.5	23.69	1.96	2.16
FG5-230	10	13/11/2015 00:10	2800	121.50	-311.3	55.04	1.89	-1.21	1.20	-300.9	44.51	1.96	2.16
FG5-233	4	11/11/2015 00:04	1495	121.00	-301.7	50.02	2.40	-1.50	1.00	-301.7	37.95	2.45	2.45
FG5-233	2	11/11/2015 20:56	2126	121.00	-301.6	58.93	2.40	-1.50	1.00	-301.6	46.87	2.45	2.45
FG5-233	5	12/11/2015 20:51	2139	121.00	-304.5	41.63	2.40	-1.50	1.00	-304.5	29.45	2.45	2.45
FG5-234	6	04/11/2015 00:07	2200	121.30	-296.5	81.94	1.93	-1.50	1.00	-296.5	70.98	2.00	2.16
FG5-234	4	05/11/2015 00:07	2200	121.35	-301.7	49.96	1.91	-1.50	1.00	-301.7	38.96	1.98	2.16
FG5-234	8	06/11/2015 00:07	2200	121.39	-298.4	73.59	1.91	-1.50	1.00	-298.4	62.83	1.98	2.16
FG5-238	1	04/11/2015 00:35	2400	121.61	-299.6	56.40	7.60	-1.50	1.20	-299.6	46.24	7.62	7.62
FG5-238	9	04/11/2015 23:24	3000	121.71	-299.0	68.20	5.70	-1.50	1.20	-299.0	58.36	5.72	5.72
FG5-238	4	06/11/2015 00:53	2400	121.61	-301.7	56.90	8.30	-1.50	1.20	-301.7	46.67	8.32	8.32
FG5X-247	6	10/11/2015 23:52	3000	127.00	-296.5	54.65	3.05			-296.5	60.58	3.09	3.09
FG5X-247	8	11/11/2015 23:30	3000	127.00	-298.4	41.53	2.25			-298.4	47.50	2.31	2.31
FG5X-247	4	12/11/2015 23:40	3000	127.00	-301.7	26.74	4.79			-301.7	32.77	4.82	4.82
FG5-301	9	04/11/2015 00:03	1196	122.00	-299.0	64.70	2.10	-1.43	2.00	-299.0	55.73	2.16	2.16
FG5-301	7	05/11/2015 00:42	1793	122.00	-295.8	71.00	2.10	-1.43	2.00	-295.8	62.13	2.16	2.16
FG5-301	6	06/11/2015 00:42	1786	122.00	-296.5	74.00	2.10	-1.43	2.00	-296.5	65.11	2.16	2.16
FG5X-302	2	03/11/2015 21:27	3500	127.30	-300.0	37.20	1.85	-1.20	1.45	-301.6	44.14	1.92	2.16
FG5X-302	6	04/11/2015 23:35	3400	127.30	-300.0	59.01	1.85	-1.20	1.45	-296.5	65.83	1.92	2.16
FG5X-302	10	05/11/2015 20:45	4800	127.30	-300.0	42.30	1.85	-1.20	1.45	-300.9	49.22	1.92	2.16
FG5X-302	1	06/11/2015 22:11	4800	127.30	-300.0	42.46	1.88	-1.20	1.45	-299.6	49.35	1.95	2.16
FG5X-302	7	07/11/2015 01:38	3600	127.30	-300.0	55.86	1.86	-1.20	1.45	-295.8	62.66	1.93	2.16
A10-020	10	03/11/2015 21:19	6360	68.03	-300.1	209.20	6.50	-0.60	1.20	-300.9	37.78	6.62	6.62
A10-020	8	04/11/2015 10:16	4800	68.03	-297.4	227.50	6.20	-0.60	1.20	-298.4	57.50	6.32	6.32
A10-020	1	05/11/2015 13:40	4800	68.03	-300.1	213.10	5.70	-0.60	1.20	-299.6	42.42	5.83	5.83

5. Measurement strategy

According to the TP, 9 gravity sites were used during the comparison organized in two consecutive sessions. The first one took place from the 3rd to the 7th of November 2015. The second session happened from the 8th to the 13th of November 2015. Originally, each gravimeter was planned to measure at 3 sites. The optimal measurement schedule was prepared by Dr. Dru Smith (NOAA) according to Smith et al. (2013). The following conditions have been driven to find the optimal schedule: 1) to avoid a meter measuring on the same site more than once, 2) to minimize the number of missing meter-to-meter comparisons, 3) to optimally balance the number of times any two meters compare against one another. This schedule was followed by all the operators. Nevertheless, due to the fact that one registered absolute gravimeter was not able to participate, three absolute gravimeters measured more sites to strengthen the ties between the 9 sites. We would like to point out that more measurements with a particular gravimeter does not mean that the KCRV (in absolute level) is more influenced by such a gravimeter. Influence to the absolute level of KCRV is given by the weighting within the constraint which does not take into account the number of measurements by a particular gravimeter, see Section 6. More measurements by a particular gravimeter just means that its bias will be determined with much better precision and also that it will more influence the gravity differences between KCRVs, because more observation equations for a particular gravimeter.

Table 5. Occupation of individual sites for each gravimeter.

	Site #									
Gravimeter	**1**	**2**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	TOTAL
FG5X-221					X	X		X		**3**
FG5-215	X			X		X	X			**4**
IMGC-02			X			X			X	**3**
FG5X-216	X	X				X				**3**
FG5X-102				X				X	X	**3**
FG5-202		X					X	X		**3**
FG5-218	X			X	X					**3**
FG5X-220	X	X					X		X	**4**
FG5X-229		X	X	X						**3**
FG5-230				X				X	X	**3**
FG5-233		X	X	X						**3**
FG5-234			X		X		X			**3**
FG5-238	X		X					X		**3**
FG5X-247			X		X		X			**3**
FG5-301					X	X		X		**3**
FG5X-302	X	X			X	X			X	**5**
A10-020	X						X		X	**3**
TOTAL	**7**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	

6. Data elaboration

As each gravimeter measured at only 3-5 of the 9 sites, the g-values cannot be directly compared. A combined (observation and constraint equations) least squares adjustment was performed using as inputs the g-values transferred to the reference comparison height (g) and their associated uncertainties (u). Every measurement made by the gravimeter "i" (with a bias δ_i) at the station "j" during the comparison may be described by the observation equation

$$g_{ij} = g_j + \delta_i + \varepsilon_{ij} \tag{1}$$

with respective weights w_{ij} ($w_{ij} = u_o^2/u_{ij}^2$ where u_o is the unit weight).

As the set of observation equations has no unique solution a constraint, which can be interpreted as definition of the KCRV is required (Koo and Clare, 2012).

Generally, the consensus value of the KCRV (Koo and Clare 2012) is obtained by taking the weighted constraint

$$\sum_{i=1}^{n} w_i \ \delta_i = d \tag{2}$$

where the w_i are the weights assigned to each participant's result $\Sigma\ w_\mathrm{i} = 1$ and d is the linking converter (Jiang et al. 2013) representing the weighted mean of the n biases from the CCM.G-K2. The weighting of biases was calculated as $w_i = u_o^2/u_i^2$, where u_i is computed as root mean square of u_{ij} for a gravimeter i. The weighted constraint was used for processing of CCM.G-K1 (Jiang et al., 2012). On the other hand, non-weighted constraint was used for processing CCM.G-K2 (Francis et. al, 2015). Therefore, we present also the approach with the non-weighted constraint

$$\sum_{i=1}^{n} \frac{1}{n} \ \delta_i = d \tag{3}$$

Let us point out that in case of zero linking converter, the constraint given by eq. (3) corresponds to $\Sigma\ \delta_\mathrm{i} = 0$. The parameter $1/n$ in eq.(3) is for achieving $\Sigma\ w_\mathrm{i} = 1$ that is needed for correct application of a non-zero linking converter.

Due to the fact that only NMI and DI gravimeters (NMI/DIs) can contribute to the definition of KCRV, the non-NMI/DI gravimeter biases cannot be included to the constraint (both weighted and non-weighted) nor to the determination of the linking converter d. Therefore, weights of biases for non-NMI/DI gravimeters are equal to zero in equations (2) and (3). By this simple mathematical operation, the non-NMI/DI gravimeters are contributing as relative gravimeters only, by ensuring links between stations. This approach is equivalent with the approach used in CCM.G-K2, where gravity differences were also computed from non-NMI/DI gravimeters together with corresponding covariances.

The linking converter was computed as weighted mean of DoEs determined at the CCM.G-K2, see table 6. DoEs of four NMI/DI linking gravimeters have been used for this purpose.

Table 6. Determination of the linking converter as weighted mean of DoEs of the CCM.G-K2.

Gravimeter	DoE /µGal	U (k=2) /µGal
FG5X-221	1.5	5.7
FG5-215	0.4	5.4
IMGC-02	-1.4	11.1
FG5X-216	-0.4	5.3
linking converter d =	**0.32**	**3.03**

7. Results

7.1 Initial solutions - choice of the adjustment approach

For the initial solutions, all the measurements presented by the operators were included in the least-squares adjustment. The References Values (RVs) and the biases (δ) are presented in tables 7,8 and figure 3. According to the TP, the initial solution was computed by following two approaches:

- **Approach A**: Using non-weighted constraint (see Eq. 3), where n = 4.
- **Approach B**: Using weighted constraint (see Eq. 2) where the weights were computed as root mean square of uncertainties (u) given in table 4. It brings weights of 0.309 for the FG5X-221, 0.299 for the FG5-215, 0.025 for the IMGC-02 and 0.367 for the FG5X-216. Sum of these weights is equal to 1, which is needed for the correct application of the linking converter.

Table 7. Reference Values (RVs) of the comparison determined by three approaches (A, B, C) using all the reported absolute measurements. Results are linked by NMI/DIs to CCM.G-K2 by means of linking converter. The constant value 980 949 000.0 µGal is subtracted from the RVs, σ is the standard deviation of RVs from the adjustment.

Station *k*	Approach A		Approach B		Approach C	
	RV /µGal	σ /µGal	RV /µGal	σ /µGal	δ /µGal	σ /µGal
1	51.4	1.0	47.9	0.7	47.8	0.7
2	47.1	1.0	43.6	0.8	43.7	0.8
4	38.6	1.2	35.1	1.0	35.3	1.0
5	31.7	1.0	28.2	0.8	28.1	0.8
6	69.0	1.0	65.6	0.7	65.6	0.8
7	65.5	1.0	62.0	0.7	62.0	0.7
8	61.7	1.1	58.2	0.9	58.2	0.9
9	59.0	1.1	55.5	0.8	55.5	0.8
10	50.8	1.1	47.3	0.9	47.2	0.9

Table 8. Biases of NMI/DIs (yellow) and non-NMI DIs related to the three processing approaches.

Gravimeter	Approach A		Approach B		Approach C	
	δ /µGal	σ /µGal	δ /µGal	σ /µGal	δ /µGal	σ /µGal
FG5X-221	-5.8	1.0	-2.4	0.7	-2.4	0.7
FG5-215	0.5	1.0	4.0	0.7	4.0	0.7
IMGC-02	11.5	2.3	15.0	2.9	14.9	2.9
FG5X-216	-4.9	1.0	-1.4	0.6	-1.4	0.6
FG5X-102	-3.4	1.1	0.0	0.9	0.1	1.0
FG5-202	1.3	1.2	4.8	1.0	4.8	0.9
FG5-218	-3.2	1.1	0.2	0.9	0.3	0.9
FG5X-220	1.9	1.2	5.3	0.9	5.3	0.9
FG5X-229	-3.5	1.2	0.0	1.0	0.0	1.0
FG5-230	-6.8	1.2	-3.3	0.9	-3.2	1.0
FG5-233	-1.0	1.3	2.4	1.1	2.4	1.1
FG5-234	1.2	1.2	4.6	1.0	4.6	1.0
FG5-238	0.2	2.6	3.7	2.5	3.6	2.5
FG5X-247	-11.3	1.4	-7.8	1.3	-7.9	1.2
FG5-301	-3.5	1.2	0.0	0.9	0.0	0.9
FG5X-302	-2.5	1.0	1.0	0.7	1.0	0.8
A10-020	-8.6	2.4	-5.1	2.3	-5.1	2.2

As it can be seen from table 7, table 8 and figure 3, there is a systematic difference of 3.5 µGal between the approaches A and B. We suppose (see Annex B for more details) that the non-weighted approach gives biased results due to the large positive bias of IMGC-02, which is however within the uncertainty budget of the meter. Therefore, the final solution below will be related to the weighted constraint given by Eq. 2. Note that the weights used within the weighting matrix are used to weight the relative g-values, similarly we can include measurement of any relative gravimeters. The shift of relative g-values to absolute g-values is realized through the constraint given by Eq. (2) or (3).

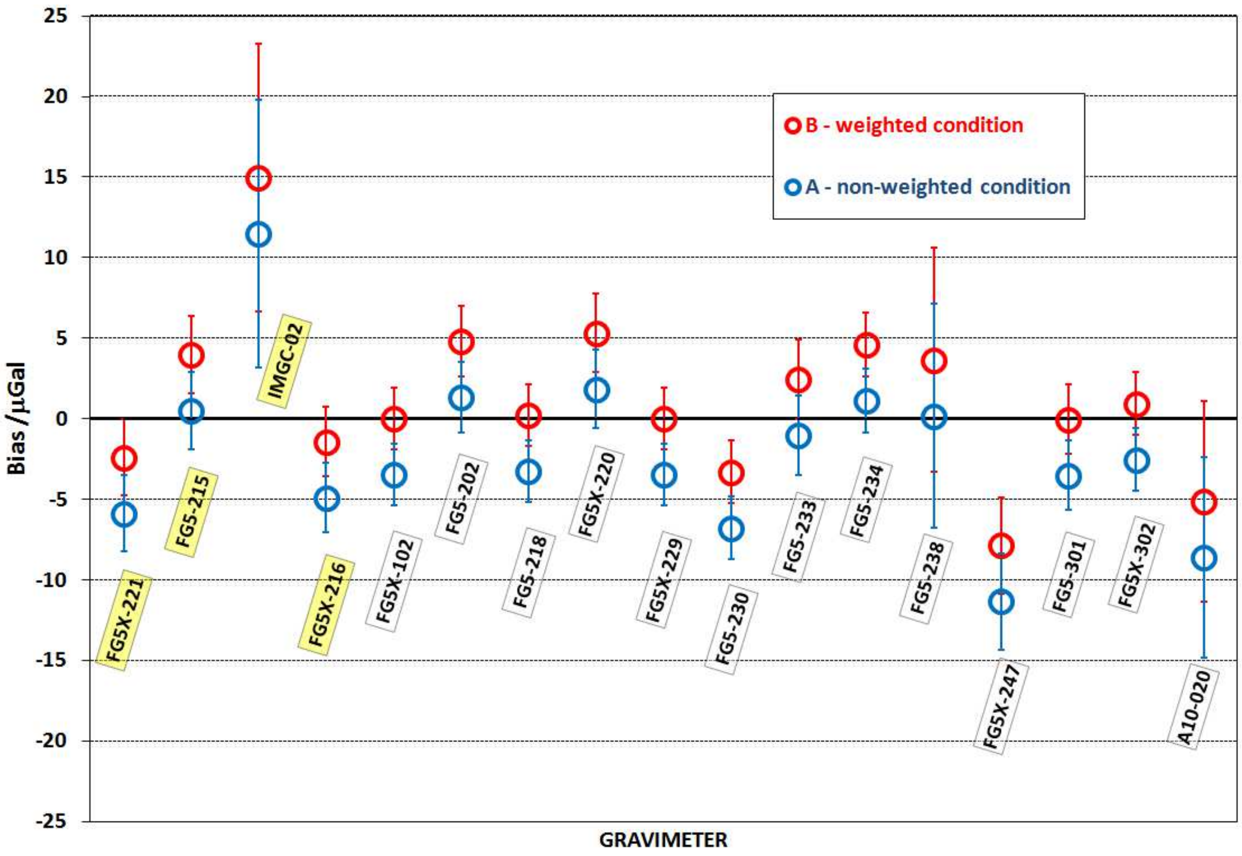

Figure 3. Biases of the gravimeters according to the adjustment approaches "A" (non-weighted constraint) and "B" (weighted constraint) linked to the CCM.G.K-2 by mean of four linking NMI/DI gravimeters. Gravimeters of NMI/DIs are highlighted in yellow. The error bars represent the RMS of uncertainties (***u*** in table 4) related to *g@125cm*.

The uncertainties declared by non-NMI/DIs (except FG5-233, FG5-238, FG5X-220 and FG5X-247, see table 4) for the same type of gravimeters are below that of declared by NMI/DIs. Due to the fact, that the RVs in absolute term are realized by NMI/DIs only, the possible overestimated uncertainties of non-NMI/DIs, used in Approach B, do not influence directly the RVs but they influencing the determination of gravity differences between sites, where differences determined by non-NMI/DIs are considered as more accurate than those determined by NMI/DIs. Such an assumption is unrealistic and comes mainly due to more detailed uncertainty estimates of NMI/DIs. Therefore, we are presenting a third approach of the adjustment:

- **Approach C**, where all the uncertainties of non NMI/DIs which are below 2.1 µGal (the best uncertainty declared by NMI/DI gravimeter) were changed to 2.1 µGal, the harmonized uncertainties are in the last column of table 4. The constraint of "B" and "C" is the same.

As it can be seen from table 7 and 8, differences between "B" and "C" are below 0.2 µGal. Our preferred approach is "C". One may argue that it does not respect the declared uncertainties. It is true only for non-NMI/DIs, however these do not present the full uncertainty budget and therefore we might assume that some source of uncertainties might be unaccounted or underestimated. The second argument for the approach "C" is that we should not relate the weighting matrix to gravimeter's uncertainty but to its reproducibility as this parameter is reflecting the capability of an absolute gravimeter to determine relative gravities. Due to the fact that majority of operators have presented the reproducibility of FG5(X) gravimeters between 1-2 µGal, which corresponds with numbers published in Van Camp et al. (2005), Rosat et al. (2009), and Pálinkáš et al. (2010), some harmonization in case of weighting matrix is not against the declared parameters.

7.2 Consistency check

We test here the consistency of measurements along with uncertainties. The compatibility index is related to the difference between the measured gravity (g_{ij}) and the RV (g_j) at given station according to the formula

$$E_n = \frac{(g_{ij} - g_j)}{\sqrt{u^2(g_{ij}) + \sigma^2(g_j) + u^2(d)}} \quad . \tag{4}$$

This is the ratio between the difference of measured and estimated reference gravity values and the uncertainty of the difference, where the following contributions are included:

$u(g_{i,j})$ ...	uncertainty of the g-values at the comparison height of 125 cm,
$\sigma(g_j)$ ...	standard deviation of the RV at the station *j* reached from the LSQ adjustment,
u_d ...	uncertainty of the linking converter.

E_n factor in absolute value larger than 2 (2.5) indicates that the two g-values are incompatible at 95% (99%) confidence level as their difference cannot be covered by their uncertainties. The consistency index (for the above described approach C) is given in table 9. One of the measurement of the FG5X-247 reaching E_n = -3.71 must be excluded. Moreover, it is suitable to check also the short-term reproducibility (Jiang et al. 2012) of a particular AG represented by the standard deviation of residuals for a given gravimeter. It amounts 4.20 µGal in case of the FG5X-247, more than twice the expected value of 1-2 µGal. Therefore, the measurement of the FG5X-247 at the station 8 was excluded. Consequently, E_n reach values higher than 2 for same measurements as in table 9: IMGC-02 at 10 (2.27), FG5X-220 at 8 (2.04), FG5-234 at 6 (2.26). The results of the FG5X-220 and FG5-234 clearly show that the consistency index fails due to the larger positive bias of these gravimeters at all the measured stations. Since these gravimeters are not contributing directly to the definition of the reference and also due to the fact that they show short-term reproducibility below 1.3 µGal, we keep these measurements. By excluding them we would lower the precisely determined gravity differences between stations. On the other hand, the measurements related to IMGC-02 are directly contributing to the definition of KCRV and the measurement at site 10 was excluded at 95% confidence level. The problem of outliers can be more robustly solved by the approach of de Viron et al. (2011), where instead of imposing the zero mean of biases, the L1 norm of biases is minimized. This approach is discussed within pilot solutions described in Annex B.

Table 9. Consistency check: Comparison of measured gravity values g_{ij} (along with uncertainties u_{ij}) with reference values g_j (along with standard deviations σ_j) by means of compatibility index E_n. σ_{rep} is the short-term reproducibility of a gravimeter computed from scatter of the residuals at individual stations. NMI/DI gravimeters are on yellow background. The constant value 980 949 000.0 µGal has been subtracted from the gravity measurements. Compatibility indexes larger than 2 are in red background.

Gravimeter	Site *K*	g_{ij} /µGal	u_{ij} /µGal	g_j /µGal	σ_j /µGal	g_{ij}-g_j /µGal	E_n /µGal	σ_{rep} /µGal
FG5X-221	7	60.12	2.35	61.99	0.66	-1.86	-0.65	
FG5X-221	6	62.73	2.35	65.62	0.76	-2.88	-0.99	
FG5X-221	9	53.08	2.35	55.45	0.81	-2.37	-0.81	0.51
FG5-215	5	31.26	2.39	28.11	0.80	3.15	1.07	
FG5-215	8	62.74	2.39	58.21	0.85	4.53	1.53	
FG5-215	7	66.67	2.39	61.99	0.66	4.68	1.61	
FG5-215	1	51.57	2.39	47.83	0.72	3.74	1.28	0.71
IMGC-02	10	66.61	8.36	47.24	0.91	19.37	2.27	
IMGC-02	4	50.50	8.26	35.27	1.04	15.23	1.80	
IMGC-02	7	72.20	8.36	61.99	0.66	10.21	1.20	4.59
FG5X-216	1	46.03	2.16	47.83	0.72	-1.80	-0.66	
FG5X-216	2	43.20	2.16	43.72	0.75	-0.52	-0.19	
FG5X-216	7	60.04	2.16	61.99	0.66	-1.95	-0.72	0.79
FG5X-102	5	29.25	1.93	28.11	0.80	1.14	0.44	
FG5X-102	10	46.73	1.92	47.24	0.91	-0.51	-0.20	
FG5X-102	9	55.17	1.92	55.45	0.81	-0.29	-0.11	0.90
FG5-202	8	63.27	2.16	58.21	0.85	5.07	1.83	

FG5-202	9	59.72	2.16	55.45	0.81	4.27	1.55	
FG5-202	2	48.77	2.16	43.72	0.75	5.04	1.84	0.45
FG5-218	5	28.42	1.93	28.11	0.80	0.31	0.12	
FG5-218	1	48.64	1.96	47.83	0.72	0.80	0.31	
FG5-218	6	65.36	1.90	65.62	0.76	-0.26	-0.10	0.53
FG5X-220	2	48.42	2.45	43.72	0.75	4.70	1.58	
FG5X-220	1	53.18	2.45	47.83	0.72	5.35	1.80	
FG5X-220	10	51.68	2.45	47.24	0.91	4.44	1.47	
FG5X-220	8	65.12	2.45	58.21	0.85	6.91	2.30	1.25
FG5X-229	4	34.25	1.93	35.27	1.04	-1.03	-0.39	
FG5X-229	2	42.99	1.93	43.72	0.75	-0.74	-0.29	
FG5X-229	5	29.74	1.93	28.11	0.80	1.63	0.63	1.46
FG5-230	9	52.95	1.96	55.45	0.81	-2.51	-0.96	
FG5-230	5	23.69	1.96	28.11	0.80	-4.42	-1.70	
FG5-230	10	44.51	1.96	47.24	0.91	-2.73	-1.04	1.04
FG5-233	4	37.95	2.45	35.27	1.04	2.68	0.87	
FG5-233	2	46.87	2.45	43.72	0.75	3.14	1.05	
FG5-233	5	29.45	2.45	28.11	0.80	1.34	0.45	0.93
FG5-234	6	70.98	2.00	65.62	0.76	5.36	2.05	
FG5-234	4	38.96	1.98	35.27	1.04	3.68	1.37	
FG5-234	8	62.83	1.98	58.21	0.85	4.62	1.76	0.84
FG5-238	1	46.24	7.62	47.83	0.72	-1.59	-0.20	
FG5-238	9	58.36	5.72	55.45	0.81	2.91	0.49	
FG5-238	4	46.67	8.32	35.27	1.04	11.40	1.34	6.60
FG5X-247	6	60.58	3.09	65.62	0.76	-5.04	-1.43	
FG5X-247	8	47.50	2.31	58.21	0.85	-10.71	-3.71	
FG5X-247	4	32.77	4.82	35.27	1.04	-2.50	-0.48	4.20
FG5-301	9	55.73	2.16	55.45	0.81	0.28	0.10	
FG5-301	7	62.13	2.16	61.99	0.66	0.14	0.05	
FG5-301	6	65.11	2.16	65.62	0.76	-0.51	-0.19	0.42
FG5X-302	2	44.14	1.92	43.72	0.75	0.41	0.16	
FG5X-302	6	65.83	1.92	65.62	0.76	0.21	0.08	
FG5X-302	10	49.22	1.92	47.24	0.91	1.98	0.76	
FG5X-302	1	49.35	1.95	47.83	0.72	1.52	0.59	
FG5X-302	7	62.66	1.93	61.99	0.66	0.67	0.27	0.76
A10-020	10	37.78	6.62	47.24	0.91	-9.46	-1.38	
A10-020	8	57.50	6.32	58.21	0.85	-0.70	-0.11	
A10-020	1	42.42	5.83	47.83	0.72	-5.41	-0.89	4.38

7.3 Final solution

A new final adjustment (using Approach C, see section 7.1) was performed excluding the measurements of the IMGC-02 at site #10 and the FG5X-247 at site #8 (see discussion in section 7.2) in order to obtain the best estimates for the KCRVs, see Table 10.

Results of biases obtained by the final adjustment are in Annex B. However, for the final solution of DoEs we have to consider also the excluded measurements (Francis et al. 2015). The official DoEs were computed according to Jiang et al. (2012) using formula

$$D_i = \left[\sum w_{ij}\left(g_{ij} - g_j\right)\right] \,/\, \sum w_{ij}, \qquad (5)$$

as the weighted average difference between the measurements of a gravimeter "i" and the KCRV at given site "j". The differences between the gravimeter measurement and the KCVR are calculated for each gravimeter at each occupied site, see table 11. The associated uncertainties ($U_{\mathrm{Di,j}}$) are computed by summing up the variances of different constituents. The DoEs are then obtained by averaging these differences (according to Eq. 5 with weights proportional to $U_{\mathrm{Di,j}}^{2}$) and the variances are calculated by summing up the different constituents divide by the number of constituent. The uncertainty U_D represents the expanded uncertainties at 95% confidence.

Table 10. Key Comparison Reference Values (KCRVs) linked to the CCM.G.K-2 using linking converter of (0.32 ± 3.03) µGal related to 4 NMI/DI gravimeters. The constant value 980 949 000.0 µGal is subtracted from the KCRVs. *U* is the expanded uncertainty at 95% confidence computed as root mean square of standard deviations σ (from the adjustment) and uncertainty of the linking converter.

OFFICIAL KEY COMPARISON RESULTS

Site	KCRV /µGal	σ /µGal	*U* (k=2) /µGal
1	**47.8**	0.6	**3.2**
2	**43.7**	0.6	**3.3**
4	**35.0**	0.8	**3.4**
5	**28.0**	0.6	**3.3**
6	**65.1**	0.6	**3.3**
7	**61.9**	0.5	**3.2**
8	**59.0**	0.7	**3.3**
9	**55.4**	0.6	**3.3**
10	**47.1**	0.7	**3.4**

Table 11. DoEs of NMI/DIs (yellow) and non-NMI DIs determined according to Eq. 5. g_{ij} are the measured gravity values transferred to 125 cm with expanded uncertainty U_{ij}. g_j are the KCRVs with associated expanded (*k*=2) uncertainties U_j. U_{Dij} is the expanded uncertainty of differences g_{ij}-g_j. D_i is the final DoE computed according to Eq. 5 along with the expanded uncertainty U_{Di}. The constant value 980 949 000.0 µGal was subtracted from the gravity measurements.

Gravimeter *i*	Site *j*	g_{ij} /µGal	U_{ij} /µGal	g_j /µGal	U_j /µGal	g_{ij}-g_j /µGal	U_{Dij} /µGal	D_i /µGal	U_{Di} /µGal
FG5X-221	7	60.12	4.71	61.90	3.21	-1.78	5.70		
FG5X-221	6	62.73	4.71	65.09	3.27	-2.35	5.73		
FG5X-221	9	53.08	4.71	55.36	3.29	-2.28	5.74	-2.14	3.30
FG5-215	5	31.26	4.79	28.00	3.29	3.26	5.81		
FG5-215	8	62.74	4.79	59.00	3.34	3.74	5.84		
FG5-215	7	66.67	4.79	61.90	3.21	4.76	5.76		
FG5-215	1	51.57	4.79	47.79	3.24	3.78	5.78	3.89	2.90
IMGC-02	10	66.61	16.71	47.10	3.36	19.51	17.05		
IMGC-02	4	50.50	16.51	34.96	3.45	15.54	16.87		
IMGC-02	7	72.20	16.71	61.90	3.21	10.29	17.01	15.11	9.80
FG5X-216	1	46.03	4.32	47.79	3.24	-1.76	5.40		
FG5X-216	2	43.20	4.32	43.70	3.26	-0.50	5.41		
FG5X-216	7	60.04	4.32	61.90	3.21	-1.87	5.38	-1.38	3.11
FG5X-102	5	29.25	3.85	28.00	3.29	1.25	5.06		
FG5X-102	10	46.73	3.84	47.10	3.36	-0.37	5.10		
FG5X-102	9	55.17	3.84	55.36	3.29	-0.19	5.05	0.23	2.93
FG5-202	8	63.27	4.32	59.00	3.34	4.28	5.46		
FG5-202	9	59.72	4.32	55.36	3.29	4.36	5.43		
FG5-202	2	48.77	4.32	43.70	3.26	5.07	5.41	4.57	3.14
FG5-218	5	28.42	3.86	28.00	3.29	0.42	5.07		
FG5-218	1	48.64	3.91	47.79	3.24	0.84	5.08		
FG5-218	6	65.36	3.80	65.09	3.27	0.27	5.01	0.51	2.92

FG5X-220	2	48.42	4.90	43.70	3.26	4.72	5.89		
FG5X-220	1	53.18	4.90	47.79	3.24	5.39	5.88		
FG5X-220	10	51.68	4.90	47.10	3.36	4.58	5.95		
FG5X-220	8	65.12	4.90	59.00	3.34	6.12	5.93	5.20	2.96
FG5X-229	4	34.25	3.85	34.96	3.45	-0.71	5.17		
FG5X-229	2	42.99	3.85	43.70	3.26	-0.71	5.05		
FG5X-229	5	29.74	3.85	28.00	3.29	1.74	5.06	0.11	2.94
FG5-230	9	52.95	3.91	55.36	3.29	-2.42	5.11		
FG5-230	5	23.69	3.91	28.00	3.29	-4.31	5.11		
FG5-230	10	44.51	3.91	47.10	3.36	-2.59	5.16	-3.11	2.96
FG5-233	4	37.95	4.91	34.96	3.45	2.99	6.00		
FG5-233	2	46.87	4.91	43.70	3.26	3.17	5.89		
FG5-233	5	29.45	4.91	28.00	3.29	1.45	5.90	2.53	3.42
FG5-234	6	70.98	3.99	65.09	3.27	5.89	5.16		
FG5-234	4	38.96	3.95	34.96	3.45	3.99	5.24		
FG5-234	8	62.83	3.95	59.00	3.34	3.83	5.17	4.58	3.00
FG5-238	1	46.24	15.23	47.79	3.24	-1.55	15.57		
FG5-238	9	58.36	11.44	55.36	3.29	3.00	11.91		
FG5-238	4	46.67	16.63	34.96	3.45	11.71	16.98	3.78	8.26
FG5X-247	6	60.58	6.18	65.09	3.27	-4.51	6.99		
FG5X-247	8	47.50	4.61	59.00	3.34	-11.50	5.69		
FG5X-247	4	32.77	9.63	34.96	3.45	-2.19	10.23	-7.69	4.05
FG5-301	9	55.73	4.32	55.36	3.29	0.37	5.43		
FG5-301	7	62.13	4.32	61.90	3.21	0.22	5.38		
FG5-301	6	65.11	4.32	65.09	3.27	0.02	5.42	0.20	3.12
FG5X-302	2	44.14	3.83	43.70	3.26	0.44	5.03		
FG5X-302	6	65.83	3.83	65.09	3.27	0.74	5.04		
FG5X-302	10	49.22	3.83	47.10	3.36	2.12	5.10		
FG5X-302	1	49.35	3.89	47.79	3.24	1.56	5.06		
FG5X-302	7	62.66	3.85	61.90	3.21	0.76	5.01	1.12	2.26
A10-020	10	37.78	13.24	47.10	3.36	-9.32	13.66		
A10-020	8	57.50	12.65	59.00	3.34	-1.50	13.08		
A10-020	1	42.42	11.67	47.79	3.24	-5.37	12.11	-5.29	7.45

In table 11, U_D represents the expanded uncertainty of the DoE as determined in the comparison. This uncertainty depends on the declared uncertainty of gravimeter in question, accuracy of linking converter and on the observation structure of the comparison, above all on the number of station occupations by the gravimeter (typically N=3). In Francis et al. (2015), it was 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.

According to Francis et al. (2015), for assessing equivalence we therefore couple the DoE with the RMS of the uncertainties ($\boldsymbol{U_{Dij}}$ in table 11) of the 3–5 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% confidence level in table 12 and figure 4. All the NMI/DI gravimeters are in equivalence.

DoE of non NMI/DIs can be found in Annex B.

Table 12. Degrees of Equivalence (DoE, according to Eq. 5) of the NMI/DI gravimeters participating in the KC. The uncertainty U_{DoE}, is the RMS uncertainty of the 3–5 differences from Table 11. It represents the expanded uncertainty at 95% confidence.

OFFICIAL KEY COMPARISON RESULTS		
Gravimeter	**Degree of Equivalence**	
	DoE /µGal	**U_{DoE} /µGal**
FG5X-221	**-2.14**	**5.72**
FG5-215	**3.89**	**5.80**
IMGC-02	**15.11**	**16.98**
FG5X-216	**-1.38**	**5.40**

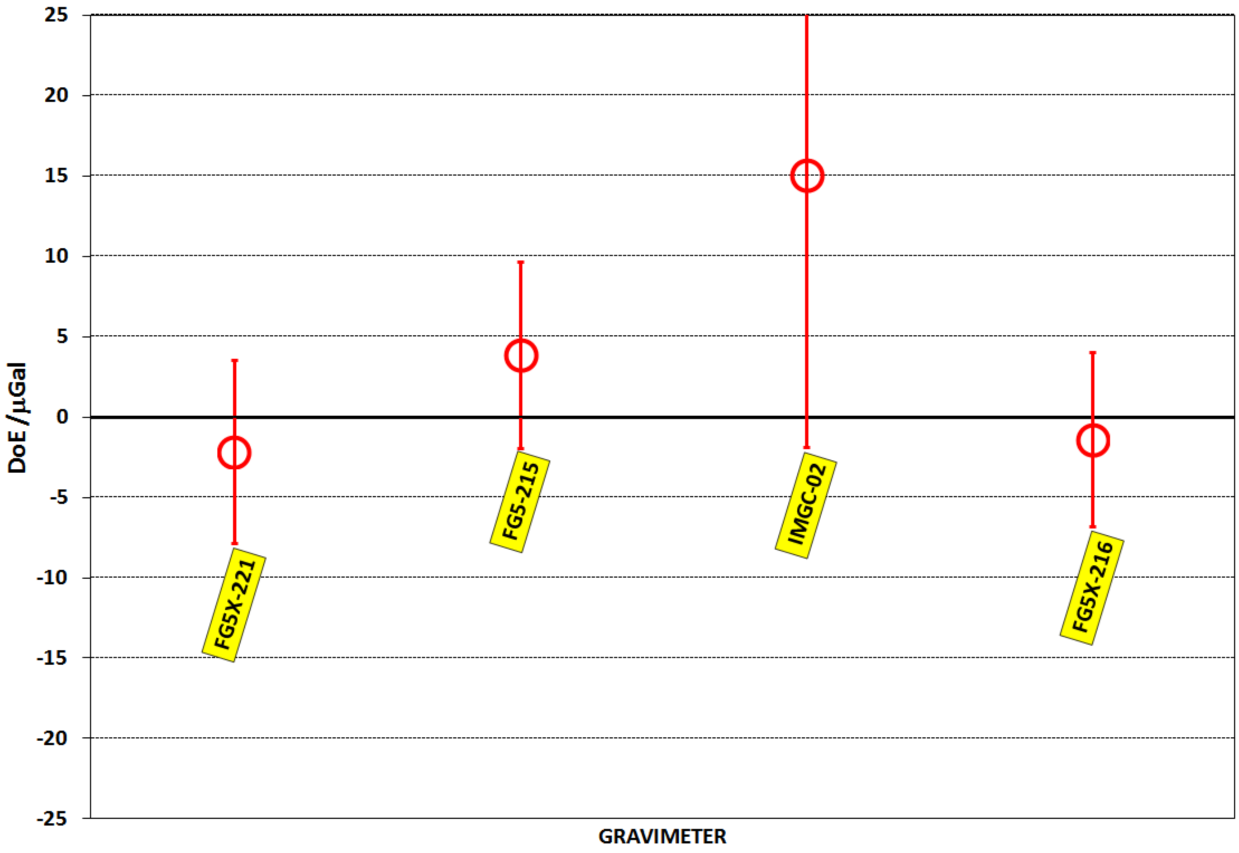

Figure 4. Degrees of Equivalence (DoE) of the NMI/DI gravimeters participating in the KC, calculated from the difference between the gravimeter measurements and the KCRVs. The error bars represent the expanded uncertainties (U_{DoE}) of the DoE at 95% confidence.

7. Conclusions

In the framework of the regional EURAMET.M.G-K2 comparison of absolute gravimeters, 17 gravimeters were compared. Four gravimeters were from different NMIs and DIs, they were used to link the regional comparison to the CCM.G.K2 (Francis et al. 2015) by means of linking converter computed as weighted average of DoEs obtained by four gravimeters at the CCM comparison.

Non-NMI/DI gravimeters participating under Pilot Study did not contributed to the determination of KCRV. Nevertheless, their *g*-values were used to determine relative gravity ties for a better estimation of gravity differences between the 9 sites used during the comparison. One measurement from a NMI gravimeter and one from non NMI/DIs were found to be not in equivalence at 95% confidence level based on the compatibility index E_n. These measurements were discarded to estimate the KCRVs but reintroduced to calculate the DoE of the gravimeters.

Combined (observation and constraint equations) least-squares adjustments with weighted constraint was used to determine KCRV. The final DoEs was estimated by weighted mean of differences between measured *g*-values and KCRV. In case of NMI/DI's gravimeters, all the weights used in the adjustment and also in the DoE estimation were computed from following source of uncertainties: 1) raw uncertainties provided by the operators, 2) contribution of the g-transfer to the comparison reference height of 1.25 m, 3) due to non applied corrections for gravity variations during the comparison and 4) uncertainty of the linking converter. In case of non NMI/DIs, the weights given by operators were slightly modified in the adjustment to avoid overvaluation of their contribution in the determination of the relative gravity ties between sites.

In conclusion, the DoEs of the 4 NMI and DI gravimeters are comprised between -2.1 and +15.1 µGal. For the non NMI/DI gravimeters (elaborated in Annex B under Pilot study), the DoEs are between -7.7 µGal and +5.2 µGal. All the gravimeters are in equivalence with declared uncertainties.

Finally, pilot solutions are presented in Annex B, where the gravimeters are not divided to NMI/DIs and non-NMI/DIs and they are treated as equivalent. Further, no link is considered to the CCM.G.K2, assuming that 17 gravimeters are able to provide an appropriate reference. Within pilot solutions, we also present results of the adjustment as proposed by de Viron et al. (2011), who minimize the L1 norm of the biases instead of imposing zero mean of biases. The difference between both approaches (in case of weighted constraint) is 0.55 µGal. Differences with respect to the official KC solution are below 1.2 µGal and 1.7 µGal in case of weighted and non-weighted constraints, respectively.

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ANNEX A: Vertical gravity gradient

In October and November 2015, gravity measurements with the Scintrex CG5#008, CG5#010 and ZLS Burris B-20 were performed by Dr. Olivier Francis and Raphaël De Plaen (University of Luxembourg), Dr. Filippo Greco (Istituto Nazionale di Geofisica e Vulcanologia) and Dr. Vojtech Pálinkáš (RIGTC/VÚGTK). CG5#008 and B-20 gravimeters measured at least three different levels at all the 9 sites. According to the results obtained by Burris gravimeters (figure A1 and A2), it was decided to approximate the VGGs by constant gradients (linear gravity change with height) at all the stations.

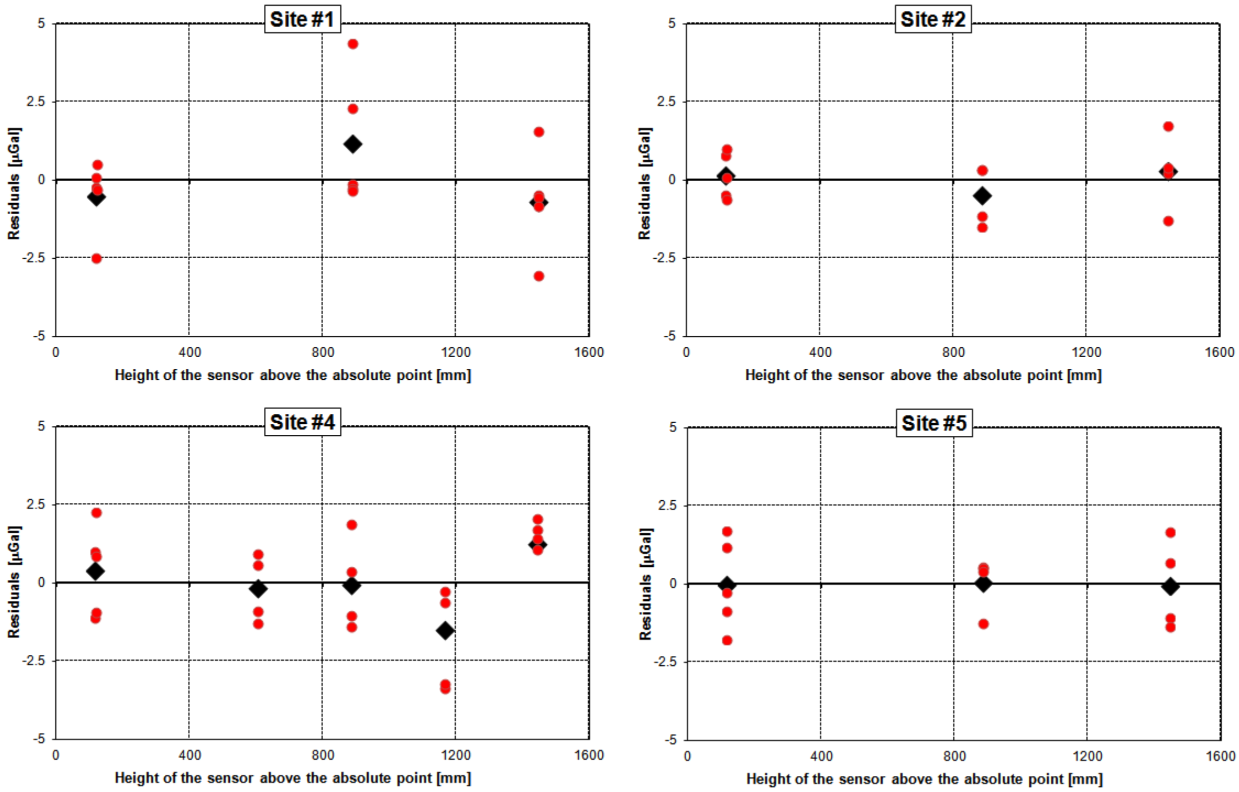

Figure A1. Residuals of the adjustment for determination of linear gravity change with heights. Red dots are representing the residuals related to individual readings of the gravimeter B-20 at different levels above the site. Black diamonds are the averaged residuals for a particular level above the site.

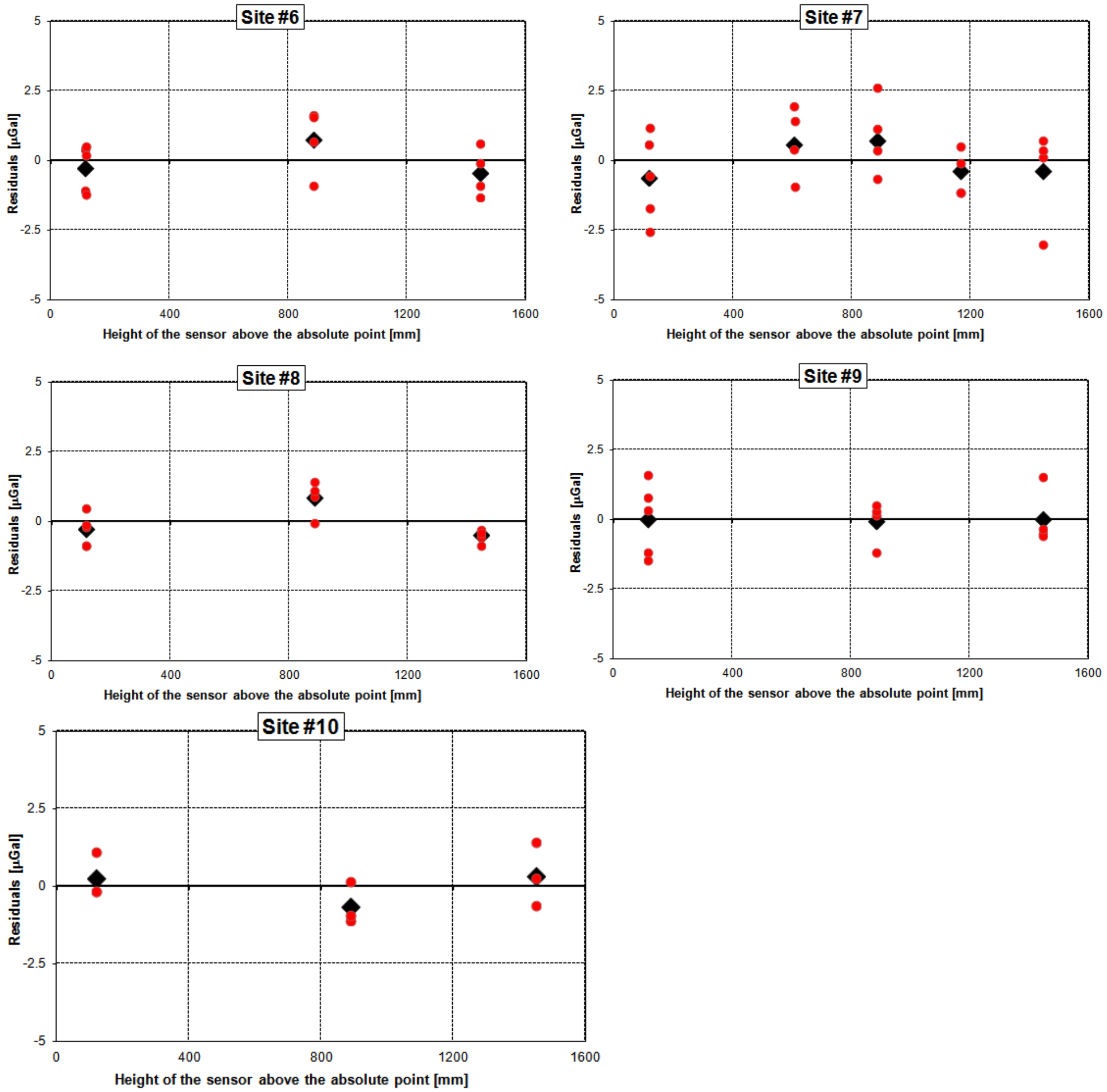

Figure A2. Residuals of the adjustment for determination of linear gravity change with heights. Red dots are representing the residuals related to individual readings of the gravimeter B-20 at different levels above the site. Black diamonds are the averaged residuals for a particular level above the site.

ANNEX B: Pilot study solutions

Official results of the key comparison are related to the final adjustment (described above in section 7.3) for which: the link to the CCM.G.K2 was established by four NMI/DI gravimeters, measurements of the IMGC-02 at site #10 and the FG5X-247 at site #8 were excluded and the adjustment approach C has been used. Corresponding results are the official KCRVs (see table 10) and biases of gravimeters presented in table B1.

Degrees of equivalence of non NMI/DI gravimeters (participating under the Pilot study) were computed as those for NMI/DI gravimeters, using equation (5) and differences between gravimeter measurements and KCRVs (table 11).

As it can be seen from table B1, the DoEs of the IMGC-02 and FG5X-247 are not the same as the biases from the final adjustment because measurements (one for both gravimeters) were excluded to compute the KCRV (Table 10) and biases (Table B1).

Table B1. Biases (from the final adjustment) and the DoEs (according to Eq. 5) of NMI/DIs (yellow) and non-NMI/DIs related to the final solution of the key comparison (KS). The uncertainty U_{DoE}, is the RMS uncertainty of the 3–5 differences from table 11. It represents the expanded uncertainty at 95% confidence. Note, that DoEs of NMI/DIs are same as in table 12 (official KC results),

Gravimeter	Approach C, 2 outliers		Degree of Equivalence	
	δ /µGal	σ /µGal	DoE /µGal	U_{DoE} /µGal
FG5X-221	-2.14	0.58	**-2.14**	**5.72**
FG5-215	3.89	0.53	**3.89**	**5.80**
IMGC-02	12.95	2.77	**15.11**	**16.98**
FG5X-216	-1.37	0.49	**-1.38**	**5.40**
FG5X-102	0.23	0.78	**0.23**	**5.07**
FG5-202	4.57	0.76	**4.57**	**5.43**
FG5-218	0.51	0.74	**0.51**	**5.05**
FG5X-220	5.20	0.73	**5.20**	**5.91**
FG5X-229	0.11	0.79	**0.11**	**5.09**
FG5-230	-3.10	0.78	**-3.11**	**5.13**
FG5-233	2.54	0.85	**2.53**	**5.93**
FG5-234	4.57	0.79	**4.58**	**5.19**
FG5-238	3.78	1.96	**3.78**	**14.98**
FG5X-247	-3.83	1.36	**-7.69**	**7.87**
FG5-301	0.21	0.73	**0.20**	**5.41**
FG5X-302	1.12	0.60	**1.12**	**5.05**
A10-020	-5.29	1.78	**-5.29**	**12.96**

The results presented below are related to the solution of the comparison, where gravimeters of NMI/DIs and non-NMI/DIs are treated equivalently. No link is considered to the CCM.G.K2 assuming that 17 gravimeters are able to provide an appropriate reference. Further, we present solutions that are related to the constraint used in de Viron et al. (2011) that minimizes the L1 norm of biases instead of imposing zero mean of biases.

Observation equations (see equation (1)) for all pilot solutions (PSs) presented below:

- were associated with weighting matrix using harmonized uncertainties given in the last column of table 4, equally as for the final solution of the key comparison (KS) of which results can be found in table 10 and table B1.
- did not contain the measurement of the FG5X-247 at site 8 that was identified as an outlier at more than 99.9% confidence. Contrary to the KS, the measurement of the IMGC-02 at site 10 has not been excluded, similarly as other measurements identified as an outlier at 95% confidence but not at 99%.

Therefore, the difference between PSs and the KS is mainly related to the choice of the constraint that ensures an unique solution for unknowns (reference values and biases). Following solutions are presented in table B2, B3 and B4:

- **PS_M**, considering mean of biases to be zero: $\frac{1}{n}\sum_{i=1}^{n}\delta_i = 0$.
- **PS_MW**, considering weighted mean of biases to be zero: $\sum_{i=1}^{n} w_i\,\delta_i = 0$, where the weights were computed as root mean square of harmonized uncertainties given in the last column of table 4. We got the following weights for gravimeters:

FG5X-221	FG5-215	IMGC-02	FG5X-216	FG5X-102	FG5-202	FG5-218	FG5X-220	FG5X-229
0.955	*0.924*	*0.076*	*1.135*	*1.134*	*1.134*	*1.134*	*0.880*	*1.135*

FG5-230	FG5-233	FG5-234	FG5-238	FG5X-247	FG5-301	FG5X-302	A10-020
1.134	*0.879*	*1.134*	*0.110*	*0.391*	*1.134*	*1.135*	*0.136*

- **PS_L**, minimizing the L1 norm of biases: $\sum_{i=1}^{n}|\delta_i| = min$.
- **PS_LW**, minimizing the weighted L1 norm of biases: $\sum_{i=1}^{n}|w_i\,\delta_i| = min$, where the weights are same as for PS_MW.

While the solutions considering zero mean of biases (PS_M and PS_MW) were obtained through normal equations that solve the linear least-squares problem, the solutions minimizing the L1 norm of biases (PS_L and PS_LW) were computed numerically. "L1 norm" results have been achieved from "zero mean" results, by shifting the biases by a value δ_c in the range of +/- 10 µGal with the step of 0.01 µGal. Finally, we detected such a δ_c for which:

- $\sum_{\mathrm{i=1}}^{\mathrm{n}}|\delta_i + \delta_c| = \mathrm{min}$, in case of PS_L solution, when δ_i have been achieved from PS_M,
- $\sum_{\mathrm{i=1}}^{\mathrm{n}}|w_i\,(\delta_i + \delta_c)| = \mathrm{min}$, in case of PS_LW solution, when δ_i have been achieved from PS_MW.

As it can be seen from table B2, δ_c (the difference between "L1 norm" and "zero mean" approaches) is +1.02 µGal when weights are not used in constraints and +0.55 µGal when weights are applied in constraints.

Differences between reference values (RVs) given by a particular PS and KCRV (Key comparison reference values, see table 10) are represented by a parameter *K*. As shown in table B3, all RVs differ less than 1.7 µGal with respect to the KCRV. Note that:

- The solution with weighted constraint have been chosen to represent the final key comparison results, while RVs related to the solution with non-weighted constraint were higher for *K* = +3.5 µGal (Approach A in section 7.1). All the pilot solutions are closer to the official solution. It supports our decision to use least-squares adjustment with weighted constraint as the official key comparison solution.
- While weights applied in the constraint of pilot solutions imposing zero mean of biases changed the RVs by of about 0.5 µGal, there is practically no change (less than 0.01 µGal) in case of solutions imposing L1 norm of biases.
- We tried to use the L1 norm approach for determination of the official key comparison solution with four linking laboratories only. In case of L1 norm with weighted constraint, we got a solution where biases were higher by δ_c = +1.70 µGal (RVs lower for *K*= -1.7 µGal) than the official results. However, in case of the L1 norm with non-weighted constraint, there was not detected an unique solution for the unknowns, since the L1 norm was minimal in the range of bias shift from δ_c = -0.55 µGal up to δ_c = +4.71 µGal.

Degrees of equivalence (DoE) with associated uncertainties for all pilot solutions (see Table B4) have been computed according to the description given in Section 7.3. We can see that the gravimeter FG5X-247 is not in equivalence with declared uncertainties at the 95% confidence level for all the pilot solutions. Comparison of DoEs for the final key comparison solution (table B1) and the pilot solution PS_MW (imposing zero mean of weighted biases) can be seen in figure B1.

Table B2. Comparison of biases (δ with standard deviations σ) determined for four pilot solutions. Two of them are related to the constraint that imposing zero mean of biases (PS_M, PS_MW). Next two solutions (PS_L, PS_LW) are achieved by shifting the biases (from zero mean solutions) by a value of δc to minimize the L1 norm of biases. PS_L and PS_M do not use weights in constraint contrary to PS_LW and PS_MW.

Gravimeter	**PS_M**		**PS_L**	**PS_MW**		**PS_LW**
	δ **/µGal**	σ **/µGal**	δc **/µGal**	δ **/µGal**	σ **/µGal**	δc **/µGal**
FG5X-221	-3.67	0.72	**+1.02**	-3.19	0.69	**+0.55**
FG5-215	2.36	0.63		2.83	0.60	
IMGC-02	13.58	2.20		14.06	2.32	
FG5X-216	-2.90	0.68		-2.42	0.64	
FG5X-102	-1.35	0.68		-0.87	0.64	
FG5-202	3.03	0.67		3.50	0.63	
FG5-218	-1.02	0.66		-0.55	0.62	
FG5X-220	3.64	0.65		4.12	0.62	
FG5X-229	-1.41	0.69		-0.93	0.65	
FG5-230	-4.68	0.68		-4.21	0.64	
FG5-233	1.02	0.75		1.50	0.72	
FG5-234	3.07	0.69		3.54	0.66	
FG5-238	2.25	1.85		2.72	1.94	
FG5X-247	-5.34	1.26		-4.87	1.29	
FG5-301	-1.32	0.68		-0.84	0.64	
FG5X-302	-0.42	0.53		0.05	0.49	
A10-020	-6.86	1.67		-6.38	1.75	

Table B3. Comparison of the Reference Values (RV with standard deviations σ) of pilot solutions with respect to the Key Comparison Reference Values (KCRVs in table 10). Difference between four pilot solutions (PS_M, PS_MW, PS_L, PS_LW) and the official solution (KS) is represented by a parameter ***K***.

Station ***k***	**PS_M**			**PS_L**	**PS_MW**			**PS_LW**
	RV /µGal	σ **/µGal**	***K*** **/µGal**	***K*** **/µGal**	**RV /µGal**	σ **/µGal**	***K*** **/µGal**	***K*** **/µGal**
1	49.33	0.56	1.54	0.52	48.86	0.54	1.07	0.52
2	45.23	0.54	1.53	0.51	44.76	0.49	1.06	0.51
4	36.43	0.71	1.46	0.44	35.95	0.70	0.99	0.44
5	29.54	0.54	1.54	0.52	29.07	0.49	1.07	0.52
6	66.61	0.55	1.53	0.51	66.14	0.51	1.05	0.50
7	63.40	0.58	1.50	0.48	62.93	0.54	1.03	0.48
8	60.53	0.64	1.53	0.51	60.06	0.61	1.06	0.51
9	56.91	0.57	1.55	0.53	56.43	0.53	1.07	0.52
10	48.74	0.62	1.64	0.62	48.27	0.60	1.17	0.62
	Mean (PS-KS)=		**1.54** ± 0.02	**0.52** ± 0.02	Mean (PS-KS)=		**1.06** ± 0.02	**0.51** ± 0.02

Table B4. Comparison of Degrees of equivalence (DoE) for four pilot solutions (PS_M, PS_MW, PS_L, PS_LW). The uncertainty U_{DoE}, is the RMS uncertainty of the 3–5 differences computed by Eq.(5). It represents the expanded uncertainty at 95% confidence.

Gravimeter	DoE /µGal				U_{DoE} /µGal
	PS_M	PS_L	PS_MW	PS_LW	
FG5X-221	-3.66	-2.64	-3.19	-2.64	4.83
FG5-215	2.36	3.38	2.83	3.38	4.91
IMGC-02	13.58	14.60	14.06	14.61	16.69
FG5X-216	-2.90	-1.88	-2.42	-1.87	4.44
FG5X-102	-1.34	-0.32	-0.87	-0.32	3.99
FG5-202	3.03	4.05	3.51	4.06	4.46
FG5-218	-1.03	-0.01	-0.56	-0.01	3.99
FG5X-220	3.64	4.66	4.11	4.66	5.03
FG5X-229	-1.40	-0.38	-0.92	-0.37	4.02
FG5-230	-4.69	-3.67	-4.21	-3.66	4.06
FG5-233	1.02	2.04	1.49	2.04	5.04
FG5-234	3.07	4.09	3.55	4.09	4.15
FG5-238	2.24	3.26	2.71	3.26	14.65
FG5X-247	-9.56	-8.54	-9.09	-8.53	7.23
FG5-301	-1.32	-0.30	-0.85	-0.30	4.45
FG5X-302	-0.43	0.59	0.04	0.59	4.00
A10-020	-6.85	-5.83	-6.38	-5.83	12.59
	Δ(PS_L - PS_M) = +1.02		**Δ(PS_LW - PS_MW) = +0.55**		

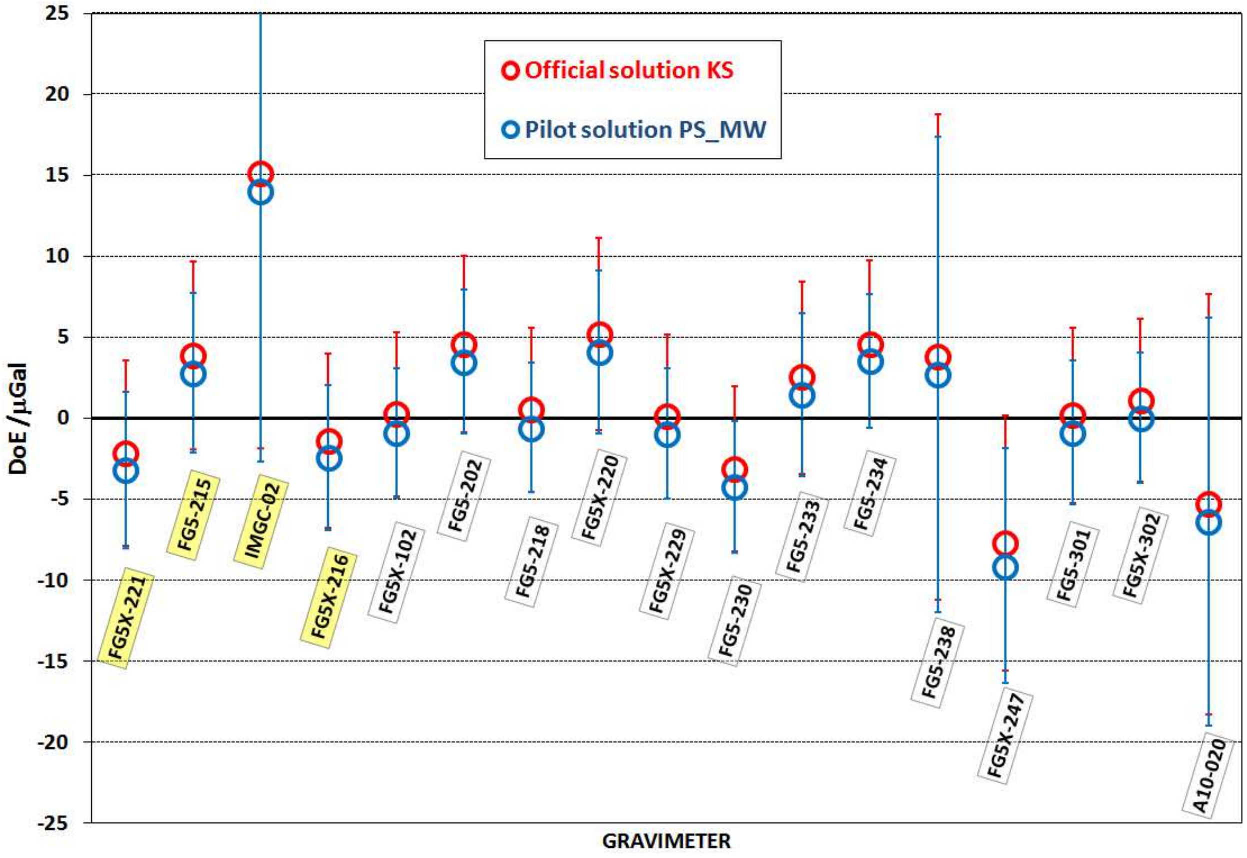

Figure B1. Comparison of DoE for the official solution (KS) and the pilot solution PS_MW (considering weighted mean of biases to be zero). The error bars represent the expanded uncertainties of DoE at 95% confidence. Gravimeters of NMI/DIs are highlighted in yellow.