Final Report

REGIONAL COMPARISON OF ABSOLUTE GRAVIMETERS

EURAMET.M.G-K2.2023 Key Comparison

and Additional Comparison

Pilot laboratory: 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-K2.2023[1] and the simultaneously organized Additional Comparison [1], was held in Germany at the Geodetic Observatory Wettzell (GOW) of the German Federal Agency for Cartography and Geodesy close to the city of Bad Kötzting in the Spring of 2024. All the measurements were collected between May 21st and June 21st, 2024.

The Technical Protocol[2] (TP) was approved before the comparison by the participants and the CCM-WGG[3]. The TP includes the list of the registered participants, a description of the comparison site, the measurement schedule and an illustrative Table to indicate the uncertainty of the gravimeters. It also specifies the data processing as well as the reporting of the results.

The schedule of absolute measurements followed the TP. However, the number of participants and their observation periods at GOW had to be changed several times, making updates of the TP necessary. One group of participants had to cancel their participation due to technical issues. Finally, 16 absolute gravimeters participated in 5 sessions.

VÚGTK/RIGTC (Research Institute of Geodesy, Topography and Cartography) under the leadership of Dr. Vojtech Pálinkáš was the Pilot Laboratory. Dr. Hartmut Wziontek, Dr. Reinhard Falk, Jan Müller, Dr. Thomas Klügel, Dr. Anna Winter and J. Konadel (all of BKG) were in charge of the local organizing committee.

The EURAMET.M.G-K2.2023 and Additional Comparison is registered as EURAMET TC project no. 1603. The comparison was organized in accordance with the CIPM-MRA-G-11. It is linked to the results of the CCM.G-K2.2023 comparison [2] at Table Mountain Geophysical Observatory (TMGO), Boulder, Colorado, USA by three absolute gravimeters that participated in both comparisons.

The main objective of a regional key comparison is the validation of the Calibration and Measurement Capabilities (CMCs) published in the KCDB of the BIPM through links to the CIPM KC. This is especially important for participants who could not be accommodated in the recent CIPM KC [1].

The Additional Comparison has been organized to ensure the compatibility of absolute gravimeters used for the realization of the International Terrestrial Gravity Reference Frame [3] and the International Database for Absolute Gravity measurements (AGrav) [4].

Here we present the list of the participants who actually performed measurements during the comparison, the observations (absolute gravity measurements and their uncertainties) submitted by the operators. The linear function for the vertical gravity gradient at the comparison sites were adopted from the EURAMET.M.G-K3 Key Comparison [5]. The measurement strategy is briefly discussed and the results of the data harmonization is documented. Finally, the results of the adjustment that takes into account correlations between measurements [6] are presented by means of the comparison reference values (CRV) deviations of each gravimeter from the CRV. The CRV were obtained by the absolute values of the linking gravimeters participating in the Key Comparison and the gravity differences measured by all the gravimeters (including those participating at the Additional Comparison), therefore CRVs are referring to KCRV of CCM.G-K2.2023[4].

This report presents all results of the six gravimeters taking part in EURAMET.M.G-K2.2023, the results of the Additional Comparison are documented in Annex A.

In this report, the microGal (µGal) is used as a unit of acceleration, 1 µGal is equal to 1 × 10^{-8} m/s^2. The standard uncertainty is denoted *u* (*k* = 1) and the expanded uncertainty *U* at a 95 % level of confidence, (*k* = 2). Sigma (σ) is denoted the standard deviation, but sometimes it also refers to standard error of estimates from least-squares adjustment, and is shown always with *k* = 1.

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[1] https://www.bipm.org/kcdb/comparison?id=1906

[2] https://www.bipm.org/kcdb/comparison/doc/download/1906/Technical_Protocol_WETCAG_2024_update_2024_May_14.pdf

[3] Consultative Committee for Mass and Related Quantities - Working Group on Gravimetry

[4] https://www.bipm.org/kcdb/comparison?id=1836

2. List of participants

The list of the participants is presented in Table 1. In total, 16 absolute gravimeters of four different types were compared. Overall, 6 teams from National Metrology Institutes (NMIs) or Designated Institutes (DIs) participated in the Key Comparison and 8 teams from non-NMI/DIs in the Additional Comparison.

Table1. Participants in the comparison (NMI = National Metrology Institute; DI = Designated Institute). The metrological institutes taking part at EURAMET.M.G-K2.2023 are in yellow.

Country	Institution	Gravimeter	NMI or DI	CCM.G-K2.2023	Operator(s)
EURAMET.M.G-K2.2023					
Czech Republic	Research Institute of Geodesy, Topography and Cartography (VÚGTK/RIGTC), Zdiby	FG5X-251/HS5	YES	YES	Vojtech Pálinkáš, Jakub Kostelecký
Finland	Finnish Geospatial Research Institute (FGI), National Land Survey of Finland (NLS), Helsinki	FG5X-221	YES	YES	Mirjam Bilker-Koivula, Jyri Näränen
France	LNE-OP / LTE, Paris (EOST, Strasbourg)	FG5X-206	YES	NO	Sébastien Merlet, Jean-Daniel Bernard
Germany	PTB, Braunschweig	FG5X-263	YES	YES	Christian Rothleitner, Johannes Konrad
Italy	Istituto Nazionale di Ricerca Metrologica (INRIM), Torino	IMGC-02	YES	NO	Andrea Prato, Alessio Facello Alessandro Germak
Switzerland	METAS, Wabern	FG5X-209	YES	NO	Henri Baumann
Additional Comparison					
Germany	GFZ German Research Centre for Geosciences, Dept. Hydrology, Potsdam	AQG-B02	NO	NO	Marvin Reich
Germany	Federal Agency for Cartography and Geodesy (BKG), Leipzig	FG5-101 FG5-227 FG5-301	NO	YES* YES* NO	André Gebauer, A. Lothhammer, Erik Brachmann
Italy	e-geos, Matera	FG5-218	NO	NO	Iacovone Domenico Giovanni Nettis
Italy	National Institute of Geophysics and Volcanology (INGV), Rome	FG5-238	NO	YES*	Filippo Greco, Alfio Messina Danilo Contrafatto
Netherlands	Delft University of Technology, Delft	FG5X-234	NO	NO	René Reudink
Poland	Institute of Geodesy and Cartography (IGiK), Warszawa	AQG-B07	NO	NO	Przemyslaw Dykowski, Adam Ciesielski
Slovakia	Slovak University of Technology, Bratislava	FG5X-247	NO	NO	Juraj Janák, Juraj Papčo
Sweden	Lantmäteriet, Gävle	FG5X-233	NO	YES*	Andreas Engfeldt

3. Station description and relative gravity measurements

The comparison was held in the Gravity Laboratory 2 at the Geodetic Observatory Wettzell (GOW) of the German Federal Agency for Cartography and Geodesy (BKG) close to the city of Bad Kötzting, situated in the Bavarian Forest in South East of Germany. The laboratory is located far from sources of anthropogenic noise (e.g. traffic). All measurements were performed on 4 separate pillars (sites) with size of 1.2 m x 1.2 m x 1.7 m (Figure 1). The site coordinates are 49.14483° North, 12.87631° East and the altitude is 606.57 m.

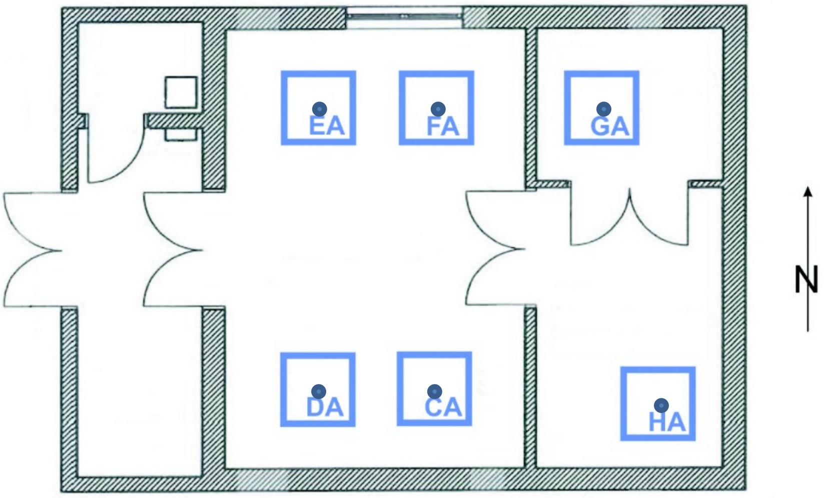

Figure 1. Floorplan of the Gravity Laboratory 2 at Geodetic Observatory Wettzell. The pillar G is occupied by the superconducting gravimeter SG030 and for AG measurements the central room is equipped with 4 pillars. The pillar H was not used during the comparison. The surface centre of each pillar is marked by a small brass benchmark, indicating the position A at each pillar.

Vertical Gravity Gradients (VGGs) were determined before and during EURAMET.M.G-K3 comparison in 2018 [5] and exclusively these values (Table 2) have been used in this report.

Table 2. Vertical gravity gradients at the 4 sites used for the comparison [5].

Site	VGG /μGal ·m^{-1}	u VGG /μGal m^{-1}
CA	-328.7	1.2
DA	-330.1	1.1
EA	-319.5	0.9
FA	-319.9	0.9

The tidal parameters (Table 3) were estimated from 12 years of continuous measurements of the superconducting gravimeter GWR SG-030 (2010-2022) up to monthly periods. This model with similar wave grouping as the one used in previous comparisons better represents diurnal and semidiurnal tides but doesn’t affect the mean level.

Gravity variations during the comparison were measured with the superconducting gravimeter SG-030 at pillar G (Figure 1). A linear instrumental drift of (1.3 ± 0.2) µGal / year has been determined based on 10 years of repeated absolute measurements with FG5-101 and FG5-301 of BKG. Figure 2 shows the residual temporal gravity variations after drift correction that reach up to 2.5 µGal. This demonstrates the need to monitor gravity variations during the comparison with high stability that a superconducting gravimeter provides. These variations were set to zero at the reference time of the comparison, June 6, 2024 00:00 UT.

These gravity variations were obtained from the measured SG signal of the upper sensor using the calibration factor of -68.0 µGal/V and applying corrections for Earth and ocean tides (Table 3), polar motion, atmospheric effects (admittance factor of -0.3 µGal/hPa) and an instrumental drift of 1.8 µGal/year.

Table 3. Simplified model of tidal parameters for Wettzell derived from 12 years of continuous observation with the superconducting gravimeter SG-030.

Wave	Start freq. /cpd	End freq. /cpd	Amplitude factor	Phase lag /deg
M0+S0	0.000000	0.000010	1.00000	0.0000
SA	0.000011	0.003426	1.16000	0.0000
SSA	0.004709	0.010952	1.16000	0.0000
Mm	0.025812	0.044652	1.14336	0.3776
Mf	0.060132	0.080797	1.14126	0.6868
Mtm	0.096423	0.249951	1.15426	-0.5090
Q1	0.721500	0.906315	1.14919	-0.2069
O1	0.921941	0.940487	1.15076	0.1142
M1	0.958086	0.974188	1.15459	0.2781
P1	0.989049	0.998028	1.15116	0.1457
S1	0.999853	1.000147	1.21046	7.7281
K1	1.001825	1.003651	1.13775	0.2080
Psi1	1.005329	1.005623	1.24997	0.3936
Phi1	1.007595	1.013689	1.16771	-0.0469
J1	1.028550	1.044800	1.15719	0.1102
Oo1	1.064841	1.216397	1.15840	0.1663
2N2	1.719381	1.872142	1.16356	2.1925
N2	1.888387	1.906462	1.17880	1.9890
M2	1.923766	1.942753	1.18698	1.4148
L2	1.958233	1.976926	1.17998	0.6928
S2	1.991787	2.002885	1.18552	0.2852
K2	2.004710	2.182843	1.18578	0.4622
M3	2.753244	3.081254	1.07216	0.3302
M4	0.000011	0.003426	1.16000	0.0000

4. Absolute gravity measurements

The measurements of absolute gravimeters are listed in Table 4. Each gravimeter measured three or four different sites. The reported time of the measurement is the average of the times of the individual observations contributing to the measurement. The submitted absolute gravity measurement g_{raw} is the mean free-fall acceleration at the individual specific measurement height which has been corrected in accordance with the ITGRS Conventions 2020 [3] for:

- the Earth and ocean tides (Table 3), referred to the zero-tide concept,
- the effect of atmospheric mass variations using the local measured air pressure record and an admittance factor of -0.3 µGal/hPa, based on the DIN5450 (ISO 2533:1975) standard atmosphere,
- the polar motion effect, estimated from the coordinates of the Celestial Ephemeris Pole relative to the IERS Reference Pole,
- vertical gravity changes above the measurement site to obtain gravity at the specified measurement height,
- known instrumental effects (e.g. speed-of light correction, self-attraction, laser beam diffraction).

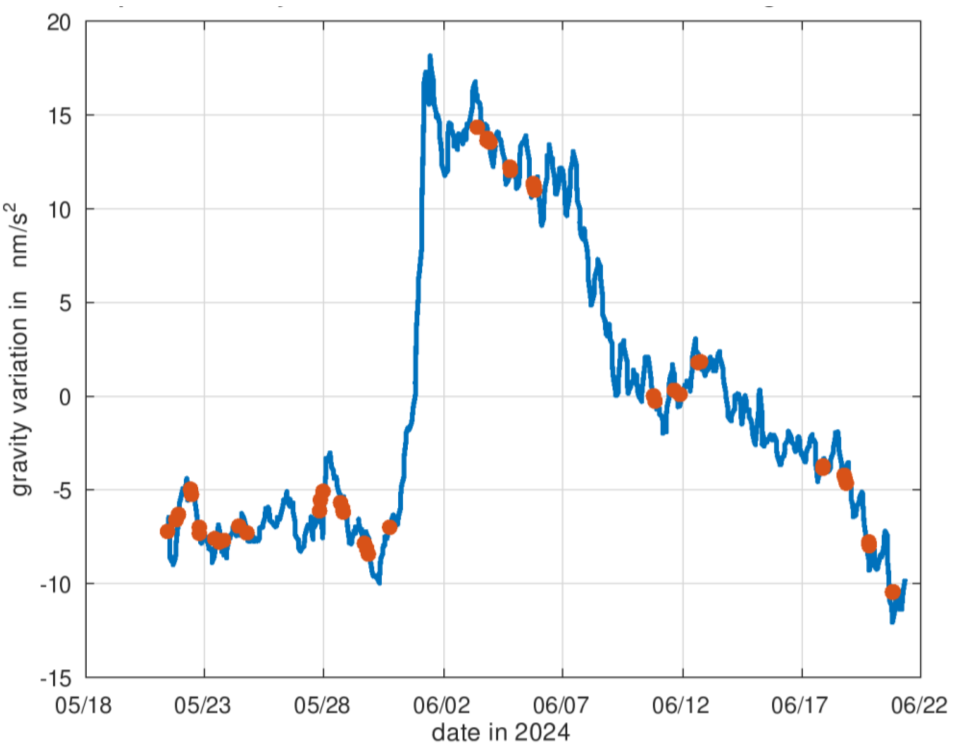

Figure 2. The residual gravity variations observed during the comparison with the superconducting gravimeter GWR SG-030, referred to June 6, 2024 00:00 UT as the reference time of the comparison. Red dots mark the reference time of the reported absolute gravity observations.

The operators were responsible for processing their gravity data. They have submitted the final gravity values and uncertainties for all measured sites. The values g_{raw} were mostly reported at the effective instrumental height [3] using VGGs given in the TP. Transfer corrections (dg_{ref}, see Table 4) and corresponding uncertainties were applied, proportionally to VGGs (Table 2) and differences between reported heights, effective instrumental heights and the comparison height of 1.25 m.

Residual temporal gravity variations have been taken into account by applying corrections based on the record of the superconducting gravimeter shown in Figure 2. Thus, the geophysical corrections (SGC, see Table 4) were computed as the negative value of the gravity residuals averaged over the period of the particular measurements. The uncertainty of such a correction was estimated to be 0.2 µGal.

The final values g at the comparison height of 1.25 m together with associated uncertainties u are listed in Table 4.

4.1. Uncertainties of absolute measurements

Following [2] the instrumental part of measurement uncertainties have been used for demonstrating equivalence of gravimeters. The reason for this approach is that corrections (SGC) applied based on monitoring of residual gravity variations are significantly reducing the contribution of errors associated to geophysical corrections in the uncertainty budget. Therefore, all measurements in Table 4 are associated with a) combined measurement uncertainty as a parameter that is usually associated with the gravity measurement (e.g. according to published CMC) and b) the instrumental part of this uncertainty, which will be used as initial for further analyses.

4.2. Systematic effects

Annex A gives an overview about systematics effects of the individual gravimeters, in particular corrections for self-attraction [7] and diffraction [8, 9], as well as for Coriolis forces [10], deviation from vertical [10] and fringe signal distortion [11] for some instruments. These corrections have been applied by operators according to their standard procedure and are included in reported gravity values in Table 4.

Table 4. List of the absolute gravity measurements during EURAMET.M.G-K2.2023. The constant value 980,836,900.00 µGal is subtracted from all gravity values.
$\boldsymbol{g_{raw}}$: raw gravity data with combined standard uncertainty $\boldsymbol{u_{com}}$ and its instrumental part $\boldsymbol{u_{raw}}$ declared by the participants, $\boldsymbol{g_{raw}}$ are corrected for tides, atmosphere, polar motion as well as instrumental effects (see Table A1), $\boldsymbol{g_{raw}}$ were reported by participants at the desired measurement height **H** above the pillar using gradient **VGG$_1$**
$\boldsymbol{dg_{ref}}$ gravity difference between reported height of raw gravity data and 1.250 m. * The reported measurement height slightly deviates from the usual reference instrumental height. To compute the transfer correction dg_{ref} , the default effective instrumental height of FG5 and FG5X of 1.22 m or 1.27 m, respectively was used with **VGG$_1$**.
$\boldsymbol{g}$: gravity values transferred to the reference height of the comparison (125 cm) using final gradients **VGG$_2$** and corrected for gravity variations **SGC** based on the record of the superconducting gravimeter.
$\boldsymbol{u}$: the standard uncertainty of $\boldsymbol{g}$ computed as root mean square of three components: the declared uncertainty of the raw gravity data by the participants $\boldsymbol{u_{raw}}$, the transfer error to the reference height of the comparison of 1.250 m, and 0.2 µGal due to SG based corrections (SGC).
$\boldsymbol{u_{har}}$: harmonized standard uncertainties (see Section 6.1), computed as u but the contribution from u_{raw} of non NMI/DIs which are below 2.20 µGal were changed to 2.20 µGal.

Gravimeter	Site	Average Time	#Drops	H /cm	VGG$_1$ /µGal·m^{-1}	g_{raw} /µGal	u_{com} /µGal	u_{raw} /µGal	VGG$_2$ /µGal·m^{-1}	dg_{ref} /µGal	SGC /µGal	g /µGal	u /µGal	u_{har} /µGal
FG5X-206	EA	17/06/2024 22:44	1681	126.20	-319.5	46.60	2.90	2.50	-319.50	3.83	0.37	50.80	2.51	2.51
FG5X-206	FA	18/06/2024 20:56	1985	126.20	-319.9	58.60	2.90	2.50	-319.90	3.84	0.42	62.86	2.51	2.51
FG5X-206	CA	19/06/2024 21:01	2086	126.20	-328.7	48.20	2.90	2.50	-328.70	3.94	0.76	52.90	2.51	2.51
FG5X-206	DA	20/06/2024 20:43	1993	126.20	-330.1	37.60	2.90	2.50	-330.10	3.96	1.02	42.58	2.51	2.51
FG5X-209	EA	03/06/2024 11:35	4180	126.22	-319.5	48.41	3.60	3.00	-319.50	3.90	-1.43	50.88	3.01	3.01
FG5X-209	FA	04/06/2024 20:17	2188	126.22	-319.9	60.38	3.70	3.00	-319.90	3.90	-1.22	63.06	3.01	3.01
FG5X-209	CA	05/06/2024 19:39	2291	126.22	-328.7	50.57	4.70	3.00	-328.70	4.01	-1.13	53.45	3.01	3.01
FG5X-221	CA	21/05/2024 20:49	2097	126.57	-328.7	48.30	2.30	2.00	-328.70	5.16	0.68	54.14	2.01	2.01
FG5X-221	DA	22/05/2024 20:12	2246	126.52	-330.1	37.20	2.30	2.00	-330.10	5.02	0.72	42.94	2.01	2.01
FG5X-221	EA	23/05/2024 20:35	2247	126.57	-319.5	44.00	2.30	2.00	-319.50	5.02	0.79	49.81	2.01	2.01
FG5X-221	FA	24/05/2024 20:02	2239	126.57	-319.9	56.60	2.30	2.00	-319.90	5.02	0.75	62.37	2.01	2.01
FG5X-251H	DA	03/06/2024 21:17	2400	127.03	-330.1	37.68	2.17	1.83	-330.10	6.70	-1.36	43.02	1.84	1.84
FG5X-251H	EA	04/06/2024 20:53	2000	127.06	-319.5	46.36	2.17	1.83	-319.50	6.58	-1.20	51.74	1.84	1.84
FG5X-251H	FA	05/06/2024 20:02	2100	126.97	-319.8	56.24	2.28	1.96	-319.90	6.30	-1.12	61.42	1.97	1.97
FG5X-263	DA	21/05/2024 23:12	1200	127.40	-330.1	36.31	2.40	2.08	-330.10	7.92	0.65	44.88	2.09	2.09
FG5X-263	EA	22/05/2024 20:10	1196	127.30	-319.5	44.81	2.40	2.08	-319.50	7.35	0.75	52.91	2.09	2.09
FG5X-263	FA	23/05/2024 16:09	1191	127.20	-319.9	56.10	2.40	2.08	-319.90	7.04	0.80	63.94	2.09	2.09
FG5X-263	CA	24/05/2024 11:53	1196	127.20	-328.7	49.30	2.40	2.08	-328.70	7.23	0.71	57.24	2.09	2.09
IMGC-02	CA	18/06/2024 22:25	1921	48.24	--	307.40	4.04	3.90	-328.70	-252.31	0.44	55.53	4.01	4.01
IMGC-02	DA	19/06/2024 21:22	1926	48.17	--	302.10	4.05	3.90	-330.10	-253.62	0.78	49.26	4.00	4.00
IMGC-02	EA	20/06/2024 21:01	1312	47.96	--	298.80	4.10	3.90	-319.50	-246.14	1.02	53.68	3.97	3.97
AQG-B02	DA	17/06/2024 23:00	121909	65.00	-330.1	226.82	10.70	10.24	-330.10	-198.06	0.35	29.11	10.26	10.26

AQG-B02	EA	18/06/2024 20:07	140567	65.00	-319.5	229.94	10.50	10.24	-319.50	-191.70	0.40	38.64	10.26	10.26
AQG-B02	FA	19/06/2024 21:03	147205	65.00	-319.9	242.64	10.70	10.24	-319.90	-191.94	0.76	51.46	10.26	10.26
AQG-B02	CA	20/06/2024 21:24	133911	65.00	-328.7	237.38	10.50	10.24	-328.70	-197.22	1.02	41.18	10.27	10.27
AQG-B07	EA	21/05/2024 18:56	129987	65.89	-319.5	216.63	10.30	10.24	-319.50	-188.86	0.68	28.45	10.26	10.26
AQG-B07	FA	22/05/2024 18:05	139986	65.64	-319.9	229.82	10.30	10.24	-319.90	-189.89	0.55	40.48	10.26	10.26
AQG-B07	CA	23/05/2024 18:33	132209	65.59	-328.7	224.72	10.30	10.24	-328.70	-195.28	0.55	29.99	10.27	10.27
AQG-B07	DA	24/05/2024 17:52	133320	65.79	-330.1	211.51	10.30	10.24	-330.10	-195.45	0.55	16.61	10.26	10.26
FG5-101	CA	10/06/2024 20:39	2880	121.66	-328.7	61.87	2.57	2.57	-328.70	-10.98	-0.01	50.88	2.58	2.58
FG5-101	DA	11/06/2024 17:26	2880	121.66	-330.1	51.68	2.57	2.57	-330.10	-11.03	-0.04	40.61	2.58	2.58
FG5-101	EA	12/06/2024 17:21	2880	121.66	-319.5	61.16	2.57	2.57	-319.50	-10.67	-0.19	50.30	2.58	2.58
FG5-218	FA	04/06/2024 00:20	1680	125.00*	-319.9	63.17	2.50	2.30	-319.90	0.00	-1.35	61.82	2.31	2.31
FG5-218	CA	04/06/2024 20:44	2640	125.00*	-328.7	56.35	2.50	2.30	-328.70	0.00	-1.22	55.13	2.31	2.31
FG5-218	DA	05/06/2024 21:15	2400	125.00*	-330.1	47.46	2.50	2.30	-330.10	0.00	-1.10	46.36	2.31	2.31
FG5-227	CA	03/06/2024 21:34	3600	122.05	-328.7	63.87	2.77	2.58	-328.70	-9.70	-1.37	52.80	2.59	2.59
FG5-227	DA	04/06/2024 20:17	3600	122.05	-330.1	53.10	2.78	2.59	-330.10	-9.74	-1.22	42.14	2.60	2.60
FG5-227	EA	05/06/2024 20:35	3750	122.05	-319.5	62.23	2.78	2.59	-319.50	-9.43	-1.13	51.67	2.60	2.60
FG5-238	EA	10/06/2024 22:09	1800	129.12	-319.5	34.51	2.70	2.70	-319.50	13.16	0.02	47.69	2.71	2.71
FG5-238	FA	11/06/2024 23:18	1400	129.12	-319.9	44.81	2.70	2.70	-319.90	13.18	-0.02	57.97	2.71	2.71
FG5-238	CA	12/06/2024 19:59	2200	128.72	-328.7	37.15	2.70	2.70	-328.70	12.23	-0.19	49.19	2.71	2.71
FG5-301	FA	21/05/2024 12:12	2400	122.85	-319.9	69.23	2.77	2.58	-319.90	-6.88	0.75	63.10	2.59	2.59
FG5-301	CA	22/05/2024 11:19	2400	122.85	-328.7	62.09	2.77	2.58	-328.70	-7.07	0.52	55.54	2.59	2.59
FG5-301	DA	23/05/2024 11:40	2400	122.85	-330.1	51.53	2.76	2.57	-330.10	-7.10	0.78	45.21	2.58	2.58
FG5-301	EA	24/05/2024 12:02	2400	122.85	-319.5	58.46	2.76	2.57	-319.50	-6.87	0.71	52.30	2.58	2.58
FG5X-233	CA	27/05/2024 21:52	4784	127.00	-328.7	43.42	2.70	2.50	-328.70	6.57	0.57	50.56	2.51	2.51
FG5X-233	DA	28/05/2024 18:04	4784	127.00	-330.1	34.70	2.70	2.50	-330.10	6.60	0.58	41.88	2.51	2.51
FG5X-233	FA	30/05/2024 19:29	4777	127.00	-319.9	53.54	2.70	2.50	-319.90	6.40	0.71	60.65	2.51	2.51
FG5X-234	EA	28/05/2024 00:31	2920	127.38	-319.5	42.57	1.95	1.66	-319.50	7.60	0.52	50.69	1.67	2.21
FG5X-234	FA	28/05/2024 20:19	2600	127.49	-319.9	51.79	1.95	1.66	-319.90	7.97	0.61	60.37	1.67	2.21
FG5X-234	CA	29/05/2024 22:04	3300	127.39	-328.7	44.94	1.95	1.66	-328.70	7.86	0.85	53.65	1.67	2.21
FG5X-247	CA	28/05/2024 20:53	1600	126.54	-328.7	49.75	2.50	2.20	-328.70	5.06	0.63	55.44	2.21	2.21
FG5X-247	DA	29/05/2024 20:23	1600	126.59	-330.1	38.39	2.50	2.20	-330.10	5.25	0.82	44.46	2.21	2.21
FG5X-247	FA	27/05/2024 21:03	1500	126.59	-319.9	59.10	2.50	2.20	-319.90	5.09	0.63	64.82	2.21	2.21

5. Measurement strategy

According to the TP, four sites were used during the comparison organized in five sessions. The first one took place from May 21st to June 21st 2024. Each gravimeter was planned to measure at least three sites.

Table 5. Occupation of individual sites by gravimeters (linking gravimeters are highlighted in bold).

	Site				
Gravimeter	**CA**	**DA**	**EA**	**FA**	**TOTAL**
FG5X-206	X	X	X	X	4
FG5X-209	X		X	X	3
FG5X-221	**X**	**X**	**X**	**X**	**4**
FG5X-251H		**X**	**X**	**X**	**3**
FG5X-263	**X**	**X**	**X**	**X**	**4**
IMGC-02	X	X	X		3
Number of KC gravimeters	5	5	6	5	
AQG-B02	X	X	X	X	4
AQG-B07	X	X	X	X	4
FG5-101	X	X	X		3
FG5-218	X	X		X	3
FG5-227	X	X	X		3
FG5-238	X		X	X	3
FG5-301	X	X	X	X	4
FG5X-233	X	X		X	3
FG5X-234	X		X	X	3
FG5X-247	X	X		X	3
Number of gravimeters occupying each site	15	13	13	13	

All sites are occupied by 5 KC gravimeters and at least 13 gravimeters occupied each site in total. The latter quantity is important to strengthen the determination of gravity differences between the CRVs. Three KC gravimeters (highlighted in Table 5) provided the link to the CCM.G-K2.2023 comparison.

6. Data elaboration

A combined (observation and constraint equations) least-squares adjustment was performed using the gravity values at the reference comparison height (g) and their associated uncertainties (u) as input. Every measurement made by the gravimeter "i" (with a bias δ_i) at the site "j" during the comparison is described by the observation equation

$$g_{ij} = g_j + \delta_i + \varepsilon_{ij} \qquad (1)$$

at respective weights w_{ij} ($w_{ij} = u_0{}^2/u_{ij}{}^2$ where u_0 is the unit weight).

As the set of observation equations has no unique solution for δ, a constraint, which can be interpreted as definition of the CRV is required [12].

Generally, the consensus value of the CRV [12] is obtained by including the weighted constraint

$$\sum_{i=1}^{n} w_i \, \delta_i = d \qquad (2)$$

where the w_i are the weights assigned indirect proportional to the mean uncertainty reported for each gravimeter, normalized by the condition $\Sigma w_i = 1$, and d is the linking converter [13]. The harmonized uncertainties (see below) were used for the determination of w_i.

The mean square error of the unit weight (MSE)

$$s_0^2 = \frac{\varepsilon^T V^{-1} \varepsilon}{DoF} \quad (3)$$

is estimated after the adjustment from the vector of the residuals ε , the input covariance matrix V of observations and the degrees of freedom DoF. The MSE should range around $s_0^2 \cong 1$ if the measurements are compatible with the covariance matrix and the functional model. Therefore, the MSE can be used for an overall consistency test between model and measurement.

Another parameter which indicates the robustness of the results is the difference between approaches constraining zero-mean biases and minimizing the L1 norm of biases, expressed by a shift δ_c of biases achieved by the solution of Eq. (1) and (2), as described in [6].

In the solution of the additional comparison (labeled ICN in [6]) all gravimeters contribute to the definition of reference values. There will be no link to other comparisons, thus $d = 0$. This solution can be found in Annex A and its benefit is to verify the results of the KC solution.

The KC solution is considering only the group of gravimeters belonging to NMI/DIs for the definition of comparison reference values (CCM 2015). Non-NMI/DI gravimeters cannot be included into the constraint nor in the determination of the linking converter d. Therefore, weights for non-NMI/DI gravimeters are all set to zero in Eq. (2). By this simple mathematical operation, this group of gravimeters is contributing only with gravity differences between the sites, which however play significant role to achieve stable and precise solutions from the adjustment.

6.1. Harmonization of uncertainties

According to [6] the declared instrumental uncertainties of those non-NMI/DI FG5/X gravimeters lower than 2.2 µGal were changed to this value, see Table 4. The reason for such a harmonization is to avoid overweighting of particular measurements.

6.2. Correlation between observations of the same instrument (solution c1)

Following [6] we used the correlation coefficient of 0.75 to account for correlations of repeated observations of the same instrument, reflecting the typical ratio between repeatability and uncertainty for all gravimeters included in this comparison. The respective covariances for a particular AG "*i*" are then obtained from the harmonized uncertainties u_{ij} as $cov = 0.75\ u_{ij,\mathrm{min}}^2$, where $u_{ij,\mathrm{min}}$ is the minimum of all u_{ij}. This approach can be understood as if the measurements of a particular gravimeter carried out within a few days are affected by the same systematic errors. So multiple measuring results of one instrument at one site after a new independent setup can be included and will provide more precise information about the instruments repeatability.

6.3. Correlation between observations of FG5/X-type of instruments (solution c2)

Majority of participating gravimeters are of FG5 and FG5X type, therefore a correlation between their results can be expected to some extent. This might be caused e.g. due to common effects like laser beam diffraction, electronic dispersion and distortion [11] or corner cube rotation [14]. Despite the fact that FG5 and FG5X are having different dropping mechanism, some FG5/X are using different type of collimators and measurement systems a common systematic component of about 25 % in declared variances can be estimated from Annex A of reported data. It means a correlation with $r = 0.25$, that will be introduced as second solution of this comparison, labeled c2.

6.4. Linking converter

The linking converter was computed according to [15] as weighted mean of *DoE* determined at the CCM.G-K2.2023, see Table 6. The *DoE* of three linking gravimeters operated by NMI/DI have been used for this purpose. The value is not deviating significantly from zero that depends only on the particular set of gravimeters.

Table 6. Linking converter as weighted mean of *DoE* from the CCM.G-K2.2023 for joint participants of the CCM.G-K2.2023 and EURAMET.M.G-K2.2023.

Gravimeter	*DoE* /µGal	$U\,(k = 2)$ /µGal
FG5X-221	-0.63	3.76
FG5X-251H	-0.96	3.58
FG5X-263	2.26	4.56
linking converter d =	-0.05	2.25

7. Results

7.1. Initial approach

For the initial solution of the key comparison, all the measurements presented by the operators (Table) were included in a least-squares adjustment. The comparison reference values (CRVs) and the biases (δ) are presented in Tables 7 and 8. This initial solution was computed based on Pálinkáš et.al. (2021), using the weighted constraint Eq. (2) where the weights are the normalized root mean squares of the uncertainties (u) given in Table 4. Thus, the values 0.32079 for FG5X-221, 0.38241 for FG5X-251H and 0.29680 for FG5X-263 are obtained. The sum of these weights is equal to 1 to ensure the correct scaling of the linking converter. The weights of the KC instrument under test (FG5X-206, FG5X-209 and IMGC-02) and of the non NMI/DI gravimeters of the Additional Comparison (AC) have been all set to zero in Eq. (2).

Both solutions of the adjustment (c1 and c2) are presented in Table 7 and Table 8. They differ by the way to account for correlations between measurements according to section 6. As it can be seen, both solutions provide practically the same estimates for CRVs and biases since differences are below 0.03 µGal. However, the estimates of associated uncertainties, obtained from the propagation of measurement uncertainties differ significantly.

The MSE for the solutions c1/c2 are $s_0 = 0.76 / 0.76$, and the differences to the L1-Norm are $\delta_c = 0.65$ µGal/ 0.67 µGal, resp.

Table 7. Two solutions for Comparison Reference Values (CRVs) using all the reported absolute measurements, reference height is 1.25 m and the constant value of 980,836,900.0 µGal is subtracted. Results are linked by 3 instruments from NMI/DIs to CCM.G-K2.2023 by means of linking converter (Table 6). The solution labeled as “c1” is accounting for correlations ($r = 0.75$) between measurements of a particular gravimeter while the solution “c2” also takes into account correlations ($r = 0.25$) between FG5/X. U refers to expanded uncertainty ($k = 2$).

Site	CRV_{c1} /µGal	U_{c1} /µGal	CRV_{c2} /µGal	U_{c2} /µGal
CA	54.31	3.13	54.33	3.52
DA	43.87	3.11	43.89	3.51
EA	51.83	3.12	51.85	3.51
FA	62.64	3.12	62.65	3.52

Table 8. Two solutions for biases δ of gravimeters at the key comparison (linking gravimeters are highlighted in bold).

Gravimeter	δ_{c1} /µGal	U_{c1} /µGal	δ_{c2} /µGal	U_{c2} /µGal
FG5X-221	-0.85	3.75	-0.84	3.36
FG5X-251H	-0.65	3.47	-0.66	3.15
FG5X-263	1.58	3.89	1.59	3.47
FG5X-206	-0.87	5.46	-0.86	4.74
FG5X-209	-0.46	6.29	-0.44	5.50
IMGC-02	2.82	7.88	2.80	8.04

7.2. Consistency check

The consistency of measurements was checked based on the reported uncertainties. The compatibility index is defined as the ratio between the deviation of the measured gravity value (g_{ij}) from the CRV (g_j) at a site and its uncertainty

$$E_{ij} = \frac{(g_{ij} - g_j)}{u(d_{ij})} \tag{4}$$

where the uncertainty of deviations $u(d_{ij})$ are achieved from error propagation accounting for correlations between observations [6].

In agreement with previous reports we have chosen the standard uncertainty to compute the compatibility index. An absolute value of E_n larger than 2 indicates then that the measured gravity value is incompatible at a 95 % confidence level, as the difference is not covered by the (expanded) uncertainties. The compatibility index E_n as given in Table 9 is using the declared uncertainties of the reported results. Indexes are generally below 2, indicating consistency with the declared uncertainties at 95 % confidence interval. Exceptions are four measurements of AQG-B07 that show a large systematic deviation exceeding the uncertainty that is however consistent with other measurements of this gravimeter. Nevertheless, these systematic and stable deviations are not affecting negatively the adjustment, because this gravimeter is not contributing to the constraint, while stable systematic effects have no impact on gravity difference. Therefore, a gravimeter showing good reproducibility should not be excluded from the adjustment.

Table 9. Consistency check: Comparison of measured gravity values g_{ij} (along with standard uncertainties u_{gij}) with reference values g_j (along with standard deviations σ_{gj}) 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 sites. The constant value 980,836,900.0 µGal has been subtracted from the gravity values.

Gravimeter i	Site j	$g_{i,j}$ /µGal	u_{gij} /µGal	g_j /µGal	$\sigma_{(gj)}$ /µGal	$g_{i,j}$ - g_j /µGal	E_n	σ_{rep} /µGal
FG5X-206	EA	50.80	5.02	51.85	1.76	-1.04	-0.40	0.75
FG5X-206	FA	62.86	5.02	62.65	1.76	0.21	0.08	
FG5X-206	CA	52.90	5.02	54.33	1.76	-1.42	-0.55	
FG5X-206	DA	42.58	5.02	43.89	1.76	-1.30	-0.50	
FG5X-209	EA	50.88	6.01	51.85	1.76	-0.97	-0.32	0.77
FG5X-209	FA	63.06	6.01	62.65	1.76	0.41	0.14	
FG5X-209	CA	53.45	6.01	54.33	1.76	-0.88	-0.29	
FG5X-221	CA	54.14	4.02	54.33	1.76	-0.19	-0.10	0.86
FG5X-221	DA	42.94	4.02	43.89	1.76	-0.95	-0.51	
FG5X-221	EA	49.81	4.02	51.85	1.76	-2.04	-1.09	
FG5X-221	FA	62.37	4.02	62.65	1.76	-0.28	-0.15	
FG5X-251H	DA	43.02	3.68	43.89	1.76	-0.86	-0.51	0.57
FG5X-251H	EA	51.74	3.68	51.85	1.76	-0.11	-0.06	
FG5X-251H	FA	61.42	3.94	62.65	1.76	-1.23	-0.67	

FG5X-263	DA	44.88	4.18	43.89	1.76	1.00	0.52	0.91
FG5X-263	EA	52.91	4.18	51.85	1.76	1.06	0.55	
FG5X-263	FA	63.94	4.18	62.65	1.76	1.29	0.67	
FG5X-263	CA	57.24	4.18	54.33	1.76	2.92	1.51	
IMGC-02	CA	55.53	8.02	54.33	1.76	1.20	0.28	2.25
IMGC-02	DA	49.26	7.99	43.89	1.76	5.38	1.24	
IMGC-02	EA	53.68	7.93	51.85	1.76	1.83	0.42	
AQG-B02	DA	29.11	20.53	43.89	1.76	-14.78	-1.42	1.47
AQG-B02	EA	38.64	20.51	51.85	1.76	-13.21	-1.27	
AQG-B02	FA	51.46	20.51	62.65	1.76	-11.19	-1.08	
AQG-B02	CA	41.18	20.53	54.33	1.76	-13.15	-1.26	
AQG-B07	EA	28.45	20.51	51.85	1.76	-23.39	-2.25	2.18
AQG-B07	FA	40.48	20.51	62.65	1.76	-22.17	-2.13	
AQG-B07	CA	29.99	20.53	54.33	1.76	-24.34	-2.34	
AQG-B07	DA	16.61	20.53	43.89	1.76	-27.28	-2.62	
FG5-101	CA	50.88	5.16	54.33	1.76	-3.44	-1.30	1.05
FG5-101	DA	40.61	5.16	43.89	1.76	-3.27	-1.24	
FG5-101	EA	50.30	5.16	51.85	1.76	-1.55	-0.59	
FG5-218	FA	61.82	4.62	62.65	1.76	-0.83	-0.34	1.65
FG5-218	CA	55.13	4.62	54.33	1.76	0.80	0.33	
FG5-218	DA	46.36	4.62	43.89	1.76	2.47	1.01	
FG5-227	CA	52.80	5.18	54.33	1.76	-1.52	-0.57	0.85
FG5-227	DA	42.14	5.20	43.89	1.76	-1.74	-0.65	
FG5-227	EA	51.67	5.20	51.85	1.76	-0.17	-0.06	
FG5-238	EA	47.69	5.42	51.85	1.76	-4.15	-1.51	0.49
FG5-238	FA	57.97	5.42	62.65	1.76	-4.68	-1.70	
FG5-238	CA	49.19	5.42	54.33	1.76	-5.14	-1.87	
FG5-301	FA	63.10	5.18	62.65	1.76	0.45	0.17	0.48
FG5-301	CA	55.54	5.18	54.33	1.76	1.22	0.46	
FG5-301	DA	45.21	5.16	43.89	1.76	1.33	0.50	
FG5-301	EA	52.30	5.16	51.85	1.76	0.45	0.17	
FG5X-233	CA	50.56	5.02	54.33	1.76	-3.76	-1.45	1.02
FG5X-233	DA	41.88	5.02	43.89	1.76	-2.00	-0.77	
FG5X-233	FA	60.65	5.02	62.65	1.76	-2.00	-0.77	
FG5X-234	EA	50.69	4.42	51.85	1.76	-1.15	-0.49	0.83
FG5X-234	FA	60.37	4.42	62.65	1.76	-2.29	-0.97	
FG5X-234	CA	53.65	4.42	54.33	1.76	-0.68	-0.29	
FG5X-247	CA	55.44	4.42	54.33	1.76	1.12	0.47	0.81
FG5X-247	DA	44.46	4.42	43.89	1.76	0.57	0.24	
FG5X-247	FA	64.82	4.42	62.65	1.76	2.16	0.91	

7.3. Final solution

Usually, in comparisons of absolute gravimeters in the past, the degree of equivalence (*DoE*) has been computed according to [13] using the 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 CRV at site *j*. Due to the fact that no measurements were excluded, the biases and their uncertainties from the adjustment are more reliable estimates for the deviation than *D* from Eq. (5) since the later doesn't consider correlations between measurements. Therefore, biases from the adjustment will represent the *DoE*s. It is based on solution c2 because the stochastic model is most realistic.

Table 10. Comparison Reference Values (CRV) linked to the CCM.G-K2.2023 using linking converter of (-0.05 ± 2.25) μGal provided by 3 NMI/DI gravimeters. The constant value 980,836,900.0 μGal was subtracted from the CRV. *U* is the expanded uncertainty at 95 % confidence level computed as root mean square of standard deviations σ (from the least-squares adjustment) and the uncertainty of the linking converter. The reference height is 1.25 m. The KCRV refer to May 15, 2018 0:00 UT as the mean time of the comparison.

OFFICIAL RESULTS		
Site	CRV /μGal	U (k = 2) /μGal
CA	54.33	3.52
DA	43.89	3.51
EA	51.85	3.51
FA	62.65	3.52

The final *DoE* with uncertainties at the 95 % confidence level is presented in Table 11 and Figure 3. All the gravimeters participating at EURAMET.M.G-K2.2023 Key Comparison are in equivalence.

(*DoE* of the participating instruments of the Additional Comparison can be found in Annex A.)

Table 11. Degrees of Equivalence of the NMI/DI gravimeters participating in the KC. The uncertainty U_{DoE} represents the expanded uncertainty at 95% confidence.

OFFICIAL RESULTS EURAMET.M.G-K2.2023 KEY COMPARISON		
Gravimeter	Degree of Equivalence	
	DoE /μGal	U_{DoE} (k = 2) /μGal
FG5X-206	-0.86	4.74
FG5X-209	-0.44	5.50
FG5X-221	-0.84	3.36
FG5X-251H	-0.66	3.15
FG5X-263	1.59	3.47
IMGC-02	2.80	8.04

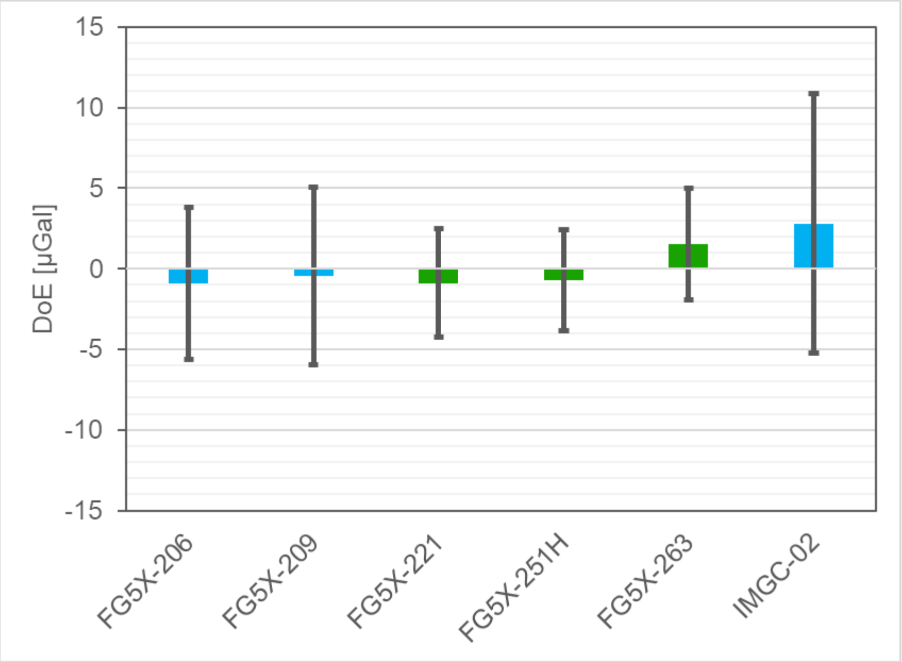

Figure 3. Degrees of Equivalence (*DoE*) of the NMI/DI gravimeters participating in the EURAMET.M.G-K2.2023. The error bars represent the expanded uncertainties (U_{DoE}) of the *DoE* at 95 % confidence, green bars indicate gravimeters providing the link.

8. Conclusions

Sixteen gravimeters were compared within the regional EURAMET.M.G-K2.2023 Key Comparison and Additional Comparison (AC). Six gravimeters were operated by different NMIs and DIs, these instruments participated at the EURAMET.M.G-K2.2023 Key Comparison. Three of them transfer the level of this regional comparison from the CCM.G.K2.2023 by means of the linking converter computed as weighted average of *DoE* for those gravimeters.

Gravimeters not operated by NMI/DI and participating in the Additional Comparison did not contribute to the definition of CRV. Nevertheless, their observations are important to strengthen the determination of the gravity differences between the 4 sites.

A least-squares adjustment with a weighted constraint was used to determine the CRV and the final *DoE*. In case of KC gravimeters, the weights used in the adjustment and in the estimation of the *DoE* were computed from: 1) instrumental uncertainties provided by the operators, 2) the contribution of the VGG to the transfer to the comparison reference height of 1.25 m, 3) the uncertainty of corrections due to temporal gravity variations and 4) the uncertainty of the linking converter.

In case of some AC gravimeters, the reported uncertainties were harmonized for the weighting scheme to avoid overweighting in the determination of the relative ties between the sites.

All the gravimeters participating in EURAMET.M.G-K2.2023 Key Comparison are in equivalence. In particular, the equivalence was demonstrated of three gravimeters not participating in the CCM.G.K2.2023. The three instruments participating in both key comparisons showed an excellent long-term stability, a very good stability and reproducibility, as deduced by comparing Tables 6 and 11 in Figure 4).

In conclusion, the *DoE* of the 6 KC gravimeters are within the range of -0.9 and +2.8 µGal. For the gravimeters participating in the Additional Comparison (elaborated in Annex A), the *DoE* ranging between -24.3 µGal and +1.3 µGal for the KC solution. The alternative solution ICN (Annex A) deviates in the mean level by only 0.66 µGal from the KC solution, which emphasizes the stability of the whole group absolute gravimeters.

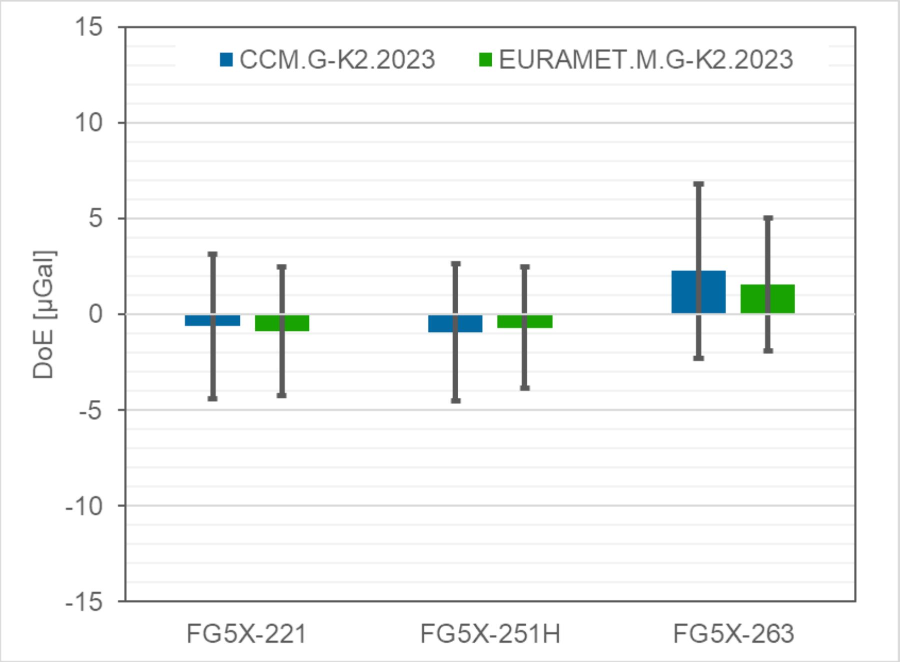

Figure 4. Degrees of equivalence of CCM.G-K2.2023 and EURAMET.M.G-K2.2023 for linking gravimeters

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Annex A: Additional comparison

The aim of the Additional comparison was to link the European absolute gravimeters operated by geodetic institutes not related to metrology to the CCM.G-K2.2023 Key Comparison by the CRV determined at EURAMET.M.G-K2.2023 key comparison. Note, the results of the Additional comparison should not be recognized as obtained according to the procedure stipulated for use within the CIPM MRA. No new adjustment has been performed. The results presented below originating from solution c2 (section 6), accounting for correlations between measurements and instruments.

Table A1 provides a summary of instrumental corrections that have been applied to the measurements by operators of gravimeters to suppress systematic effects. Only for a subset of gravimeters, the majority of effects have been applied, while other assume the cancelation of particular effects due to opposite magnitudes (i.e. self-attraction and diffraction) or by measurement scheme (Coriolis forces in two diametral setups). For the assessment of the biases this should be considered. For quantum gravimeters (e.g. AQG) different systematic effects, like wavefront aberration or two-photon lightshift are relevant, which not included in this compilation.

Table A1. Summary of instrumental corrections applied by operators to the reported measurements

	Instrumental corrections /µGal					
Gravimeter	Self-attraction	Diffraction	Coriolis	Verticality	Fringe Cable length	Fringe signal distortion
FG5X-206	-1.17	0.33				
FG5X-209						
FG5X-221	-1.2	1.4				
FG5X-251H	-1.18	2.8**	0.40	0.02	-0.32	-0.30
FG5X-263	-1.17	2.72**				
IMGC-02						
AQG-B02						
AQG-B07			2 orientations*			
FG5-101	-1.4	2.8**		0.4	-0.4	
FG5-218						
FG5-227	-1.4	2.8**	-0,52; +0,52 2 orientations*	0.1	-0.4	
FG5-238	-1.05	1.2				
FG5-301	-1.4	2.8**	-0,65; +0,65 2 orientations*	0.3	-0.4	
FG5X-233						
FG5X-234	-1.2	1.5	-0.5			
FG5X-247	-1.18	2.8**	-0.08	0.09	-0.37	

- * The reported measurement results have been obtained as average of measurements from two setups of the gravimeter, with different orientation of the gravimeter by 180° to suppress the effect of Coriolis forces
- ** The gravimeter has been equipped by Thorlabs TC25APC-633 collimator

The alternative solution ICN as described in [6] is also given. Here all gravimeters contributing to the comparison reference values according to their harmonized uncertainties and no link is applied. The harmonization of instrumental uncertainties has been carried out for all measurements with declared instrumental uncertainties below 2.2 µGal, see Table A2. Moreover, due to the biased results of AQG-B07, this gravimeter did not contribute to the constraint.

Table A2. Harmonization of declared uncertainties to the lower value of 2.2 μGal for solution ICN

Gravimeter	Site	u_{raw} /μGal	u_{har} /μGal
FG5X-221	CA	/μGal	2.2
FG5X-221	DA	2.00	2.2
FG5X-221	EA	2.00	2.2
FG5X-221	FA	2.00	2.2
FG5X-234	EA	1.66	2.2
FG5X-234	FA	1.66	2.2
FG5X-234	CA	1.66	2.2
FG5X-251H	DA	1.83	2.2
FG5X-251H	EA	1.83	2.2
FG5X-251H	FA	1.96	2.2
FG5X-263	DA	2.08	2.2
FG5X-263	EA	2.08	2.2
FG5X-263	FA	2.08	2.2
FG5X-263	CA	2.08	2.2

The ICN solution deviates from the KC in the mean level by only 0.66 μGal, which corresponds with the shift of KC (0.67 μGal) in case of L1 norm approach. Nevertheless, compared to the uncertainties, it emphasizes the stability of the whole group of absolute gravimeters in both comparisons. Following additional parameters have been obtained for the ICN solution: $s_0 = 0.75$; $\delta_c = 0.20$ μGal.

Table A3 shows both solutions. The uncertainties of the ICN solution are lower, mainly because there is no contribution from the linking converter. Table A4 and Figures A1 and A2 present the final results for all gravimeters from the KC solution. However, the three gravimeters (FG5-101, FG5-227 and FG5X-233) participating also in the Additional comparison at TMGO in 2023 show bias changes in the few μGal range that can be attributed to maintenance in between (Figure A2).

Table A3. Biases with expanded uncertainties of NMI/DIs (yellow marked) and non-NMI DIs form both approaches and used weights *w* in Eq. (2).

Gravimeter	KC			ICN		
	δ /μGal	U /μGal	w	δ /μGal	U /μGal	w
FG5X-206	-0.86	4.74	0	-0.23	3.64	0.06911
FG5X-209	-0.44	5.50	0	0.19	4.54	0.04809
FG5X-221	-0.84	3.36	0.32079	-0.21	3.17	0.08907
FG5X-251H	-0.66	3.15	0.38241	-0.09	3.23	0.08907
FG5X-263	1.59	3.47	0.29680	2.22	3.17	0.08907
IMGC-02	2.80	8.04	0	3.46	7.50	0.02763
AQG-B02	-13.08	18.81	0	-12.42	18.59	0.00413
AQG-B07	-24.29	18.81	0	-23.63	18.66	0
FG5-101	-2.72	4.89	0	-2.10	3.82	0.06541
FG5-218	0.85	4.54	0	1.48	3.39	0.08156
FG5-227	-1.11	4.91	0	-0.49	3.84	0.06490
FG5-238	-4.62	5.07	0	-3.99	4.04	0.05929
FG5-301	0.90	4.83	0	1.52	3.75	0.06541
FG5X-233	-2.56	4.80	0	-1.93	3.71	0.06911
FG5X-234	-1.34	4.42	0	-0.71	3.23	0.08907
FG5X-247	1.31	4.42	0	1.95	3.23	0.08907

Table A4. Biases (δ) of all gravimeters participating in the KC (yellow) and Additional Comparison. The expanded uncertainties at 95 % confidence level are computed based on declared uncertainties of the observations.

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Gravimeter	Bias	
	δ /µGal	U_δ /µGal
FG5X-206	-0.86	4.74
FG5X-209	-0.44	5.50
FG5X-221	-0.84	3.36
FG5X-251H	-0.66	3.15
FG5X-263	1.59	3.47
IMGC-02	2.80	8.04
AQG-B02	-13.08	18.81
AQG-B07	-24.29	18.81
FG5-101	-2.72	4.89
FG5-218	0.85	4.54
FG5-227	-1.11	4.91
FG5-238	-4.62	5.07
FG5-301	0.90	4.83
FG5X-233	-2.56	4.80
FG5X-234	-1.34	4.42
FG5X-247	1.31	4.42

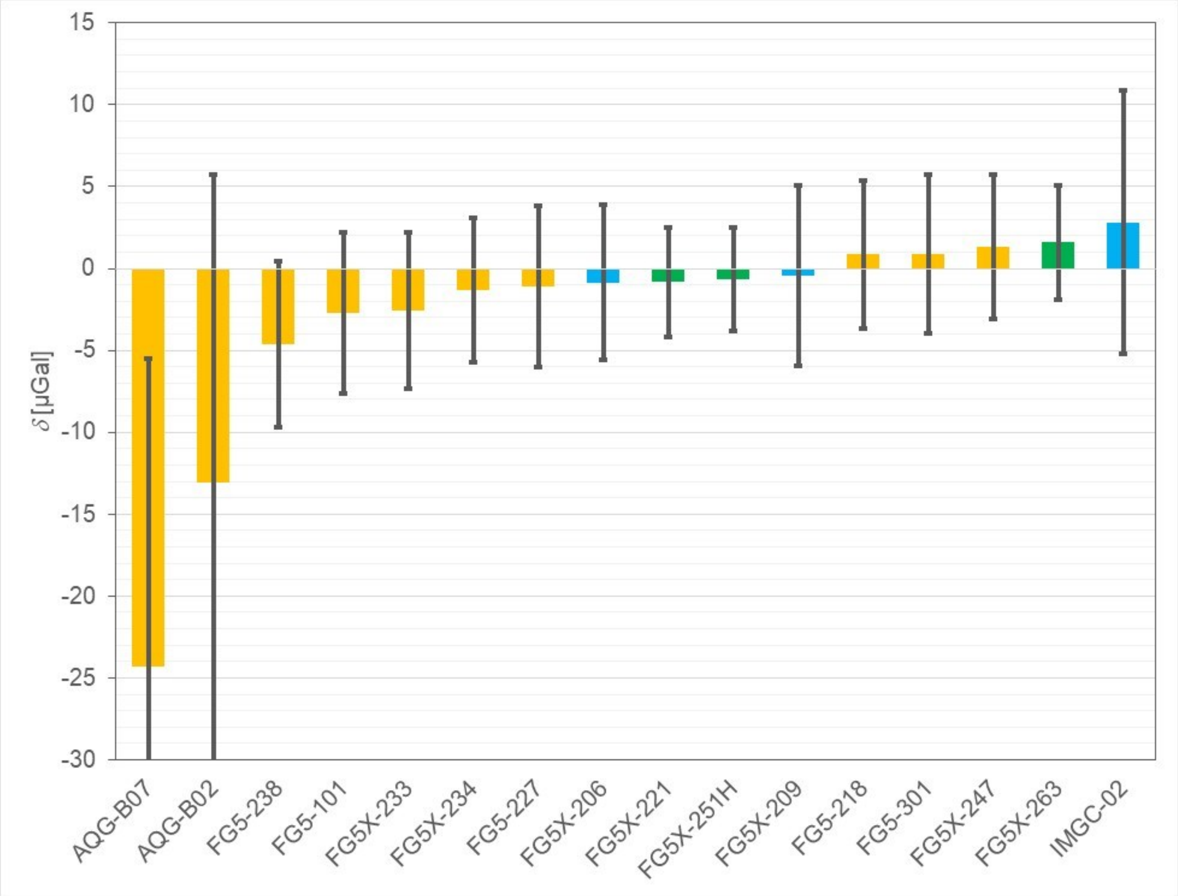

Figure A1. Biases (δ) for all gravimeters (linked to the CCM.G-K2.2023). The values for gravimeters of NMI/DIs are highlighted in green (participants of CCM.G-K2.2023) or blue. The error bars represent the expanded uncertainties (U_δ inTable A4).

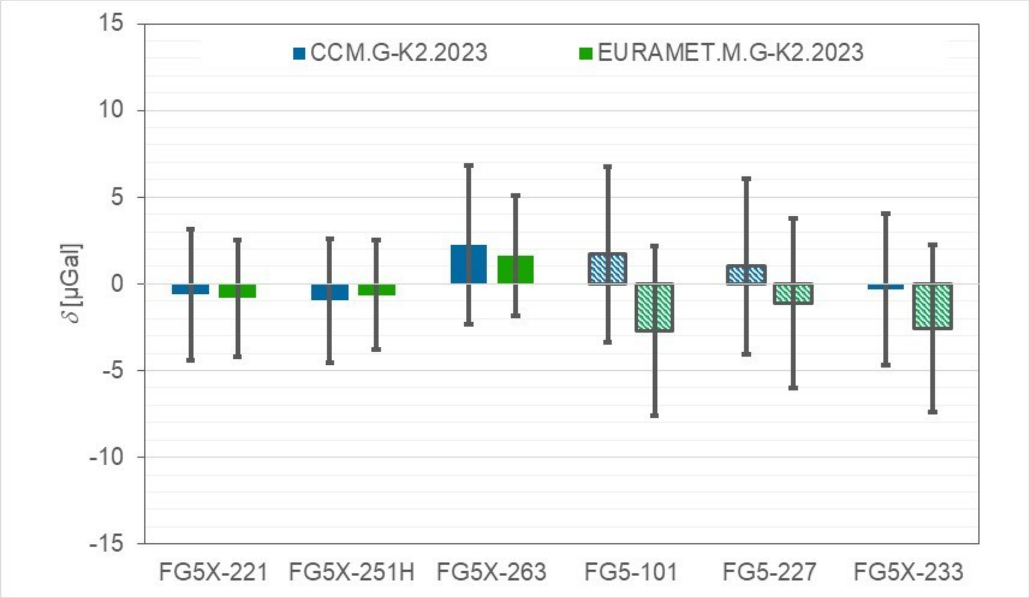

Figure A2. Biases (δ) of CCM.G-K2.2023 and EURAMET.M.G-K2.2023 for all gravimeters taking part in both comparisons. Gravimeters providing the link are shown as solid bars while gravimeters in the Additional Comparison are hatched.