Final Report

CCM.G-K2.2023 Key Comparison

and Additional Comparison

Table Mountain Geophysical Observatory (TMGO)
Boulder, Colorado

Pilot laboratory: National Institute of Standards and Metrology (NIST)
Gaithersburg, MD USA

David Newell, Derek van Westrum, and all the participants

INTERNATIONAL COMPARISON OF ABSOLUTE GRAVIMETERS 2023

Introduction

The Key Comparison of Absolute Gravimeters, CCM.G-K2.2023, and an Additional Comparison were conducted at the Table Mountain Geophysical Observatory (TMGO) near Boulder, Colorado between 21 August and 29 September, 2023.

The procedures and schedule for the measurements were spelled out in the Technical Protocol, approved by all participants and the Consultative Committee on Mass and Related Quantities Working Group on Gravimetry (CCM-WGG). However, due to logistical constraints, a few teams were not able to attend, and the schedule was optimized accordingly.

Dr. David Newell of NIST, Gaithersburg, Maryland served as the Pilot Laboratory representative, while Dr. Derek van Westrum of the National Oceanic and Atmospheric Administration National Geodetic Survey (NOAA-NGS), Boulder, Colorado, served as the site host and coordinator. The comparison was organized in accordance with the International Committee for Weights and Measures (CIPM) document CIPM MRA-G-11 of the CCM and is registered with the CIPM as CCM.G-K2.2023.

The list of participants and a description of the site (including vertical gravity gradients, observed tidal parameters, and a continuous relative gravimeter signal observed during the comparison) are presented, followed by a discussion of the analysis. The results of the data analysis, the degrees of equivalence (DoE) of the gravimeters, and the key comparison reference values (KCRVs) are also presented. For the final and official solution of the KCRVs, the contributions of absolute gravity data inconsistent near the 95% confidence level are investigated. Overall, the results and uncertainties indicate an excellent agreement among the gravimeters, with a standard deviation of the gravimeters' DoEs less than 1.3 μGal.

The Additional Comparison is a complete solution where all participating gravimeters were treated as equivalent in terms of their contribution to the definition of the reference values (RVs). The results of the Additional Comparison are given in Appendix A.

Participants

Table 1 lists the participants in the comparison. In total, 30 absolute gravimeters from 27 institutes participated, including 2 atom gravimeters. Fifteen institutes were a National Metrology Institute (NMI) or a Designated Institute (DI). Those shaded in pink are the NMI/DI gravimeters that contributed to the KCRVs of CCM.G-K.2023.

Site description

A schematic of the TMGO facility, renovated in 2010, is shown in Figure 1. Eight of the 11 piers were employed during CCM.G-K2.2023: AG, AH, AI, AJ, AO, AQ, AS, and AT (AK was reserved for three Micro-g LaCose gPhonesX continuous relative gravity meters, AN was occupied by FG5X-102 to initally serve as a control for the gPhoneXs, and AP was unused). Each pier is constructed of approximately 1m^3 of concrete, isolated from the building's foundation. The building itself is located on top of a remote mesa, far from any cultural noise sources.

Table 1. Participants in the comparison. Those shaded in pink are the NMI/DI gravimeters that contributed to the KCRVs of CCM.G-K.2023.

#	Country	Institution	NMI or DI	Gravimeter	Operator(s)
1	Austria	Federal Office of Metrology and Surveying (BEV)	YES	FG5-242	Christian Ullrich Hubert Butta
2	Brazil	Gravity Laboratory of Observatório Nacional (ON)	YES	FG5-223	Mauro Andrade de Sousa Daniel Quaresma
3	Canada	National Research Council, Canada (NRC)	YES	FG5-105	Richard Green Harold Parks Jacques Liard
4	People's Republic of China	Innovation Academy for Precision Measurement Science and Technology (APM)	NO	WAG-H5-2	Panwei Huang Haoran Zhu
5	People's Republic of China	National Institute of Metrology (NIM)	YES	NIM-3A	Qiyu Wang Jinyang Feng
6	People's Republic of China	National Institute of Metrology (NIM)	YES	FG5X-249	Ruo Hu JiaminYao
7	People's Republic of China	National Institute of Metrology (NIM)	YES	NIM-AGRb2	Wei Zhuang Yang Zhao Chuanjing Ruan
8	Chinese Taipei	Industrial Technology Research Institute (ITRI)	YES	FG5-231	Wen-Chi Hsieh
9	Czech Republic	RIGTC/VUGTK Geodetic Observatory Pecný	YES	FG5X-251/HS5	Jakub Kostelecký Vojtech Pálinkás
10	Finland	Finnish Geospatial Research Institute (FGI), National Land Survey of Finland	YES	FG5X-221	Mirjam Bilker-Koivula Jyri Näränen
11	France	European Plate Observing System, France (Epos-Fr)	NO	FG5-228	Nicolas Le Moigne
12	Germany	Federal Agency for Cartography and Geodesy (BKG)	NO	FG5-101	Erik Brachmann
13	Germany/ Argentina	Federal Agency for Cartography and Geodesy (BKG); Argentine-German Geodetic Observatory in La Plata, Argentina	NO	FG5-227	Alfredo Pasquare Alexander Lothhammer
14	Germany	Physikalisch-Technische Bundesanstalt (PTB)	YES	FG5X-263	Christian Rothleitner Johannes Konrad
15	Italy	National Institute of Geophysics and Volcanology (INGV), Catania	NO	FG5-238	Luca Timoteo Mirabella Danilo Contrafatto

Table 1 (continued). Participants in the comparison Those shaded in pink are the NMI/DI gravimeters that contributed to the KCRVs of CCM.G-K.2023.

#	Country	Institution	NMI or DI	Gravimeter	Operator(s)
16	Japan	National Metrology Institute of Japan, National Institute of Advanced Science and Technology (NMIJ/AIST)	YES	FG5-213	Souichi Telada and Yohei Kayukawa
17	Republic of Korea	Korea Research Institute of Standards and Science (KRISS)	YES	FG5X-104	In-Mook Choi Jin-Wan Chung
18	Mexico	Centro Nacional de Metrologia (CENAM)	YES	FG5X-252	Alfredo Esparza-Ramirez
19	Saudi Arabia	Saudi Standards Metrology-National Measurements Calibration Center (SASO-NMCC)	YES	FG5X-253	Ahmed Aljuwayr Homood Alotaibi
20	South Africa	National Metrology Institute of South Africa (NMISA)	YES	FG5X-261	Thapelo Mametja
21	Spain	Instituto Geografico Nacional	NO	FG5-211	Arturo Villar García Félix Manuel Chaves Ruiz
22	Sweden	Lantmäteriet	NO	FG5X-233	Örjan Josefsson Holger Steffen
23	Turkey	TÜBİTAK National Metrology Institute (TÜBİTAK UME)	YES	FG5X-254	Cafer KIRBAŞ
24	UK	British Geological Survey	NO	FG5-222	Victoria Smith
25	USA	Louisiana State University (LSU)	NO	FG5X-258	Benjamin Fernandez Jon Cilburn
26	USA	Micro-g LaCoste (MGL)	NO	FG5X-302	Brian Ellis Derrick Hammett
27	USA	National Geospatial-Intelligence Agency (NGA)	NO	FG5X-107	David Wheeler Daniel Steineman
28	USA	National Geospatial-Intelligence Agency (NGA)	NO	FG5X-205	David Wheeler Daniel Steineman
29	USA	National Oceanic and Atmospheric Administration, National Geodetic Survey (NOAA-NGS)	NO	FG5X-102	Derek van Westrum Jeff Kanney
30	USA	National Institute of Standards and Technology (NIST)	YES	FG5X-204	Frank Seifert David Newell

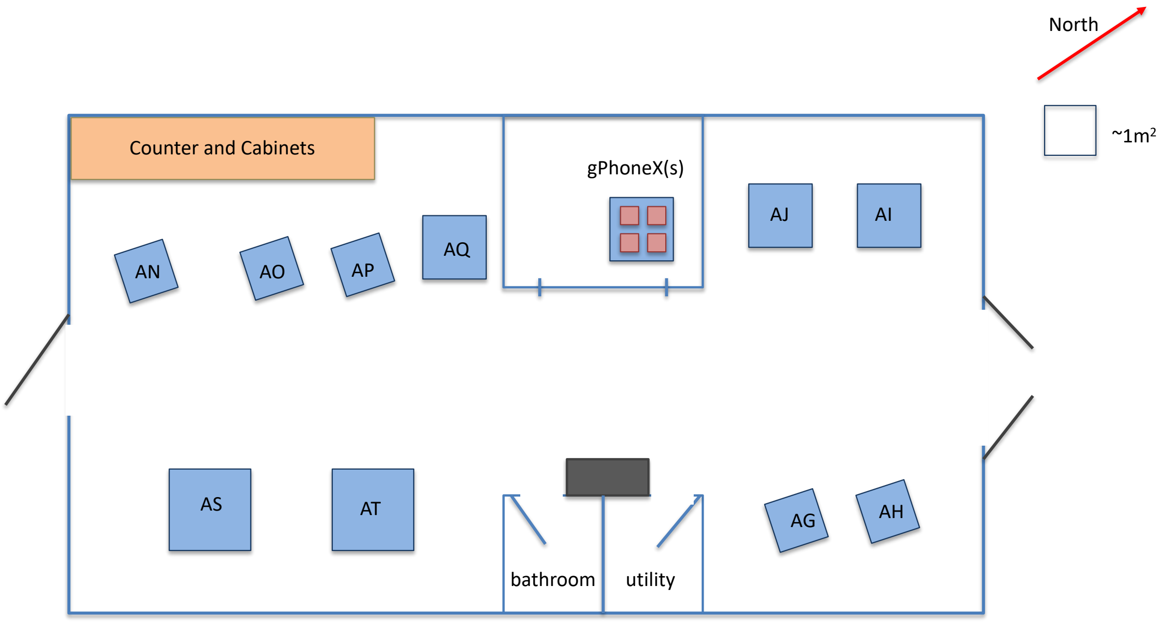

Figure 1. Schematic of the TMGO gravity piers. AK is permanently occupied by three gPhoneXs, and only piers AG, AH, AI, AJ, AO, AQ, AS, and AT were used in the comparison.

Gravity gradient measurements

In the summer of 2023, a Scintrex CG-6 Autograv portable relative gravity meter (SN #169) was used to measure relative gravity values on a fixed tripod at three heights above each pier at TMGO. Three heights allow the determination of any nonlinearity in the vertical gravity gradient. A given measurement consists of six or more "laps" of each gravimeter up the three-tiered tripod. Each tier occupation consists of approximately 200 gravity samples at 1 Hz. After first rejecting any sample outliers (>3σ, k=1), a weighted least-squares analysis provides a quadratic fit to all measured gravity differences and instrument drift simultaneously, resulting in the following function of gravity with height:

$$g(z) = az^2 + bz + c. \tag{1}$$

Note that when determining the difference in gravity value at two different heights, the constant term, c, cancels. Uncertainties of the parameters a and b are derived from the variance-covariance matrix. Uncertainties in the height measurements (tier locations) are negligible, as is the CG6 calibration factor uncertainty. The parameters are listed in Table 2.

Finally, note that the gradient value is not expected to change at TMGO over the time-frame discussed. TMGO is located on a broad, flat, undisturbed expanse of land, and even unmodeled environmental factors like water table fluctuations will not cause a change in the value of the gradient.

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

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

and the associated uncertainty

$$\sigma_{\Delta g}^2 = (z_2^2 - z_1^2)^2 \times \sigma_a^2 + (z_2 - z_1)^2 \times \sigma_b^2 + 2 \times (z_2^2 - z_1^2) \times (z_2 - z_1) \times \sigma_{ab} \tag{3}$$

The participants reported gravity results nominally at the effective instrumental height, h_{eff}, of their respective gravimeters where the gravity value is least sensitive to the effect of the gradient [1] [2]. The gradient formula for that respective pier was then used to transfer the reported value to a final, comparison reference height of 125 cm (an approximate average of the effective measurement height for FG5 and FG5-X gravimeters).

The observed tidal parameters for TMGO – used by all participants to correct for earth tides and ocean loading simultaneously – were stated in the protocol and were provided by Olivier Francis, based on an analysis of SG CT-024 [3]. They are listed in Table 3.

Table 2. Vertical gravity gradients at the TMGO piers (only AG, AH, AI, AJ, AO, AQ, AS, and AT were used for the comparison).

Site	a /µGal m^{-2}	σ_a /µGal m^{-2}	b /µGal m^{-1}	σ_b /µGal m^{-1}	σ_{ab} /µGal^2 m^{-3}
AG	1.2	1.6	-317.8	2.5	2.0
AH	0.6	1.0	-316.7	1.6	1.2
AI	3.6	1.5	-323.8	2.3	1.8
AJ	1.5	1.7	-319.6	2.5	2.0
AO	0.0	1.5	-316.7	2.4	1.9
AQ	3.8	1.8	-321.6	2.8	2.3
AS	2.7	1.8	-320.6	2.8	2.3
AT	4.0	1.8	-323.1	2.9	2.3

Table 3. Observed tidal parameters for TMGO from SG CT-024 via Olivier Francis.

Wave	Start Frequency (cpd)	Stop Frequency (cpd)	Amplitude Factor	Phase Lag (degrees)
DC	0.000000	0.000001	1.00000	0.0000
long	0.000002	0.249951	1.16000	0.0000
Q1	0.721500	0.906315	1.16052	1.1570
O1	0.921941	0.940487	1.16468	1.1775
NO1	0.958085	0.974188	1.15951	1.0326
P1	0.989049	0.998028	1.16539	1.1041
S1	0.999853	1.000147	1.49457	15.9599
K1	1.001825	1.003651	1.15452	1.1761
PSI1	1.005329	1.005623	1.30377	1.3908
PHI1	1.007595	1.011099	1.20411	0.6319
J1	1.013689	1.044800	1.18028	1.1094
OO1	1.064841	1.216397	1.18279	0.3491
2N2	1.719381	1.872142	1.16806	-0.4567
N2	1.888387	1.906462	1.15681	-0.2398
M2	1.923766	1.942754	1.15945	0.1973
L2	1.958233	1.976926	1.16297	0.3812
S2	1.991787	2.002885	1.17172	-0.5305
K2	2.003032	2.182843	1.17348	-0.4844
M3	2.753244	3.081253	1.07285	-0.2409
M4	3.381379	4.347615	1.03900	0.0000

Relative gravity measurements

Three gPhoneX relative gravimeters (SN #162, #179, and #182) were operated continuously throughout the comparison on pier AK, situated near the center of the absolute piers, with their outputs corrected for the same tidal predictions and atmospheric admittance factor as used for the absolute gravity measurements. The gPhoneX signals were averaged together, smoothed with a 36 hour filter, and adjusted to zero nominal drift throughout the 40 day measurement campaign.

FG5X-102 had technical issues during the measurement campaign, so the absolute drift was obtained from all absolute gravity observations during the comparison. The gravity difference from pier to pier was determined by an initial Least Squares Analysis (LSA) (see section 'Analysis Method' and Table 6). Each absolute gravity measurement was then adjusted to pier AQ by applying the observed gravity difference and plotted as a function of time, resulting in a linear fitted drift of -0.037 µGal/day during the measurement campaign.

The total gPhoneX correction is shown in Figure 2, adjusted to the average value of the adjusted gravity measurements to pier AQ, nominally day 21, DOY 254 00:00:00 UTC. The uncertainty on the gPhoneX correction is estimated to be ± 0.7 µGal from previous comparisons with superconducting gravimeters over a four-month period and comparison of collocated gPhoneXs [4, 5]. The resulting relative change in gravity throughout the comparison is presumed to be observed by all gravity meters. The correction applied to each gravity observation is listed in Table 5.

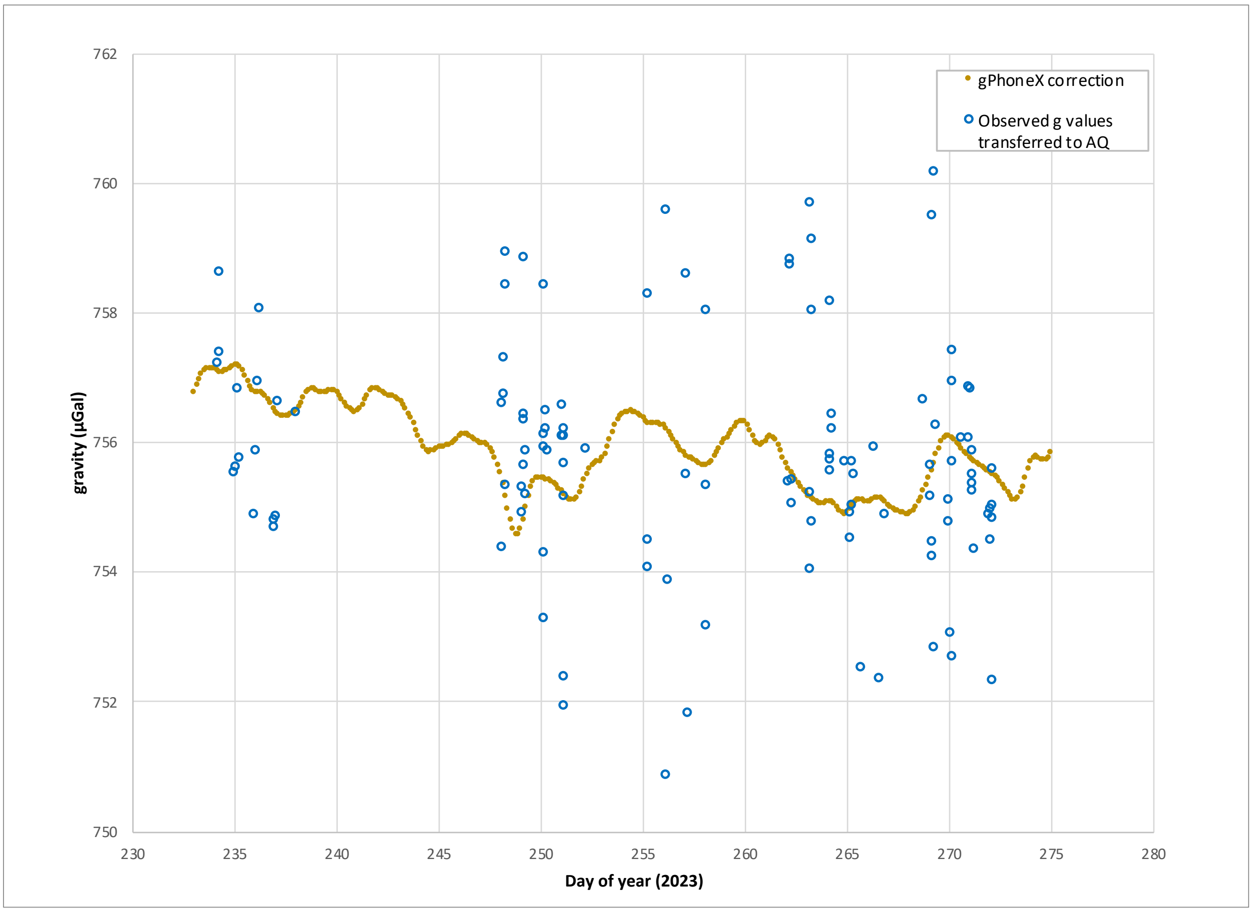

Figure 2. Absolute gravity observations transferred to pier AQ and total averaged gPhoneX output with a linear drift of -0.037 µGal/day. The constant value 979 622 000.0 µGal has been subtracted from the gravity measurements.

Absolute gravity measurements

With the exception of WAG-H5-2, each gravimeter measured four gravity stations or piers. The comparison was organized in five weekly sessions each with measurements occurring over four nights. Each participant was free to measure gravity over a duration of their choosing within a maximum window of approximately 24 hours (before being required to move to the next scheduled pier). Table 4 lists the measurement schedule (NMI/DI gravimeters are shaded in pink). The schedule was designed to maximize the overlap of gravimeters, minimize the number of occupied piers, and prohibit reoccupations of the same pier by a single gravimeter [6]. Every gravimeter overlapped with every other gravimeter at least two times and no more than three times.

Table 4. Pier occupation schedule for the comparison. Due to real-time logistical constraints, not all instruments could observe on their scheduled date. The actual occupation times are listed in Table 5.

Instrument \ Pier	AG	AH	AI	AJ	AO	AQ	AS	AT	Total
FG5-242	X	X	X				X		4
FG5-223	X	X	X				X		4
FG5-105	X		X	X		X			4
WAG-H5-2		X	X					X	3
NIM-3A	X			X	X			X	4
FG5X-249			X	X	X	X			4
NIM-AGRb2		X				X	X	X	4
FG5-231	X			X	X			X	4
FG5X-251/HS5		X	X	X				X	4
FG5X-221	X	X	X				X		4
FG5-228	X	X	X		X				4
FG5-101			X		X		X	X	4
FG5-227		X				X	X	X	4
FG5X-263	X	X	X	X					4
FG5-238	X			X	X			X	4
FG5-213	X	X			X	X			4
FG5X-104	X			X		X	X		4
FG5X-252		X	X	X				X	4
FG5X-253			X	X	X	X			4
FG5X-261		X	X	X	X				4
FG5-211			X	X		X	X		4
FG5X-233	X	X			X	X			4
FG5X-254	X			X		X	X		4
FG5-222	X	X			X	X			4
FG5X-258				X	X		X	X	4
FG5X-302		X				X	X	X	4
FG5X-107			X	X	X	X			4
FG5X-205	X			X		X	X		4
FG5X-102			X		X		X	X	4
FG5-204		X		X		X	X		4
Total	15	16	16	17	14	15	14	12	

Gravity was reported nominally above each pier benchmark at h_{eff} unique to each gravimeter (and in principle, each gravimeter set up) with a declared instrument uncertainty u_{decl} by each participant. Each raw gravity value is corrected for:

- Earth tides and ocean loading via a common set of observed tidal parameters [3]
- Barometric pressure changes from the nominal value of 826.74 mBar using a common admittance factor of -0.3 μGal/mbar [7]
- Polar Motion using common values obtained from the Earth Rotation and Reference Systems Service (IERS) [8]
- and all known instrumental effects (e.g. self-attraction [9] [10], laser beam diffraction [11], etc.)
- The relative change in the local gravity signal, as recorded by the mean of the three gPhoneXs, beginning at 00:00 UTC on 20 August, 2023. The filtered mean gPhoneX signal was sampled at 3-hour increments, and the sample nearest to mean time of each absolute observation was used to correct the raw absolute gravity value.

These gravity values were then transferred to a common height of 125 cm using the quadratic gradient parameters for each pier listed in Table 2. The final gravimeter results are listed in Table 5.

Table 5. Absolute gravity observations g_{ij}. u_{ij} is the standard measurement uncertainty (k=1). See text for discussion. NMI/DI gravimeters are shaded in pink, and a common value of 979 622 000 µGal has been subtracted from each value. The times are UTC.

Day of Year	Mean Time (UTC)	Instrument	Site	h_{eff} (m)	g at h_{eff} (µGal)	u_{decl} (k=1) (µGal)	VGG Coeff. a (µGal/m^2)	VGG Coeff. b (µGal/m)	g transfer to 1.25 m (µGal)	u_{trans} (k=1) (µGal)	g_{ij} at 1.25 m (µGal)	u_{ij} (k=1) (µGal)	gPhoneX output (µGal)	g_{ij} corrected (k=1) (µGal)
248	7:01	FG5-242	AG	1.210	771.30	2.40	1.20	-317.80	-12.59	0.22	758.71	2.42	-0.74	759.45
249	5:06	FG5-242	AH	1.210	772.30	2.50	0.60	-316.70	-12.61	0.15	759.69	2.51	-1.10	760.79
250	7:51	FG5-242	AI	1.210	776.00	2.40	3.60	-323.80	-12.60	0.21	763.40	2.41	-0.50	763.90
251	4:37	FG5-242	AS	1.210	766.80	2.40	2.70	-320.60	-12.56	0.25	754.24	2.42	-0.73	754.97
269	3:48	FG5-223	AG	1.257	757.22	2.58	1.20	-317.80	2.05	0.04	759.27	2.58	-0.36	759.63
270	0:49	FG5-223	AH	1.258	753.27	2.58	0.60	-316.70	2.36	0.03	755.63	2.59	0.18	755.46
271	1:39	FG5-223	AI	1.251	763.89	2.58	3.60	-323.80	0.46	0.01	764.35	2.58	-0.15	764.50
272	1:40	FG5-223	AS	1.250	753.16	2.58	2.70	-320.60	-0.16	0.00	753.00	2.59	-0.39	753.39
234	6:09	FG5-105	AI	1.238	768.70	1.71	3.60	-323.80	-3.78	0.06	764.92	1.72	1.17	763.75
235	5:47	FG5-105	AJ	1.236	768.90	1.71	1.50	-319.60	-4.42	0.08	764.48	1.72	1.27	763.21
236	4:57	FG5-105	AQ	1.238	761.80	1.71	3.80	-321.60	-3.75	0.08	758.05	1.72	0.84	757.21
236	23:36	FG5-105	AG	1.239	757.90	1.71	1.20	-317.80	-3.46	0.06	754.45	1.72	0.61	753.84
266	20:03	WAG-H5-2	AI	1.140	797.00	2.79	3.60	-323.80	-34.57	0.57	762.43	2.88	-0.81	763.23
266	15:02	WAG-H5-2	AH	1.140	787.80	2.79	0.60	-316.70	-34.59	0.41	753.21	2.84	-0.78	753.99
265	16:15	WAG-H5-2	AT	1.140	786.40	2.79	4.00	-323.10	-34.34	0.67	752.06	2.88	-0.80	752.86
262	6:50	NIM-3A	AG	1.042	820.70	4.42	1.20	-317.80	-65.53	1.12	755.17	4.84	-0.39	755.56
263	7:22	NIM-3A	AO	1.038	828.40	4.42	0.00	-316.70	-67.14	1.09	761.26	4.78	-0.78	762.04
264	5:30	NIM-3A	AT	1.041	823.30	4.42	4.00	-323.10	-65.61	1.25	757.69	4.78	-0.83	758.51
265	6:00	NIM-3A	AJ	1.042	829.50	4.42	1.50	-319.60	-65.76	1.15	763.74	4.70	-0.90	764.64
262	6:32	FG5X-249	AQ	1.280	749.31	2.29	3.80	-321.60	9.41	0.19	758.72	2.31	-0.39	759.11
263	6:46	FG5X-249	AJ	1.279	757.55	2.29	1.50	-319.60	9.22	0.17	766.77	2.32	-0.78	767.55
264	5:52	FG5X-249	AI	1.275	755.96	2.29	3.60	-323.80	7.77	0.13	763.73	2.32	-0.83	764.56
265	7:50	FG5X-249	AO	1.277	749.24	2.29	0.00	-316.70	8.40	0.14	757.64	2.32	-0.90	758.54
263	7:00	NIM-AGRb2	AT	1.070	810.80	5.35	4.00	-323.10	-56.49	1.09	754.31	5.46	-0.78	755.09
264	7:00	NIM-AGRb2	AQ	1.071	812.40	5.35	3.80	-321.60	-55.99	1.07	756.41	5.46	-0.84	757.25
265	7:00	NIM-AGRb2	AH	1.077	811.10	5.35	0.60	-316.70	-54.55	0.64	756.55	5.40	-0.90	757.45
266	8:00	NIM-AGRb2	AS	1.072	809.90	5.35	2.70	-320.60	-55.95	1.07	753.95	5.46	-0.80	754.75
269	5:51	FG5-231	AT	1.226	767.16	2.50	4.00	-323.10	-7.47	0.15	759.69	2.51	-0.36	760.05
270	5:08	FG5-231	AO	1.221	768.68	2.50	0.00	-316.70	-9.14	0.16	759.54	2.51	0.16	759.38
271	4:14	FG5-231	AG	1.219	764.99	2.50	1.20	-317.80	-9.88	0.18	755.11	2.51	-0.19	755.30
272	3:24	FG5-231	AJ	1.218	773.97	2.50	1.50	-319.60	-10.22	0.19	763.75	2.51	-0.41	764.16
248	4:00	FG5X-251/HS5	AH	1.271	748.63	1.84	0.60	-316.70	6.59	0.08	755.22	1.97	-0.56	755.78
249	3:32	FG5X-251/HS5	AI	1.269	756.37	1.84	3.60	-323.80	6.08	0.10	762.45	1.97	-1.10	763.55
250	3:46	FG5X-251/HS5	AJ	1.270	756.63	2.26	1.50	-319.60	6.38	0.12	763.01	2.37	-0.48	763.50
251	3:56	FG5X-251/HS5	AT	1.268	746.24	2.26	4.00	-323.10	5.67	0.12	751.91	2.37	-0.73	752.64
262	4:20	FG5X-221	AI	1.266	757.85	2.10	3.60	-323.80	5.08	0.09	762.93	2.11	-0.32	763.25
263	5:08	FG5X-221	AH	1.268	749.18	2.10	0.60	-316.70	5.72	0.07	754.90	2.11	-0.74	755.64
264	4:34	FG5X-221	AG	1.268	750.03	2.10	1.20	-317.80	5.55	0.10	755.58	2.11	-0.83	756.41
265	4:09	FG5X-221	AS	1.265	747.96	2.10	2.70	-320.60	4.59	0.09	752.55	2.11	-0.96	753.51
255	6:49	FG5-228	AG	1.220	763.57	2.59	1.20	-317.80	-9.33	0.17	754.24	2.60	0.38	753.86
256	4:39	FG5-228	AH	1.220	761.21	2.59	0.60	-316.70	-9.50	0.12	751.71	2.60	0.29	751.42
257	4:35	FG5-228	AI	1.218	769.46	2.59	3.60	-323.80	-10.11	0.17	759.35	2.61	-0.12	759.47
258	4:01	FG5-228	AO	1.218	765.31	2.59	0.00	-316.70	-10.02	0.17	755.29	2.61	-0.27	755.56
248	4:12	FG5-101	AS	1.230	761.61	2.77	2.70	-320.60	-6.28	0.13	755.33	2.80	-0.56	755.89
249	3:57	FG5-101	AT	1.230	762.14	2.77	4.00	-323.10	-6.26	0.13	755.88	2.80	-1.10	756.98
250	3:47	FG5-101	AO	1.230	766.88	2.77	0.00	-316.70	-6.33	0.11	760.55	2.80	-0.48	761.03
251	3:47	FG5-101	AI	1.230	769.50	2.77	3.60	-323.80	-6.30	0.11	763.20	2.80	-0.73	763.93
248	2:26	FG5-227	AQ	1.213	768.15	2.75	3.80	-321.60	-11.55	0.23	756.60	2.79	-0.39	756.99
249	4:15	FG5-227	AS	1.213	766.09	2.75	2.70	-320.60	-11.62	0.23	754.47	2.78	-1.10	755.58
250	4:18	FG5-227	AT	1.213	767.04	2.75	4.00	-323.10	-11.59	0.23	755.45	2.79	-0.48	755.93
251	4:07	FG5-227	AH	1.213	768.62	2.75	0.60	-316.70	-11.66	0.14	756.96	2.78	-0.73	757.69
255	5:58	FG5X-263	AH	1.276	750.96	2.53	0.60	-316.70	8.18	0.10	759.14	2.55	0.41	758.73
256	2:53	FG5X-263	AI	1.276	758.94	2.53	3.60	-323.80	8.18	0.14	767.12	2.54	0.33	766.78
257	3:33	FG5X-263	AJ	1.275	759.36	2.53	1.50	-319.60	7.95	0.15	767.31	2.54	-0.12	767.43
258	3:22	FG5X-263	AG	1.278	749.07	2.53	1.20	-317.80	8.73	0.16	757.80	2.54	-0.27	758.08
250	3:58	FG5-238	AG	1.215	764.18	2.24	1.20	-317.80	-11.13	0.20	753.05	2.31	-0.48	753.53
251	2:34	FG5-238	AJ	1.212	776.83	2.24	1.50	-319.60	-12.01	0.22	764.82	2.30	-0.68	765.50
249	3:05	FG5-238	AO	1.212	769.60	2.24	0.00	-316.70	-12.16	0.21	757.44	2.27	-1.10	758.55
248	6:27	FG5-238	AT	1.211	770.13	2.24	4.00	-323.10	-12.18	0.24	757.95	2.28	-0.74	758.69

Table 5 (continued). Absolute gravity observations g_{ij}. u_{ij} is the standard measurement uncertainty (k=1). See text for discussion. NMI/DI gravimeters are shaded in pink, and a common value of 979 622 000 µGal has been subtracted from each value. The times are UTC.

Day of Year	Mean Time (UTC)	Instrument	Site	h_{eff} (m)	g at h_{eff} (µGal)	u_{decl} (k=1) (µGal)	VGG Coeff. a (µGal/m^2)	VGG Coeff. b (µGal/m)	g transfer to 1.25 m (µGal)	u_{trans} (k=1) (µGal)	g_{ij} at 1.25 m (µGal)	u_{ij} (k=1) (µGal)	gPhoneX and drift (µGal)	g_{ij} corrected (k=1) (µGal)
262	5:57	FG5-213	AH	1.224	767.71	2.68	0.60	-316.70	-8.04	0.10	759.67	2.69	-0.32	759.99
263	4:42	FG5-213	AG	1.225	767.34	2.68	1.20	-317.80	-7.88	0.14	759.46	2.69	-0.74	760.20
264	4:57	FG5-213	AO	1.224	766.07	2.68	0.00	-316.70	-8.39	0.14	757.68	2.69	-0.83	758.51
264	22:00	FG5-213	AQ	1.223	764.28	2.68	3.80	-321.60	-8.59	0.17	755.69	2.70	-1.03	756.73
262	6:54	FG5X-104	AS	1.273	746.00	2.24	2.70	-320.60	7.09	0.14	753.09	2.25	-0.39	753.48
263	5:30	FG5X-104	AQ	1.275	747.40	2.24	3.80	-321.60	7.82	0.16	755.22	2.25	-0.74	755.96
264	4:22	FG5X-104	AJ	1.274	757.00	2.24	1.50	-319.60	7.45	0.14	764.45	2.25	-0.83	765.28
265	3:18	FG5X-104	AG	1.274	747.10	2.24	1.20	-317.80	7.58	0.14	754.68	2.25	-0.96	755.64
269	8:42	FG5X-252	AH	1.311	737.81	2.24	0.60	-316.70	19.30	0.24	757.11	2.26	-0.24	757.35
270	5:18	FG5X-252	AI	1.310	744.29	2.24	3.60	-323.80	18.95	0.33	763.24	2.27	0.16	763.09
271	3:38	FG5X-252	AJ	1.308	746.19	2.24	1.50	-319.60	18.39	0.35	764.58	2.27	-0.19	764.77
272	4:26	FG5X-252	AT	1.307	737.35	2.24	4.00	-323.10	17.75	0.36	755.10	2.27	-0.41	755.52
248	4:24	FG5X-253	AI	1.318	742.82	2.24	3.60	-323.80	21.45	0.37	764.27	2.28	-0.56	764.83
249	6:49	FG5X-253	AJ	1.280	755.01	2.24	1.50	-319.60	9.59	0.18	764.60	2.25	-0.93	765.53
250	5:57	FG5X-253	AQ	1.285	745.30	2.24	3.80	-321.60	10.89	0.22	756.19	2.25	-0.48	756.67
251	1:38	FG5X-253	AO	1.286	747.35	2.24	0.00	-316.70	11.36	0.20	758.71	2.25	-0.68	759.39
234	3:45	FG5X-261	AH	1.271	751.52	2.24	0.60	-316.70	6.56	0.08	758.08	2.25	1.19	756.89
235	2:09	FG5X-261	AI	1.271	756.44	2.24	3.60	-323.80	6.71	0.11	763.15	2.25	1.27	761.88
236	2:36	FG5X-261	AJ	1.271	757.85	2.24	1.50	-319.60	6.73	0.13	764.58	2.25	0.85	763.72
237	1:41	FG5X-261	AO	1.273	749.62	2.24	0.00	-316.70	7.38	0.13	757.00	2.26	0.54	756.46
258	3:52	FG5-211	AI	1.236	767.28	2.65	3.60	-323.80	-4.41	0.07	762.87	2.69	-0.27	763.14
255	7:03	FG5-211	AJ	1.236	767.22	2.51	1.50	-319.60	-4.42	0.08	762.80	2.56	0.38	762.41
256	5:03	FG5-211	AQ	1.237	757.83	2.56	3.80	-321.60	-3.96	0.08	753.87	2.60	0.29	753.57
257	3:48	FG5-211	AS	1.236	758.10	2.60	2.70	-320.60	-4.55	0.09	753.55	2.64	-0.12	753.67
248	6:20	FG5X-233	AO	1.270	751.13	2.40	0.00	-316.70	6.33	0.11	757.46	2.41	-0.74	758.21
249	4:56	FG5X-233	AG	1.270	749.10	2.40	1.20	-317.80	6.30	0.11	755.40	2.41	-1.10	756.50
250	5:26	FG5X-233	AH	1.270	751.02	2.40	0.60	-316.70	6.30	0.08	757.32	2.41	-0.48	757.81
251	3:31	FG5X-233	AQ	1.270	745.69	2.40	3.80	-321.60	6.24	0.13	751.93	2.41	-0.73	752.66
249	7:43	FG5X-254	AQ	1.278	746.46	2.24	3.80	-321.60	8.73	0.18	755.19	2.25	-0.93	756.12
250	4:13	FG5X-254	AS	1.275	746.33	2.24	2.70	-320.60	7.84	0.16	754.17	2.26	-0.48	754.65
251	3:08	FG5X-254	AG	1.277	746.29	2.24	1.20	-317.80	8.65	0.16	754.94	2.25	-0.73	755.67
252	5:55	FG5X-254	AJ	1.277	756.24	2.24	1.50	-319.60	8.37	0.16	764.61	2.25	-0.51	765.12
270	1:02	FG5-222	AG	1.221	764.04	2.24	1.20	-317.80	-9.16	0.16	754.88	2.26	0.18	754.70
270	23:25	FG5-222	AH	1.221	766.72	2.24	0.60	-316.70	-9.00	0.11	757.72	2.25	-0.11	757.83
269	2:45	FG5-222	AO	1.221	766.34	2.24	0.00	-316.70	-9.05	0.15	757.29	2.28	-0.48	757.77
271	22:24	FG5-222	AQ	1.221	763.80	2.24	3.80	-321.60	-8.92	0.18	754.88	2.27	-0.36	755.24
234	5:56	FG5X-258	AS	1.267	751.16	2.24	2.70	-320.60	5.49	0.11	756.65	2.26	1.19	755.46
235	4:36	FG5X-258	AT	1.266	751.34	2.24	4.00	-323.10	5.00	0.10	756.34	2.26	1.27	755.07
236	4:16	FG5X-258	AO	1.266	754.02	2.24	0.00	-316.70	5.05	0.09	759.07	2.25	0.84	758.23
237	4:06	FG5X-258	AJ	1.265	760.46	2.24	1.50	-319.60	4.89	0.09	765.35	2.25	0.50	764.85
268	17:36	FG5X-302	AQ	1.276	748.60	2.03	3.80	-321.60	8.04	0.16	756.64	2.06	-0.77	757.41
269	4:33	FG5X-302	AS	1.275	744.50	2.03	2.70	-320.60	7.77	0.16	752.27	2.08	-0.36	752.63
270	14:41	FG5X-302	AT	1.271	749.00	2.03	4.00	-323.10	6.60	0.13	755.60	2.05	0.03	755.57
271	3:06	FG5X-302	AH	1.272	749.00	2.03	0.60	-316.70	7.09	0.09	756.09	2.04	-0.19	756.28
271	3:11	FG5X-107	AQ	1.268	749.85	2.24	3.80	-321.60	5.65	0.11	755.50	2.25	-0.19	755.69
270	3:46	FG5X-107	AJ	1.267	760.25	2.24	1.50	-319.60	5.41	0.10	765.66	2.24	0.16	765.50
272	3:56	FG5X-107	AO	1.269	750.91	2.24	0.00	-316.70	6.06	0.10	756.97	2.25	-0.41	757.38
269	4:39	FG5X-107	AI	1.266	756.94	2.24	3.60	-323.80	5.06	0.09	762.00	2.25	-0.36	762.37
269	6:32	FG5X-205	AJ	1.283	751.13	2.45	1.50	-319.60	10.43	0.20	761.56	2.51	-0.24	761.80
270	4:54	FG5X-205	AQ	1.286	741.39	2.45	3.80	-321.60	11.30	0.23	752.69	2.47	0.16	752.53
271	5:39	FG5X-205	AS	1.283	741.95	2.45	2.70	-320.60	10.42	0.21	752.37	2.47	-0.19	752.56
272	3:31	FG5X-205	AG	1.278	743.40	2.45	1.20	-317.80	8.70	0.16	752.10	2.48	-0.41	752.51
269	2:54	FG5X-102	AS	1.273	746.30	2.15	2.70	-320.60	7.37	0.15	753.67	2.16	-0.48	754.15
270	1:27	FG5X-102	AT	1.272	745.70	2.15	4.00	-323.10	6.88	0.14	752.58	2.17	0.18	752.40
271	0:31	FG5X-102	AO	1.276	750.00	2.15	0.00	-316.70	8.20	0.14	758.20	2.17	-0.15	758.35
272	0:33	FG5X-102	AI	1.274	754.40	2.15	3.60	-323.80	7.61	0.13	762.01	2.16	-0.39	762.40
235	0:13	FG5-204	AQ	1.265	750.92	2.03	3.80	-321.60	4.61	0.09	755.53	2.03	1.27	754.25
235	23:24	FG5-204	AS	1.262	749.07	2.03	2.70	-320.60	3.85	0.08	752.92	2.03	0.88	752.03
236	22:55	FG5-204	AH	1.265	751.01	2.03	0.60	-316.70	4.64	0.06	755.65	2.04	0.61	755.05
238	0:10	FG5-204	AJ	1.263	760.99	2.03	1.50	-319.60	4.19	0.08	765.18	2.04	0.56	764.61

Analysis Methods

Following Koo and Clare [12], the gravity values for each gravimeter on each pier are expressed as

$$g_{ij} = g_j + \delta_i + \varepsilon_{ij} \tag{4}$$

where g_{ij} is the gravity value measured on pier j by gravimeter i as given in Table 5, g_j is the true (unknown) gravity value at pier j, δ_i is the true (unknown) bias of gravimeter i, and ε_{ij} is the measurement error. A variance weighted least squares analysis (LSA) is performed [13] to give the best estimates of the pier gravity Reference Values g_j and the gravimeter biases δ_i. The input (or measurement) covariance matrix $\boldsymbol{V}$ has diagonal elements that are the sum of u_{ij}^2 given in Table 5 and the square of the gPhoneX uncertainty, (0.7 μGal)^2. Covariances [14,15] $u(g_{ij},g_{ik})$, $j \neq k$, for a given gravimeter i are included for the four piers measured by the same gravimeter i (three by WAG H5-2) where $u(g_{ij},g_{ik}) = r\,(u_{\mathrm{decl}ij})(u_{\mathrm{decl}ik})$, r is the correlation coefficient, and u_{decl} are the declared uncertainties by the participants given in Table 5. Thus the covariance matrix $\boldsymbol{V}$ is block diagonal with 4 × 4 matrices for each gravimeter i (3 × 3 for WAG H5-2). The corresponding weight matrix is $\boldsymbol{W} = \boldsymbol{V}^{-1}$. The set of equations is ill defined with an infinite number of solutions, so an additional constraint on the weighted sum of the biases is imposed:

$$\sum_{i=1}^{n} \bar{w}_i \;\; \delta_i = 0 \tag{5}$$

The normalized variance weights $\bar{w}_i$ have the condition that

$$\sum_{i=1}^{n} \bar{w}_i \;\; = 1 \tag{6}$$

and are defined as

$$\bar{w}_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad , \tag{7}$$

where $w_i = 1/u_i^2$. Only NMI/DI gravimeters can contribute to the KCRVs of CCM.G-K.2023. Therefore, an initial LSA is performed with the NMI/DI gravimeters weights equal, i.e. $w_i = 1$, and non-NMI/DI gravimeters with zero weight. The resulting LSA NMI/DI gravimeters output uncertainties, u_i for NMI/DI gravimeter i, are then used to determine the input weights, w_i, for the NMI/DI gravimeters for a second LSA. Results for the Additional Comparison where all participating gravimeters are treated as equivalent with nonzero normalized weights are given in Appendix A.

Results

Initial results were performed with zero correlations, i.e. $r = 0$. All measurements presented by the operators as given in Table 5 were included in the LSA. For 81 degrees of freedom N (120 input data, 1 constraint, 38 unknowns), the chi square statistic is $\chi^2 = 24.5$ with probability $p(24.5|81) = 1$ and a Birge ratio of $R_{\mathrm{B}} = \sqrt{24.5/81} = 0.55$, indicating a high level of consistency for the input data. The gravimeter biases (δ) and pier Reference Values (g) with zero correlations are presented in Table 6. Following [15], the value of the correlation coefficient is adjusted such that the mean square error or reduced chi square = χ^2/N (and equivalently the Birge ratio R_B) is equal to 1, indicating a statistically good fit of the input data. The determined value of the correlation coefficient is r = 0.78, consistent with the results of [15]. The gravimeter biases (δ) and pier Reference Values (g) with r = 0.78 are presented in Table 7 and Figure 3.

Table 6. Biases (δ) of NMI/DIs and pier Reference Values (g) at a height of 125 cm of the comparison using all the reported absolute measurements with zero correlations. The constant value 979 622 000.0 µGal is subtracted from the pier values, U is the expanded uncertainty (k=2) at a 95% confidence level.

Gravimeter	δ/µGal	U/µGal
FG5-242	1.93	2.49
FG5-223	0.43	2.64
FG5-105	-0.76	1.80
NIM-3A	1.38	4.81
FG5-231	0.92	2.60
FG5X-251	-1.43	2.23
FG5X-221	-0.61	2.18
FG5X-263	2.27	2.58
FG5-213	1.91	2.76
FG5X-104	-0.31	2.32
FG5X-252	-0.24	2.35
FG5X-253	0.75	2.34
FG5X-261	-1.33	2.32
FG5X-254	0.00	2.32
FG5X-204	-1.68	2.12

Pier	g/µGal	U/µGal
AG	756.04	1.40
AH	757.12	1.39
AI	763.79	1.33
AJ	764.99	1.28
AO	758.40	1.60
AQ	756.24	1.44
AS	754.30	1.53
AT	755.80	1.82

Table 7. Biases (δ) of NMI/DIs and pier Reference Values (g) at a height of 125 cm of the comparison using all the reported absolute measurements with correlation coefficient r = 0.78. The constant value 979 622 000.0 µGal is subtracted from the pier values, U is the expanded uncertainty (k=2) at a 95% confidence level.

Gravimeter	δ/µGal	U/µGal
FG5-242	1.81	4.35
FG5-223	0.43	4.64
FG5-105	-0.76	3.04
NIM-3A	1.34	8.23
FG5-231	0.89	4.50
FG5X-251	-0.96	3.58
FG5X-221	-0.63	3.76
FG5X-263	2.26	4.56
FG5-213	1.91	4.84
FG5X-104	-0.32	4.02
FG5X-252	-0.24	4.03
FG5X-253	0.77	4.03
FG5X-261	-1.32	4.02
FG5X-254	-0.02	4.02
FG5X-204	-1.67	3.63

Pier	g/µGal	U/µGal
AG	756.12	1.29
AH	757.11	1.29
AI	763.74	1.27
AJ	765.00	1.26
AO	758.39	1.36
AQ	756.19	1.31
AS	754.33	1.33
AT	755.84	1.45

Consistency of input data

The consistency of the input data is initially investigated by calculating the normalized residuals R_{ij} from the LSA,

$$R_{ij} = \frac{(g_{ij} - g_j)}{U_{ij}} \quad , \tag{8}$$

where U_{ij} is the expanded uncertainty (k=2) of the rms value of u_{ij} given in Table 5 and the gPhoneX uncertainty of 0.7 μGal. Another test is to calculate the ratio of the difference between measured values of gravity and the reference value to the uncertainty of the difference, called the compatibility index E_{ij},

$$E_{ij} = \frac{(g_{ij} - g_j)}{\sqrt{U_{ij}^2 \pm U_j^2}} \quad , \tag{9}$$

where U_j is the expanded uncertainty (k=2) of the reference value g_j from the weighted LSA in Table 7 and the sign on U_j^2 depends on different analyses on the uncertainty of the difference [16,17]. An absolute value of R_{ij} or E_{ij} larger than 1 indicates inconsistency at the 95% confidence level for the given test. Values of R_{ij} and E_{ij} are given in Table 8.

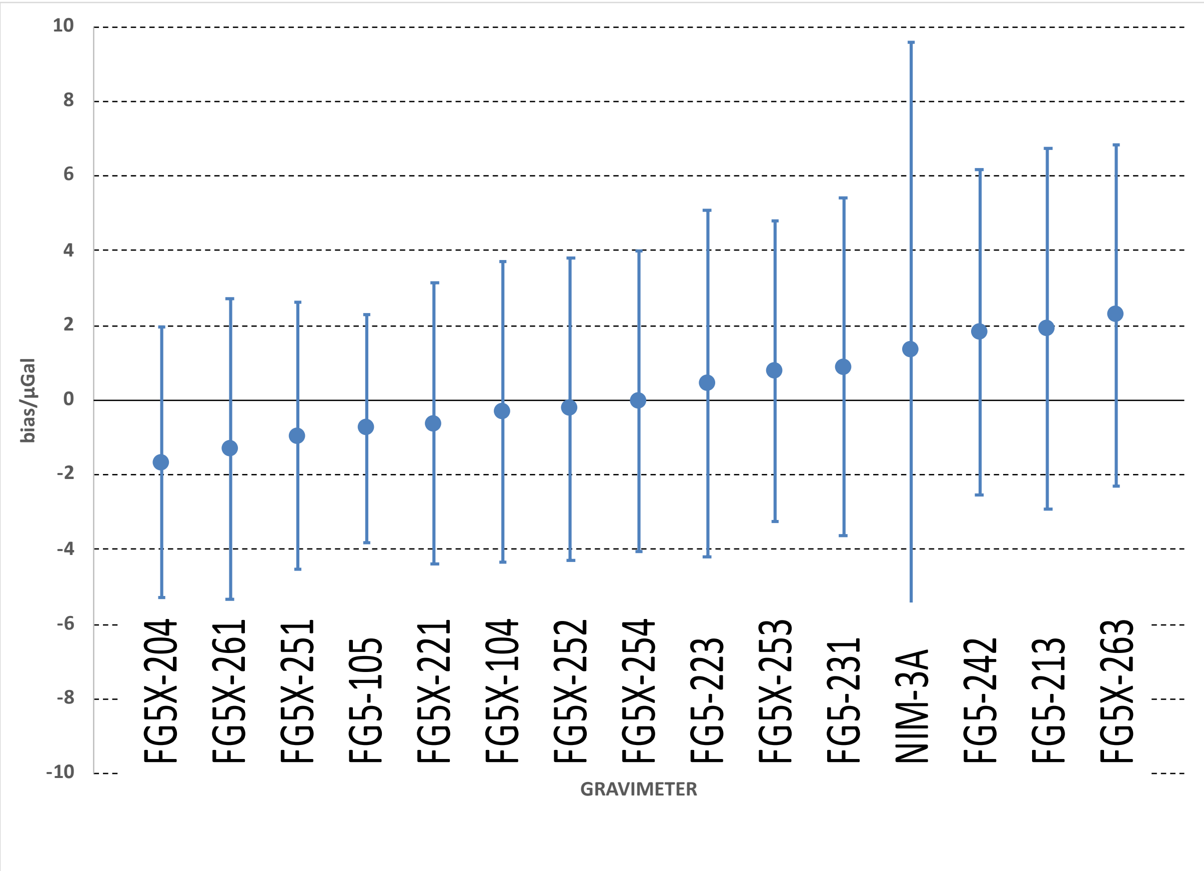

Figure 3. Biases of the NMI/DI gravimeters from the weighted LSA. The error bars are expanded uncertainty (k=2) at a 95% confidence level from the weighted LSA and are listed in Table 6.

Table 8. Consistency of input data: Comparison of measured gravity values g_{ij} (along with expanded uncertainties U_{ij}) with reference values g_j (along with expanded uncertainties U_j) by means of R_{ij} and E_{ij}. The constant value 979 622 000.0 µGal has been subtracted from the gravity measurements.

Gravimeter	Pier	g_{ij} /µGal	U_{ij} /µGal	g_j /µGal	U_j /µGal	g_{ij}-g_i /µGal	R_{ij}	E_{ij} $(+U_j)$	E_{ij} $(-U_j)$
FG5-242	AG	759.45	5.03	756.12	1.29	3.33	0.66	0.64	0.68
FG5-242	AH	760.79	5.21	757.11	1.29	3.68	0.71	0.69	0.73
FG5-242	AI	763.90	5.03	763.74	1.27	0.16	0.03	0.03	0.03
FG5-242	AS	754.97	5.03	754.33	1.33	0.64	0.13	0.12	0.13
FG5-223	AG	759.63	5.35	756.12	1.29	3.51	0.66	0.64	0.68
FG5-223	AH	755.46	5.36	757.11	1.29	-1.66	-0.31	-0.30	-0.32
FG5-223	AI	764.50	5.35	763.74	1.27	0.76	0.14	0.14	0.15
FG5-223	AS	753.39	5.36	754.33	1.33	-0.94	-0.17	-0.17	-0.18
FG5-105	AI	763.75	3.71	763.74	1.27	0.01	0.00	0.00	0.00
FG5-105	AJ	763.21	3.71	765.00	1.26	-1.79	-0.48	-0.46	-0.51
FG5-105	AQ	757.21	3.71	756.19	1.31	1.02	0.28	0.26	0.29
FG5-105	AG	753.84	3.71	756.12	1.29	-2.28	-0.61	-0.58	-0.66
NIM-3A	AG	755.56	9.77	756.12	1.29	-0.56	-0.06	-0.06	-0.06
NIM-3A	AO	762.04	9.67	758.39	1.36	3.65	0.38	0.37	0.38
NIM-3A	AT	758.51	9.66	755.84	1.45	2.67	0.28	0.27	0.28
NIM-3A	AJ	764.64	9.51	765.00	1.26	-0.36	-0.04	-0.04	-0.04
FG5-231	AT	760.05	5.21	755.84	1.45	4.21	0.81	0.78	0.84
FG5-231	AO	759.38	5.21	758.39	1.36	0.99	0.19	0.18	0.20
FG5-231	AG	755.30	5.22	756.12	1.29	-0.82	-0.16	-0.15	-0.16
FG5-231	AJ	764.16	5.21	765.00	1.26	-0.84	-0.16	-0.16	-0.17
FG5X-251	AH	755.78	4.18	757.11	1.29	-1.33	-0.32	-0.30	-0.34
FG5X-251	AI	763.55	4.18	763.74	1.27	-0.19	-0.05	-0.04	-0.05
FG5X-251	AJ	763.50	4.95	765.00	1.26	-1.50	-0.30	-0.29	-0.31
FG5X-251	AT	752.64	4.94	755.84	1.45	-3.20	-0.65	-0.62	-0.68
FG5X-221	AI	763.25	4.44	763.74	1.27	-0.50	-0.11	-0.11	-0.12
FG5X-221	AH	755.64	4.44	757.11	1.29	-1.48	-0.33	-0.32	-0.35
FG5X-221	AG	756.41	4.44	756.12	1.29	0.29	0.06	0.06	0.07
FG5X-221	AS	753.51	4.44	754.33	1.33	-0.81	-0.18	-0.18	-0.19
FG5X-263	AH	758.73	5.29	757.11	1.29	1.61	0.31	0.30	0.31
FG5X-263	AI	766.78	5.27	763.74	1.27	3.04	0.58	0.56	0.59
FG5X-263	AJ	767.43	5.28	765.00	1.26	2.43	0.46	0.45	0.47
FG5X-263	AG	758.08	5.27	756.12	1.29	1.96	0.37	0.36	0.38

Table 8 (continued). Consistency of input data: Comparison of measured gravity values g_{ij} (along with expanded uncertainties U_{ij}) with reference values g_j (along with expanded uncertainties U_j) by means of R_{ij} and E_{ij}. The constant value 979 622 000.0 µGal has been subtracted from the gravity measurements.

Gravimeter	Pier	g_{ij} /µGal	U_{ij} /µGal	g_j /µGal	U_j /µGal	g_{ij}-g_i /µGal	R_{ij}	E_{ij} $(+U_j)$	E_{ij} $(-U_j)$
FG5-213	AH	759.99	5.56	757.11	1.29	2.88	0.52	0.50	0.53
FG5-213	AG	760.20	5.57	756.12	1.29	4.08	0.73	0.71	0.75
FG5-213	AO	758.51	5.56	758.39	1.36	0.11	0.02	0.02	0.02
FG5-213	AQ	756.73	5.58	756.19	1.31	0.54	0.10	0.09	0.10
FG5X-104	AS	753.48	4.71	754.33	1.33	-0.85	-0.18	-0.17	-0.19
FG5X-104	AQ	755.96	4.71	756.19	1.31	-0.22	-0.05	-0.05	-0.05
FG5X-104	AJ	765.28	4.71	765.00	1.26	0.27	0.06	0.06	0.06
FG5X-104	AG	755.64	4.71	756.12	1.29	-0.48	-0.10	-0.10	-0.11
FG5X-252	AH	757.35	4.73	757.11	1.29	0.24	0.05	0.05	0.05
FG5X-252	AI	763.09	4.75	763.74	1.27	-0.66	-0.14	-0.13	-0.14
FG5X-252	AJ	764.77	4.76	765.00	1.26	-0.23	-0.05	-0.05	-0.05
FG5X-252	AT	755.52	4.76	755.84	1.45	-0.32	-0.07	-0.06	-0.07
FG5X-253	AI	764.83	4.76	763.74	1.27	1.09	0.23	0.22	0.24
FG5X-253	AJ	765.53	4.72	765.00	1.26	0.53	0.11	0.11	0.12
FG5X-253	AQ	756.67	4.72	756.19	1.31	0.48	0.10	0.10	0.11
FG5X-253	AO	759.39	4.71	758.39	1.36	0.99	0.21	0.20	0.22
FG5X-261	AH	756.89	4.72	757.11	1.29	-0.22	-0.05	-0.05	-0.05
FG5X-261	AI	761.88	4.72	763.74	1.27	-1.86	-0.39	-0.38	-0.41
FG5X-261	AJ	763.72	4.71	765.00	1.26	-1.28	-0.27	-0.26	-0.28
FG5X-261	AO	756.46	4.73	758.39	1.36	-1.94	-0.41	-0.39	-0.43
FG5X-254	AQ	756.12	4.72	756.19	1.31	-0.07	-0.02	-0.01	-0.02
FG5X-254	AS	754.65	4.72	754.33	1.33	0.33	0.07	0.07	0.07
FG5X-254	AG	755.67	4.71	756.12	1.29	-0.45	-0.10	-0.09	-0.10
FG5X-254	AJ	765.12	4.71	765.00	1.26	0.12	0.03	0.03	0.03
FG5X-204	AQ	754.25	4.30	756.19	1.31	-1.93	-0.45	-0.43	-0.47
FG5X-204	AS	752.03	4.30	754.33	1.33	-2.29	-0.53	-0.51	-0.56
FG5X-204	AH	755.05	4.31	757.11	1.29	-2.07	-0.48	-0.46	-0.50
FG5X-204	AJ	764.61	4.31	765.00	1.26	-0.39	-0.09	-0.09	-0.09

Final results

Since no input data from the NMI/DI participants for CCM.G-K.2023 had an absolute value of R_{ij} or E_{ij} larger than 1, no data were omitted in the final LSA, the degrees of equivalence (DoEs) for CCM.G-K2.2023 are simply the biases given in table 7 and Figure 3 following [12], given again in Table 9. The standard deviation of the gravimeters' DoEs is less than 1.3 µGal, indicating excellent agreement among the gravimeters.

Table 9. DoEs of NMI/Dis and Key Comparison Reference Values (KCRVs) of CCM.G-K2.2023. The uncertainty U_{DoE} is the expanded uncertainty at a 95% confidence level. The constant value 979 622 000.0 µGal is subtracted from the KCRVs. U is the expanded uncertainty (k=2) at a 95% confidence level.

Official Key Comparison Results		
Gravimeter	DoE/µGal	U_{DoE}/µGal
FG5-242	1.81	4.35
FG5-223	0.43	4.64
FG5-105	-0.76	3.04
NIM-3A	1.34	8.23
FG5-231	0.89	4.50
FG5X-251	-0.96	3.58
FG5X-221	-0.63	3.76
FG5X-263	2.26	4.56
FG5-213	1.91	4.84
FG5X-104	-0.32	4.02
FG5X-252	-0.24	4.03
FG5X-253	0.77	4.03
FG5X-261	-1.32	4.02
FG5X-254	-0.02	4.02
FG5X-204	-1.67	3.63

Official Key Comparison Results		
Pier	KCRV/µGal	*U*/µGal
AG	756.12	1.29
AH	757.11	1.29
AI	763.74	1.27
AJ	765.00	1.26
AO	758.39	1.36
AQ	756.19	1.31
AS	754.33	1.33
AT	755.84	1.45

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Appendix A: Additional Comparison

The Additional Comparison follows the same analysis method as the Key Comparison with the exception that it is a complete solution where all participating gravimeters were treated as equivalent in terms of their contribution to the definition of the reference values (RVs). An initial LSA is performed with all gravimeters' weights equal, i.e. w_i =1. The resulting LSA gravimeters output uncertainties, u_i for gravimeter i, are then used to determine the input weights, w_i, for all gravimeters for a second LSA. Following the same analysis as the Key Comparison, the correlation coefficient was determined to be the same, with r = 0.78.

Table A1. Biases (δ) of NMI/DIs (pink) and non-NMI/DIs and pier Reference Values (g) at a height of 125 cm of the comparison using all the reported absolute measurements. The constant value 979 622 000.0 µGal is subtracted from the pier values, U is the expanded uncertainty (k=2) at a 95% confidence level.

Gravimeter	δ/µGal	U/µGal
FG5-242	2.13	4.42
FG5-223	0.75	4.71
FG5-105	-0.44	3.12
WAG H5-2	-1.92	5.23
NIM-3A	1.66	8.27
FG5X-249	1.94	4.19
NIM-AGRb2	0.59	9.82
FG5-231	1.21	4.57
FG5X-251	-0.64	3.66
FG5X-221	-0.31	3.84
FG5-228	-3.45	4.74
FG5-101	1.70	5.07
FG5-227	1.00	5.04
FG5X-263	2.58	4.63
FG5-238	0.59	4.11
FG5-213	2.23	4.90
FG5X-104	0.00	4.09
FG5X-252	0.08	4.10
FG5X-253	1.09	4.09
FG5X-261	-1.00	4.09
FG5-211	-1.48	4.72
FG5X-233	-0.33	4.38
FG5X-254	0.30	4.09
FG5-222	-0.24	4.10
FG5X-258	0.33	4.10
FG5X-302	-0.07	3.71
FG5X-107	-0.27	4.09
FG5X-205	-2.73	4.48
FG5X-102	-0.92	3.93
FG5X-204	-1.36	3.70

Pier	g/µGal	U/µGal
AG	755.80	1.07
AH	756.79	1.06
AI	763.42	1.04
AJ	764.68	1.03
AO	758.07	1.10
AQ	755.87	1.06
AS	754.01	1.10
AT	755.52	1.21

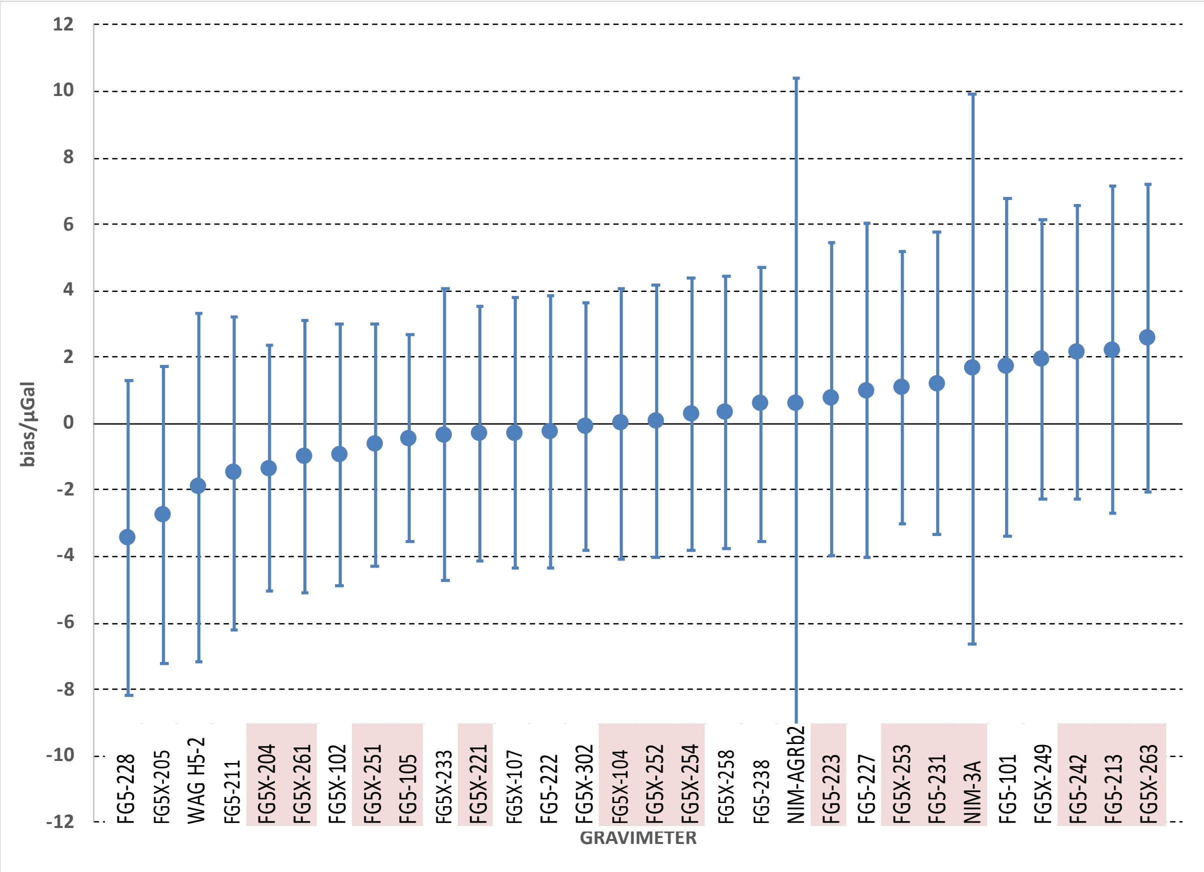

Figure A1. Biases of the gravimeters from the weighted LSA. Gravimeters of NMI/DIs are highlighted in pink. The error bars are expanded uncertainty (k=2) at a 95% confidence level from the weighted LSA and are listed in Table A1.

Consistency of input data

Values of the normalized residuals, R_{ij}, and compatibility index, E_{ij}, from the LSA are given in Table A2. Only one of the input data has an R_{ij} or E_{ij} value that is insignificantly larger than 1, with FG5-228 on pier AH at R_{ij} = -1.00 and E_{ij} (-) = -1.02, resulting in all data being retained.

Final results

Since no data were omitted in the final LSA of all participating gravimeters, the DoEs are simply the biases given in table A1 and Figure A1 following [12], given again in table A3. The official DoE results for comparison CCM.G-K2.2023 are given in Table 9.

Table A2. Consistency of input data: Comparison of measured gravity values g_{ij} (along with expanded uncertainties U_{ij}) with reference values g_j (along with expanded uncertainties U_j) by means of R_{ij} and E_{ij}. NMI/DI gravimeters are in pink. The constant value 979 622 000.0 µGal has been subtracted from the gravity measurements.

Gravimeter	Pier	g_{ij} /µGal	U_{ij} /µGal	g_j /µGal	U_j /µGal	g_{ij}-g_i /µGal	R_{ij}	E_{ij} $(+U_j)$	E_{ij} $(-U_j)$
FG5-242	AG	759.45	5.03	755.80	1.07	3.65	0.72	0.71	0.74
FG5-242	AH	760.79	5.21	756.79	1.06	4.00	0.77	0.75	0.78
FG5-242	AI	763.90	5.03	763.42	1.04	0.47	0.09	0.09	0.10
FG5-242	AS	754.97	5.03	754.01	1.10	0.96	0.19	0.19	0.20
FG5-223	AG	759.63	5.35	755.80	1.07	3.83	0.72	0.70	0.73
FG5-223	AH	755.46	5.36	756.79	1.06	-1.34	-0.25	-0.24	-0.25
FG5-223	AI	764.50	5.35	763.42	1.04	1.08	0.20	0.20	0.21
FG5-223	AS	753.39	5.36	754.01	1.10	-0.62	-0.11	-0.11	-0.12
FG5-105	AI	763.75	3.71	763.42	1.04	0.33	0.09	0.08	0.09
FG5-105	AJ	763.21	3.71	764.68	1.03	-1.47	-0.40	-0.38	-0.41
FG5-105	AQ	757.21	3.71	755.87	1.06	1.34	0.36	0.35	0.38
FG5-105	AG	753.84	3.71	755.80	1.07	-1.96	-0.53	-0.51	-0.55
WAG H5-2	AI	763.23	5.93	763.42	1.04	-0.19	-0.03	-0.03	-0.03
WAG H5-2	AH	753.99	5.86	756.79	1.06	-2.81	-0.48	-0.47	-0.49
WAG H5-2	AT	752.86	5.92	755.52	1.21	-2.66	-0.45	-0.44	-0.46
NIM-3A	AG	755.56	9.77	755.80	1.07	-0.24	-0.02	-0.02	-0.02
NIM-3A	AO	762.04	9.67	758.07	1.10	3.97	0.41	0.41	0.41
NIM-3A	AT	758.51	9.66	755.52	1.21	2.99	0.31	0.31	0.31
NIM-3A	AJ	764.64	9.51	764.68	1.03	-0.04	0.00	0.00	0.00
FG5X-249	AQ	759.11	4.84	755.87	1.06	3.25	0.67	0.66	0.69
FG5X-249	AJ	767.55	4.85	764.68	1.03	2.87	0.59	0.58	0.60
FG5X-249	AI	764.56	4.85	763.42	1.04	1.14	0.23	0.23	0.24
FG5X-249	AO	758.54	4.85	758.07	1.10	0.46	0.10	0.09	0.10
NIM-AGRb2	AT	755.09	11.01	755.52	1.21	-0.43	-0.04	-0.04	-0.04
NIM-AGRb2	AQ	757.25	11.00	755.87	1.06	1.38	0.13	0.12	0.13
NIM-AGRb2	AH	757.45	10.88	756.79	1.06	0.66	0.06	0.06	0.06
NIM-AGRb2	AS	754.75	11.01	754.01	1.10	0.75	0.07	0.07	0.07
FG5-231	AT	760.05	5.21	755.52	1.21	4.53	0.87	0.85	0.89
FG5-231	AO	759.38	5.21	758.07	1.10	1.31	0.25	0.25	0.26
FG5-231	AG	755.30	5.22	755.80	1.07	-0.50	-0.10	-0.09	-0.10
FG5-231	AJ	764.16	5.21	764.68	1.03	-0.52	-0.10	-0.10	-0.10
FG5X-251	AH	755.78	4.18	756.79	1.06	-1.01	-0.24	-0.24	-0.25
FG5X-251	AI	763.55	4.18	763.42	1.04	0.13	0.03	0.03	0.03
FG5X-251	AJ	763.50	4.95	764.68	1.03	-1.18	-0.24	-0.23	-0.24
FG5X-251	AT	752.64	4.94	755.52	1.21	-2.88	-0.58	-0.57	-0.60
FG5X-221	AI	763.25	4.44	763.42	1.04	-0.18	-0.04	-0.04	-0.04
FG5X-221	AH	755.64	4.44	756.79	1.06	-1.16	-0.26	-0.25	-0.27
FG5X-221	AG	756.41	4.44	755.80	1.07	0.61	0.14	0.13	0.14
FG5X-221	AS	753.51	4.44	754.01	1.10	-0.49	-0.11	-0.11	-0.11
FG5X-228	AG	753.86	5.39	755.80	1.07	-1.94	-0.36	-0.35	-0.37
FG5X-228	AH	751.42	5.39	756.79	1.06	-5.38	-1.00	-0.98	-1.02
FG5X-228	AI	759.47	5.40	763.42	1.04	-3.95	-0.73	-0.72	-0.75
FG5X-228	AO	755.56	5.40	758.07	1.10	-2.51	-0.47	-0.46	-0.48
FG5-101	AS	755.89	5.77	754.01	1.10	1.88	0.33	0.32	0.33
FG5-101	AT	756.98	5.77	755.52	1.21	1.46	0.25	0.25	0.26
FG5-101	AO	761.03	5.77	758.07	1.10	2.96	0.51	0.50	0.52
FG5-101	AI	763.93	5.77	763.42	1.04	0.51	0.09	0.09	0.09
FG5-227	AQ	756.99	5.76	755.87	1.06	1.12	0.19	0.19	0.20
FG5-227	AS	755.58	5.74	754.01	1.10	1.57	0.27	0.27	0.28
FG5-227	AT	755.93	5.74	755.52	1.21	0.41	0.07	0.07	0.07
FG5-227	AH	757.69	5.72	756.79	1.06	0.89	0.16	0.15	0.16
FG5X-263	AH	758.73	5.29	756.79	1.06	1.93	0.37	0.36	0.37
FG5X-263	AI	766.78	5.27	763.42	1.04	3.36	0.64	0.63	0.65
FG5X-263	AJ	767.43	5.28	764.68	1.03	2.75	0.52	0.51	0.53
FG5X-263	AG	758.08	5.27	755.80	1.07	2.28	0.43	0.42	0.44
FG5-238	AG	753.53	4.82	755.80	1.07	-2.27	-0.47	-0.46	-0.48
FG5-238	AJ	765.50	4.80	764.68	1.03	0.82	0.17	0.17	0.17
FG5-238	AO	758.55	4.74	758.07	1.10	0.47	0.10	0.10	0.10
FG5-238	AT	758.69	4.77	755.52	1.21	3.17	0.66	0.64	0.69

Table A2 (continued). Consistency of input data: Comparison of measured gravity values g_{ij} (along with expanded uncertainties U_{ij}) with reference values g_j (along with expanded uncertainties U_j) by means of R_{ij} and E_{ij}. NMI/DI gravimeters are in pink. The constant value 979 622 000.0 µGal has been subtracted from the gravity measurements.

Gravimeter	Pier	g_{ij} /µGal	U_{ij} /µGal	g_j /µGal	U_j /µGal	g_{ij}-g_i /µGal	R_{ij}	E_{ij} $(+U_j)$	E_{ij} $(-U_j)$
FG5-213	AH	759.99	5.56	756.79	1.06	3.20	0.57	0.56	0.59
FG5-213	AG	760.20	5.57	755.80	1.07	4.40	0.79	0.78	0.81
FG5-213	AO	758.51	5.56	758.07	1.10	0.43	0.08	0.08	0.08
FG5-213	AQ	756.73	5.58	755.87	1.06	0.86	0.15	0.15	0.16
FG5X-104	AS	753.48	4.71	754.01	1.10	-0.53	-0.11	-0.11	-0.12
FG5X-104	AQ	755.96	4.71	755.87	1.06	0.09	0.02	0.02	0.02
FG5X-104	AJ	765.28	4.71	764.68	1.03	0.59	0.13	0.12	0.13
FG5X-104	AG	755.64	4.71	755.80	1.07	-0.16	-0.03	-0.03	-0.04
FG5X-252	AH	757.35	4.73	756.79	1.06	0.56	0.12	0.12	0.12
FG5X-252	AI	763.09	4.75	763.42	1.04	-0.34	-0.07	-0.07	-0.07
FG5X-252	AJ	764.77	4.76	764.68	1.03	0.09	0.02	0.02	0.02
FG5X-252	AT	755.52	4.76	755.52	1.21	0.00	0.00	0.00	0.00
FG5X-253	AI	764.83	4.76	763.42	1.04	1.41	0.30	0.29	0.30
FG5X-253	AJ	765.53	4.72	764.68	1.03	0.85	0.18	0.18	0.18
FG5X-253	AQ	756.67	4.72	755.87	1.06	0.80	0.17	0.17	0.17
FG5X-253	AO	759.39	4.71	758.07	1.10	1.31	0.28	0.27	0.29
FG5X-261	AH	756.89	4.72	756.79	1.06	0.10	0.02	0.02	0.02
FG5X-261	AI	761.88	4.72	763.42	1.04	-1.54	-0.33	-0.32	-0.34
FG5X-261	AJ	763.72	4.71	764.68	1.03	-0.96	-0.20	-0.20	-0.21
FG5X-261	AO	756.46	4.73	758.07	1.10	-1.62	-0.34	-0.33	-0.35
FG5-211	AI	763.14	5.55	763.42	1.04	-0.28	-0.05	-0.05	-0.05
FG5-211	AJ	762.41	5.30	764.68	1.03	-2.27	-0.43	-0.42	-0.44
FG5-211	AQ	753.57	5.38	755.87	1.06	-2.30	-0.43	-0.42	-0.44
FG5-211	AS	753.67	5.46	754.01	1.10	-0.34	-0.06	-0.06	-0.06
FG5X-233	AO	758.21	5.02	758.07	1.10	0.13	0.03	0.03	0.03
FG5X-233	AG	756.50	5.01	755.80	1.07	0.70	0.14	0.14	0.14
FG5X-233	AH	757.81	5.01	756.79	1.06	1.01	0.20	0.20	0.21
FG5X-233	AQ	752.66	5.03	755.87	1.06	-3.21	-0.64	-0.62	-0.65
FG5X-254	AQ	756.12	4.72	755.87	1.06	0.25	0.05	0.05	0.05
FG5X-254	AS	754.65	4.72	754.01	1.10	0.64	0.14	0.13	0.14
FG5X-254	AG	755.67	4.71	755.80	1.07	-0.13	-0.03	-0.03	-0.03
FG5X-254	AJ	765.12	4.71	764.68	1.03	0.44	0.09	0.09	0.10
FG5-222	AG	754.70	4.72	755.80	1.07	-1.10	-0.23	-0.23	-0.24
FG5-222	AH	757.83	4.72	756.79	1.06	1.03	0.22	0.21	0.22
FG5-222	AO	757.77	4.77	758.07	1.10	-0.30	-0.06	-0.06	-0.06
FG5-222	AQ	755.24	4.75	755.87	1.06	-0.62	-0.13	-0.13	-0.13
FG5X-258	AS	755.46	4.74	754.01	1.10	1.46	0.31	0.30	0.32
FG5X-258	AT	755.07	4.73	755.52	1.21	-0.45	-0.10	-0.09	-0.10
FG5X-258	AO	758.23	4.71	758.07	1.10	0.16	0.03	0.03	0.03
FG5X-258	AJ	764.85	4.71	764.68	1.03	0.17	0.04	0.04	0.04
FG5X-302	AQ	757.41	4.36	755.87	1.06	1.54	0.35	0.34	0.36
FG5X-302	AS	752.63	4.38	754.01	1.10	-1.37	-0.31	-0.30	-0.32
FG5X-302	AT	755.57	4.33	755.52	1.21	0.05	0.01	0.01	0.01
FG5X-302	AH	756.28	4.31	756.79	1.06	-0.52	-0.12	-0.12	-0.12
FG5X-107	AQ	755.69	4.71	755.87	1.06	-0.18	-0.04	-0.04	-0.04
FG5X-107	AJ	765.50	4.70	764.68	1.03	0.82	0.17	0.17	0.18
FG5X-107	AO	757.38	4.71	758.07	1.10	-0.69	-0.15	-0.14	-0.15
FG5X-107	AI	762.37	4.71	763.42	1.04	-1.06	-0.22	-0.22	-0.23
FG5X-205	AJ	761.80	5.21	764.68	1.03	-2.88	-0.55	-0.54	-0.57
FG5X-205	AQ	752.53	5.14	755.87	1.06	-3.34	-0.65	-0.64	-0.66
FG5X-205	AS	752.56	5.13	754.01	1.10	-1.45	-0.28	-0.28	-0.29
FG5X-205	AG	752.51	5.15	755.80	1.07	-3.29	-0.64	-0.62	-0.65
FG5X-102	AS	754.15	4.54	754.01	1.10	0.14	0.03	0.03	0.03
FG5X-102	AT	752.40	4.56	755.52	1.21	-3.12	-0.68	-0.66	-0.71
FG5X-102	AO	758.35	4.55	758.07	1.10	0.27	0.06	0.06	0.06
FG5X-102	AI	762.40	4.55	763.42	1.04	-1.02	-0.22	-0.22	-0.23
FG5X-204	AQ	754.25	4.30	755.87	1.06	-1.61	-0.38	-0.36	-0.39
FG5X-204	AS	752.03	4.30	754.01	1.10	-1.98	-0.46	-0.44	-0.47
FG5X-204	AH	755.05	4.31	756.79	1.06	-1.75	-0.41	-0.39	-0.42
FG5X-204	AJ	764.61	4.31	764.68	1.03	-0.07	-0.02	-0.02	-0.02

Table A3. DoEs of NMI/DIs (pink) and non-NMI/Dis and Reference Values (RVs). The uncertainty U_{DoE} is the expanded uncertainty (k=2) at a 95% confidence level. The constant value 979 622 000.0 μGal is subtracted from the RVs. U is the expanded uncertainty (k=2) at a 95% confidence level.

Gravimeter	DoE/μGal	U_{DoE}/μGal
FG5-242	2.13	4.42
FG5-223	0.75	4.71
FG5-105	-0.44	3.12
WAG H5-2	-1.92	5.23
NIM-3A	1.66	8.27
FG5X-249	1.94	4.19
NIM-AGRb2	0.59	9.82
FG5-231	1.21	4.57
FG5X-251	-0.64	3.66
FG5X-221	-0.31	3.84
FG5-228	-3.45	4.74
FG5-101	1.70	5.07
FG5-227	1.00	5.04
FG5X-263	2.58	4.63
FG5-238	0.59	4.11
FG5-213	2.23	4.90
FG5X-104	0.00	4.09
FG5X-252	0.08	4.10
FG5X-253	1.09	4.09
FG5X-261	-1.00	4.09
FG5-211	-1.48	4.72
FG5X-233	-0.33	4.38
FG5X-254	0.30	4.09
FG5X-222	-0.24	4.10
FG5X-258	0.33	4.10
FG5X-302	-0.07	3.71
FG5X-107	-0.27	4.09
FG5X-205	-2.73	4.48
FG5X-102	-0.92	3.93
FG5X-204	-1.36	3.70

Pier	RV/μGal	*U*/μGal
AG	755.80	1.07
AH	756.79	1.06
AI	763.42	1.04
AJ	764.68	1.03
AO	758.07	1.10
AQ	755.87	1.06
AS	754.01	1.10
AT	755.52	1.21