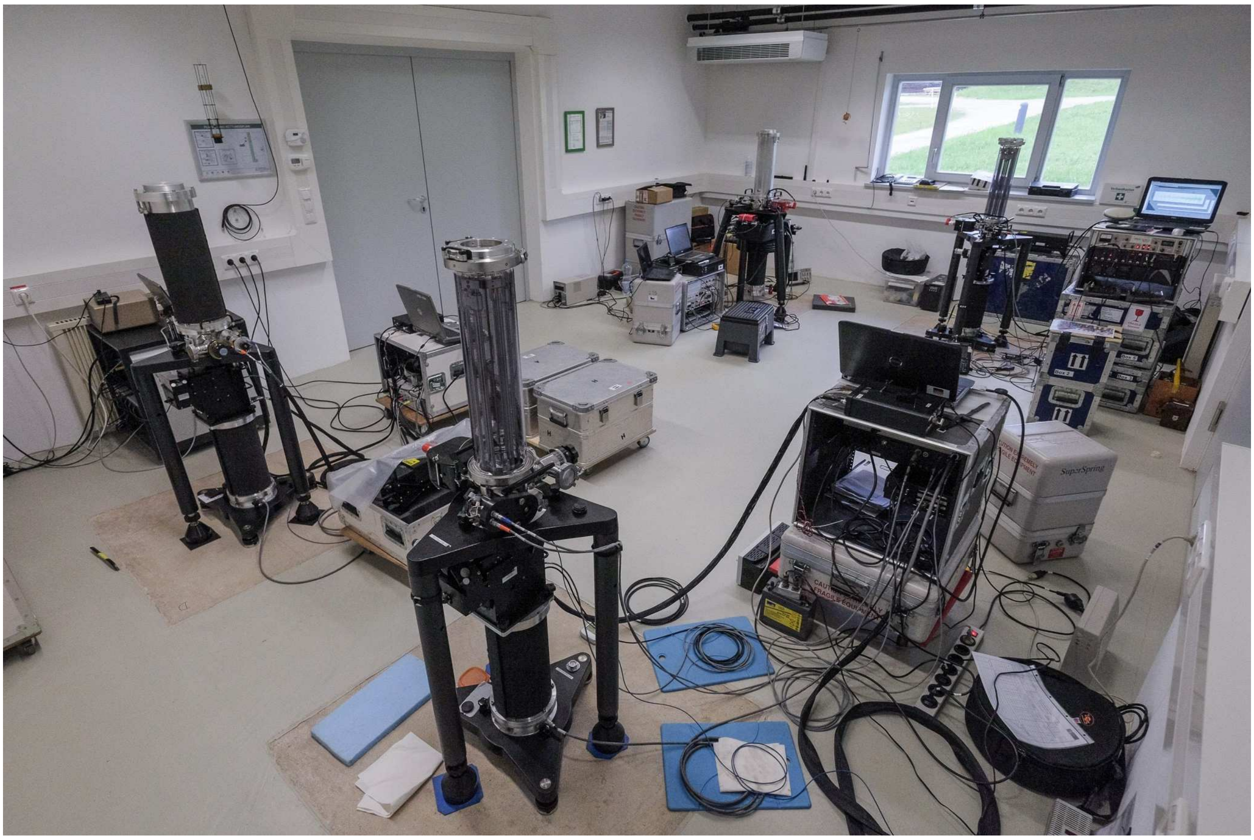
Final report of EURAMET.M.G-K3 regional comparison of absolute gravimeters

Final Report

REGIONAL COMPARISON OF ABSOLUTE GRAVIMETERS

EURAMET.M.G-K3 Key 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-K3 and the simultaneously organized Additional Comparison (CCM, 2015), 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 2018. All the measurements were collected between April 16 and June 15, 2018.

The Technical Protocol (TP) was approved before the comparison by the participants and the CCM-WGG[1] (Technical protocol Version 3.0). 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. 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. Reinhard Falk, Dr. Axel Rülke, Dr. Hartmut Wziontek and Dr. Thomas Klügel (all of BKG) were in charge of the local organizing committee.

The EURAMET.M.G-K3 and Additional Comparison is registered as EURAMET project 1432. The comparison was organized in accordance with the CIPM MRA-D-05 of the Consultative Committee on Mass and Related Quantities (CCM). It is linked to the results of the CCM.G-K2.2017 comparison (Wu et al. 2020) in Changping (China) in 2017 by four 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 CIPM KC (CCM, 2015).

The Additional Comparison has been organized to ensure the compatibility of absolute gravimeters used for the realization of the International Gravity Reference System (Drewes and Kuglitsch 2019) and the International Database for Absolute Gravity measurements (Wziontek et al. 2012).

Here we present the list of the participants who actually performed measurements during the comparison, the data (absolute gravity measurements and their uncertainties) submitted by the operators as well as the results of the determination of the gravity as a function of height (and consequently vertical gravity gradient) at the comparison sites. The measurement strategy is briefly discussed and the results of the data harmonization is documented. Finally, the results of the adjustment are presented including the degrees of equivalence (*DoE*) of each gravimeter and the key comparison reference values (KCRV). The KCRV were obtained by the absolute values of the gravimeters participating in the KC and the gravity differences measured by all the gravimeters (including those participating at the Additional Comparison).

This report presents all results of the 5 gravimeters taking part in EURAMET.M.G-K3, the results of the Additional Comparison are documented in Annex B.

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

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

2. List of participants

The list of the participants is presented in Table 1. In total, 16 absolute gravimeters of three different types were compared. As to FG5 gravimeters, the FG5-202 and FG5-215 are equipped with a bulk type of interferometer. Overall, 5 teams from National Metrology Institutes (NMIs) or Designated Institutes (DIs) participated in the Key Comparison and 11 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-K3 are in yellow.

Country	Institution	Gravimeter	NMI or DI	CCM.G-K2.2017	Operator(s)
EURAMET.M.G-K3					
Austria	Bundesamt für Eich und Vermessungswesen (BEV), Vienna	FG5-242	YES	YES	Christian Ullrich, Hubert Butta
Czech Republic	VÚGTK/ RIGTC, Geodetic Observatory Pecný	FG5-215H	YES	YES	Vojtech Pálinkáš, Jakub Kostelecký
Finland	Finnish Geospatial Research Institute, National Land Survey of Finland, Masala	FG5X-221	YES	YES	Mirjam Bilker-Koivula, Jyri Näränen
Italy	Istituto nazionale di Ricerca Metrologica, Torino	IMGC-02	YES	NO	Andrea Prato, Fabrizzio Mazzolleni
Turkey	Ulusal Metroloji Enstitüsü (TUBITAK UME), Gebze-Kocaeli	FG5X-254	YES	YES	Cafer Kirbaş, İlkcan Coşkun
Additional Comparison					
Belgium	Royal Observatory of Belgium Brussels	FG5-202	NO	NO	Michel Van Camp, Stefaan Castelein
France	University of Strasbourg	FG5-206	NO	NO	Jean-Daniel Bernard
Germany	Federal Agency of Cartography and Geodesy (BKG) Frankfurt/Leipzig	FG5-301	NO	YES*	Alexander Lothhammer Reinhard Falk
Germany	Federal Agency of Cartography and Geodesy (BKG) Frankfurt/Leipzig	FG5-101	NO	NO	Alexander Lothhammer
Germany	Leibniz Universität Hannover	FG5X-220	NO	NO	Manuel Schilling, Ludger Timmen
Italy	Agenzia Spaziale Italiana (ASI) / e-geos, Matera	FG5-218	NO	NO	Domenico Iacovone, Giovanni Nettis
Italy	Istituto Nazionale di Geofisica e Vulcanologia (INGV)	FG5-238	NO	NO	Filippo Greco, Alfio Alex Messina
Netherlands	Delft University of Technology	FG5-234	NO	NO	René Reudink, Michele Petrini
Poland	Institute of Geodesy and Cartography Warszawa	A10-020	NO	NO	Przemysław Dykowski, Marcin Sękowski
Slovakia	Slovak University of Technology in Bratislava	FG5X-247	NO	NO	Juraj Janák, Juraj Papčo
Sweden	Lantmäteriet Gävle	FG5X-233	NO	NO	Andreas Engfeldt, Holger Steffen

* FG5-301 of non NMI/DI took part in the Pilot Study part of the CCM.G-K2.2017

Participants in the relative measurements

Przemysław Dykowski and Marcin Sękowski:
Institute of Geodesy and Cartography, Warszawa, Poland
and
Andreas Reinhold, Jan Müller, Reinhard Falk and Alexander Lothhammer:
Federal Agency of Cartography and Geodesy, Germany.

3. Station description and relative gravity measurements

The comparison was held in the New Gravity Laboratory 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.

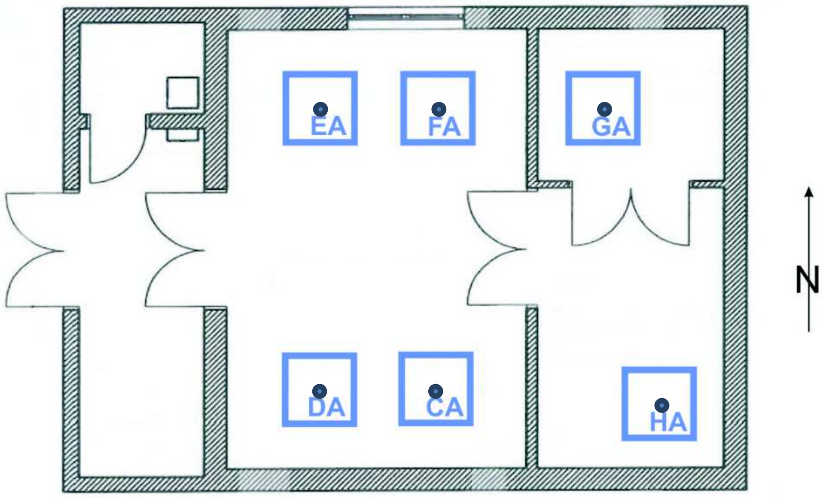

Figure 1. Sketch and Photo of the New Gravity Laboratory at Geodetic Observatory Wettzell on May 15, 2018. The pillar G is occupied by the SG030 and for AG measurements the central room is equipped with 4 pillars. The pillar H was not used during the comparison. The surface centre of each pillar is marked by a small brass benchmark, indicating the position A at each pillar.

To determine Vertical Gravity Gradients (VGGs) measurements were carried out with 3 Scintrex CG-5, 1 CG-6 and 2 LaCoste&Romberg model G gravimeters (with LRFB-300 feedback) at 2 or 3 different vertical levels at each site. The gravity as a function of height above the 4 sites were approximated by a linear function. The corresponding constant values of VGGs (derivatives of linear approximations) including standard uncertainties are shown in Table 2, results of measurements can be found in Annex A.

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

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 10 years of continuous measurements of the superconducting gravimeter GWR SG-029 installed at the Old Gravity Laboratory of GOW, at a distance of about 215 m from the New Gravity Laboratory.

Table 3. Simplified model of tidal parameters for Wettzell derived from 10 years of continuous observation with the superconducting gravimeter SG-029.

Wave	Start freq. /cpd	End freq. /cpd	Amplitude factor	Phase lag /deg
M0+S0	0.000000	0.000010	1.00000	0.00000
SA	0.000011	0.003426	1.16000	0.00000
SSA	0.004709	0.010952	1.16000	0.00000
Mm	0.025812	0.044652	1.16448	-0.22820
Mf	0.060132	0.080797	1.14607	0.54690
Mtm	0.096423	0.249951	1.14570	0.40950
Q1	0.721500	0.906315	1.14617	-0.16000
O1	0.921941	0.940487	1.14852	0.12220
M1	0.958086	0.974188	1.15165	0.20040
P1	0.989049	0.998028	1.14896	0.16850
S1	0.999853	1.000147	1.12175	2.99680
K1	1.001825	1.003651	1.13560	0.22390
Psi1	1.005329	1.005623	1.25164	0.91950
Phi1	1.007595	1.013689	1.16481	-0.18350
J1	1.028550	1.044800	1.15572	0.10940
Oo1	1.064841	1.216397	1.15299	0.17630
2N2	1.719381	1.872142	1.16034	2.14020
N2	1.888387	1.906462	1.17625	1.93910
M2	1.923766	1.942753	1.18426	1.43640
L2	1.958233	1.976926	1.17887	0.84120
S2	1.991787	2.002885	1.18395	0.34170
K2	2.004710	2.182843	1.18466	0.53710
M3	2.753244	3.081254	1.06924	0.39180
M4	3.791964	3.937897	0.25996	48.32660

Gravity variations during the comparison were measured with the superconducting gravimeter SG-030 at pillar G, see Figure 1. As it can be seen from Figure 2, the residual temporal gravity variations reach up to 4 µGal during the period of the comparison. These gravity variations were obtained from the measured SG signal of the lower sensor using the calibration factor of -74.1 µGal/V and including corrections for Earth and ocean tides (Table 3), polar motion, atmospheric effects (admittance factor of -0.3 µGal/hPa) and an instrumental drift of 13.6 µGal/year.

4. Absolute gravity measurements

The 15 AG measurements of the 5 absolute gravimeters participating in EURAMET.M.G-K3 are listed in Table 4. Each gravimeter measured at three different sites. The reported time of the measurement is the average of the times of the 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 for:

- the Earth and ocean tides, referred to the zero-tide system,
- 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).

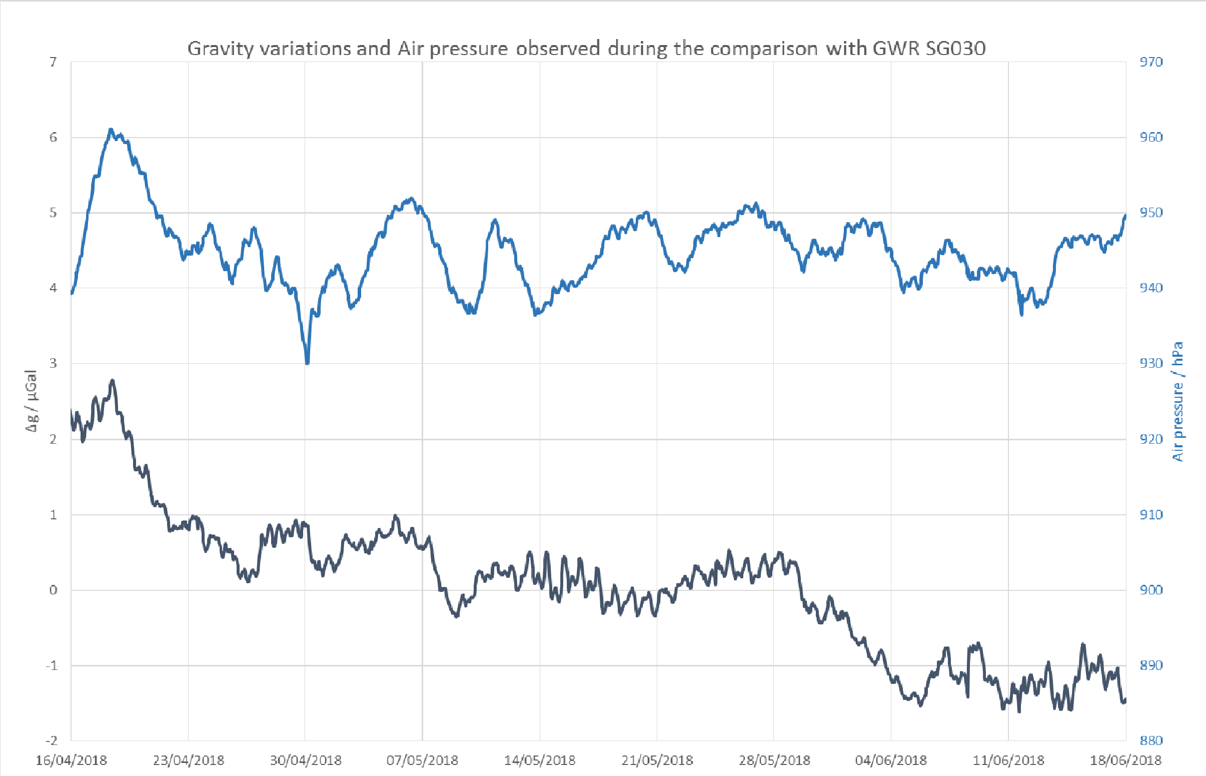

Figure 2. The residual gravity (lower graph) and air pressure (upper graph) variations observed during the comparison with the superconducting gravimeter GWR SG-030 (gravity variations in relation to the value on May 15, 2018 0:00 UT as the mean time of the comparison).

The corrections for tides, polar motion and atmospheric mass redistribution are in compliance with the International Earth Rotation and Reference Systems Service (IERS) conventions 2010 (Petit and Luzum, 2010) and IAGBN (International Absolute Gravity Base-station Network) processing standards (Boedecker, 1988).

The operators were responsible for processing their gravity data. They have submitted the final gravity values and uncertainties for all measured sites. The values g_{raw} were reported at the required measurement height using preliminary VGGs given in the TP. Due to the fact that the final VGGs (constant values for a particular site) have slightly changed, the transfer to the comparison height was performed in two steps:

1) Preliminary gradients were used for transferring reported gravity values to the instrument's reference height (distance between a benchmark and the effective position of free-fall), see Timmen (2003) and Pálinkáš et al. (2012), where the measurand is invariant of the VGG used in the equation of motion.

2) Final gradients (from Table 2) were used for transferring the values from the instrument's reference height to the comparison height of 1.250 m. The height was chosen to minimize the contribution of uncertainty from VGGs to the uncertainty of KCRV.

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 1.250 m together with associated uncertainties u are listed in Table 4.

Table 4. List of the absolute gravity measurements during EURAMET.M.G-K3**.** The constant value 980,836,900.00 µGal is subtracted from all gravity values.
$\boldsymbol{g_{raw}}$: raw gravity data with standard uncertainty $\boldsymbol{u_{raw}}$ declared by the participants, $\boldsymbol{g_{raw}}$ are corrected for all the known geophysical (tides, atmosphere, polar motion and the vertical gravity gradient) as well as instrumental effects (speed-of light correction, laser beam diffraction **DC**, self-attraction **SAC**, etc.), $\boldsymbol{g_{raw}}$ were reported at the desired measurement height **H** above the pillar using gradient $\mathbf{VGG_1}$
$\boldsymbol{dg_{ref}}$: 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 reference height of FG5 and FG5X of 1.22 m or 1.27 m, respectively was used with $\mathbf{VGG_1}$.
g: gravity values transferred to the reference height of the comparison (125 cm) using final gradients $\mathbf{VGG_2}$ and corrected for gravity variations **SGC** based on the record of the superconducting gravimeter.
u: the standard uncertainty of ***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 1.25 m, and 0.2 µGal due to SG based corrections (SGC).

Gravimeter	Site	Average Time	#Drops	H /cm	VGG_1 /µGal·m^{-1}	SAC /µGal	DC /µGal	g_{raw} /µGal	u_{raw} /µGal	VGG_2 /µGal·m^{-1}	dg_{ref} /µGal	SGC /µGal	g /µGal	u /µGal
FG5-215H	CA	23/04/2018 23:32	2250	122.29	-330.0	-1.73	2.1	60.04	2.13	-328.7	-8.91	-0.61	50.52	2.14
FG5-215H	DA	24/04/2018 21:21	2000	122.59	-330.0	-1.73	2.1	49.10	2.13	-330.1	-7.96	-0.52	40.62	2.14
FG5-215H	EA	25/04/2018 20:04	2200	122.42	-320.0	-1.73	2.1	57.69	2.13	-319.5	-8.24	-0.31	49.14	2.14
FG5-242	DA	11/06/2018 23:44	2875	121.00	-330.0	-1.5	1.4	51.8	2.7	-330.1	-13.20	1.39	39.99	2.71
FG5-242	EA	12/06/2018 18:42	3586	121.00	-320.0	-1.5	1.4	59.5	2.4	-319.5	-12.78	1.39	48.11	2.41
FG5-242	FA	13/06/2018 22:34	2994	121.00	-320.0	-1.5	1.4	70.6	2.5	-319.9	-12.80	1.63	59.43	2.51
FG5X-221	DA	23/04/2018 20:25	2148	126.40	-330.0	-1.2	1.4	38.2	2.3	-330.1	4.62	-0.68	42.14	2.31
FG5X-221	EA	24/04/2018 20:08	2249	126.50	-320.0	-1.2	1.4	46.1	2.3	-319.5	4.79	-0.53	50.36	2.31
FG5X-221	FA	25/04/2018 19:59	2175	126.50	-320.0	-1.2	1.4	57.3	2.3	-319.9	4.80	-0.31	61.79	2.31
FG5X-254	FA	02/05/2018 18:36	2189	127.70	-320.0	-1.4	1.6	49.79	2.25	-319.9	8.64	-0.51	57.92	2.26
FG5X-254	DA	04/05/2018 19:29	2098	127.75	-330.0	-1.4	1.6	30.50	2.23	-330.1	9.08	-0.65	38.93	2.24
FG5X-254	CA	05/05/2018 08:34	598	127.75	-330.0	-1.4	1.6	43.19	2.38	-328.7	9.04	-0.89	51.34	2.39
IMGC-02	FA	11/06/2018 23:08	471	47.43	-320.0	0.7	4.43	299.6	5.0	-319.9	-248.15	1.40	52.85	5.29
IMGC-02	CA	12/06/2018 17:51	537	47.77	-330.0	0.7	4.43	310.2	5.0	-328.7	-253.86	1.39	57.73	5.58
IMGC-02	DA	13/06/2018 22:35	553	47.73	-330.0	0.7	4.43	294.2	5.0	-330.1	-255.07	1.63	40.76	5.51

Remark to FG5-215H: "H" is related to the modified measurement and evaluation system of the FG5-215 gravimeter that was applied also in CCM.G-K2.2017. During the comparison, the new system provided lower gravity value (by -1.7 µGal in average) than the original system. Further, following additional corrections were included into the measurements: verticality correction of +0.10 µGal, Coriolis correction of +0.50 µGal and cable length correction of -0.15 µGal.

Remark to IMGC-02: Additionally a verticality correction of +0.66 µGal was included into the measurements.

5. Measurement strategy

According to the TP, four sites were used during the comparison organized in five sessions. The first one took place from 16th to 19th of April 2018. The last session was from 11th to 16th of June 2018. Each gravimeter was planned to measure at three sites.

Table 5. Occupation of individual sites by gravimeters.

	Site				
Gravimeter	CA	DA	EA	FA	TOTAL
FG5-215H	x	x	x		3
FG5X-221		x	x	x	3
FG5-242		x	x	x	3
FG5X-254	x	x		x	3
IMGC-02	x	x		x	3
Number of KC gravimeters	3	5	3	4	
A10-020	x		x	x	3
FG5-101	x		x	x	3
FG5-202	x	x	x		3
FG5-206	x	x		x	3
FG5-218	x	x	x		3
FG5-234	x	x		x	3
FG5-238		x	x	x	3
FG5-301		x	x	x	3
FG5X-220	x		x	x	3
FG5X-233	x		x	x	3
FG5X-247	x	x		x	3
Number of gravimeters occupying each site	12	12	11	13	

However, due to the fact that registration for the comparison was extended into the period of the comparison, the final measurement schedule could not be perfectly tuned. Thus, at least 3 KC gravimeter and at least 11 gravimeters occupied each site. The first quantity is important with respect to the definition of KCRV (in sense of absolute gravity values) and the second quantity is important to strengthen the determination of gravity differences between the KCRVs.

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 may be described by the observation equation

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

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

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

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

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

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 (Jiang et al. 2013).

Due to the fact that only NMI and DI gravimeters (NMI/DIs) should contribute to the definition of KCRV, non-NMI/DI gravimeters cannot be included into the constraint nor to the determination of the linking converter *d*. Therefore, weights for non-NMI/DI gravimeters are all set to zero in equation (2). By this simple mathematical operation, the non-NMI/DI gravimeters are contributing only with gravity differences, according to the links between the sites.

The linking converter was computed as weighted mean of *DoE* determined at the CCM.G-K2.2017 (Wu et. al, 2020), see Table 6. The *DoE* of four linking gravimeters operated by NMI/DI have been used for this purpose.

Table 6. Determination of the linking converter as weighted mean of *DoE* determined at the CCM.G-K2.2017 (Wu et. al, 2020) of joint participants of the CCM.G-K2.2017 and EURAMET.M.G-K3.

Gravimeter	*DoE* /µGal	*U* (*k* = 2) /µGal
FG5-215H	-1.0	4.5
FG5-242	-0.1	6.9
FG5X-221	0.9	4.7
FG5X-254	-2.7	4.9
linking converter d =	-0.78	2.52

7. Results

7.1 The initial approach

For the initial solution of the key comparison, all the measurements presented by the operators (Table 4 and Table B1) were included in a least-squares adjustment. The reference values (RVs) and the biases (δ) are presented in Tables 7 and 8. This initial solution was computed based on Pálinkáš et.al. (2017), using the weighted constraint (Eq. 2) where the weights were computed as the normalized root mean square of the uncertainties (*u*) given in Table 4. Thus the values 0.292 for FG5-215H, 0.206 for FG5-242, 0.250 for FG5X-221, 0.253 for FG5X-254 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 (IMGC-02) and of the non NMI/DI gravimeters of the Additional Comparison (AC) have been set to zero in eq. (2).

In Pálinkáš et al. 2017 it has been shown that uncertainties of AC gravimeters should be harmonized, since their uncertainty estimates are sometimes underestimated. Such a harmonization should ensure more realistic weighting of the g-values in eq. (1). Declared uncertainties of AC FG5/X gravimeters lower than the best uncertainty declared for the KC FG5/X gravimeters (2.13 µGal) were set to this value. In case of the A10 participating in the AC, the uncertainty was changed to 12 µGal.

No alternative solutions are presented, because, in previous reports, e.g. Pálinkáš et.al. (2017), it has been demonstrated that gravity differences determined using the non-NMI/DI meters are necessary to achieve a stable and precise solution for the CRV and that the weighted constraint represents the most appropriate way to reflect the contribution of the KC meters to the comparison reference level.

In the specific configuration of this comparison, test computations have not shown a significant difference of the variants.

Table 7. Reference Values (RVs) of the comparison using all the reported absolute measurements, reference height is 1.250 m. Results are linked by 4 instruments from NMI/DI to CCM.G-K2.2017 by means of linking converter (Table 6). The constant value 980,836,900.0 µGal is subtracted from the RVs, σ is the standard deviation of RVs from the adjustment.

Site	RV /µGal	σ /µGal
CA	52.80	0.44
DA	41.34	0.39
EA	49.60	0.43
FA	59.93	0.43

Table 8. Biases δ of gravimeters at the key comparison

Gravimeter	δ /µGal	σ /µGal
FG5-215H	-1.15	0.48
FG5-242	-1.11	0.59
FG5X-221	1.14	0.52
FG5X-254	-1.98	0.53
IMGC-02	-1.12	1.44

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 difference of the measured gravity value (g_{ij}) and the RV (g_j) at a site and its uncertainty

$$E_n = \frac{(g_{ij} - g_j)}{\sqrt{u^2(g_{ij}) + \sigma^2(g_j) + u^2(d)}} \quad . \qquad (3)$$

where

$u(g_{i,j})$ ... uncertainty of the g-values at the comparison height of 1.250 m,
$\sigma(g_j)$ ... standard deviation of the RV at the site j obtained from the least-squares adjustment,
u_d ... uncertainty of the linking converter.

An absolute value of E_n larger than 2 indicates that the measured gravity value is incompatible at a 95% confidence level, as the difference is not covered by the uncertainties. The compatibility index is given in Table 9.

Table 9. Consistency check: Comparison of measured gravity values g_{ij} (along with 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
FG5-215H	CA	50.52	2.14	52.80	0.44	-2.28	-0.90	
FG5-215H	DA	40.62	2.14	41.34	0.39	-0.71	-0.28	
FG5-215H	EA	49.14	2.14	49.60	0.43	-0.47	-0.18	0.98
FG5-242	DA	39.99	2.71	41.34	0.39	-1.35	-0.45	
FG5-242	EA	48.11	2.41	49.60	0.43	-1.49	-0.54	
FG5-242	FA	59.43	2.51	59.93	0.43	-0.50	-0.17	0.54
FG5X-221	DA	42.14	2.31	41.34	0.39	0.80	0.30	
FG5X-221	EA	50.36	2.31	49.60	0.43	0.76	0.29	
FG5X-221	FA	61.79	2.31	59.93	0.43	1.86	0.70	0.62
FG5X-254	FA	57.92	2.26	59.93	0.43	-2.01	-0.77	
FG5X-254	DA	38.93	2.24	41.34	0.39	-2.41	-0.93	
FG5X-254	CA	51.34	2.39	52.80	0.44	-1.46	-0.53	0.48
IMGC-02	FA	52.85	5.29	59.93	0.43	-7.08	-1.30	
IMGC-02	CA	57.73	5.58	52.80	0.44	4.94	0.86	
IMGC-02	DA	40.76	5.52	41.34	0.39	-0.58	-0.10	6.01

The compatibility index of all measurements of EURAMET.M.G-K3 is below 2, indicating consistency with the declared uncertainties. Four observations within the Additional Comparison (AC) turned out to be incompatible at the 95% confidence level (cf. Table B2), but have not been removed from the final solution, as they showed stable deviations, not affecting the gravity differences.

7.3 Final solution

Due to the fact that all measurements are consistent with the declared uncertainties, no measurements were excluded for the final solution. This means that the CRV of the initial solution (Table 7) is equivalent to the KCRV (Table 10), similarly to the *DoE* presented below which are practically equivalent with biases.

The official *DoE* (cf. Table 12 and Figure 3) were computed according to Jiang et al. (2012) using the formula

$$D_i = \left[\sum w_{ij}\left(g_{ij} - g_j\right)\right] \;/\; \sum w_{ij}. \qquad (4)$$

as the weighted average difference between the measurements of a gravimeter *i* and the KCRV at site *j*. The differences between measurement and the KCRV are calculated for each gravimeter at each occupied site, see Table 11. The associated uncertainties ($U_{Di.j}$) are computed by summing up the variances of all constituents. The *DoE* are then obtained by averaging these differences (according to Eq. 4 with weights proportional to $U_{Di.j}$) and its final uncertainty (Table 12) is associated with the smallest achieved $U_{Di.j}$ (Table 11) for the particular gravimeter and labeled by U_{DoE} (Table 12).

This solution has been chosen to avoid

1) the *DoE* uncertainty of a gravimeter (U_{Di} in Table 11) converging towards zero with increasing numbers of measurements as discussed in Francis et al. (2015),

2) inconsistencies in the usual approach when *DoE* is associated with RMS of $U_{Di.j}$ that allows for associating the average *DoE* to an higher uncertainty estimate than for a single measurement of a particular gravimeter.

Table 10. Key Comparison Reference Values (KCRV) linked to the CCM.G.K-2.2017 using linking converter of (-0.78 ± 1.26) µGal related to 4 NMI/DI gravimeters. The constant value 980,836,900.0 µGal was subtracted from the KCRV. *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 1.250 m. The KCRV refer to May 15, 2018 0:00 UT as the mean time of the comparison.

OFFICIAL RESULTS EURAMET.M.G-K3 KEY COMPARISON			
Site	KCRV /µGal	σ /µGal	U (k = 2) /µGal
CA	52.8	0.4	2.7
DA	41.3	0.4	2.6
EA	49.6	0.4	2.7
FA	59.9	0.4	2.7

Table 11. *DoE* of NMI/DIs determined according to Eq. 4.

g_{ij} are the measured gravity values transferred to 1.250 m with expanded uncertainty U_{ij}.

g_j are the KCRVs with associated expanded (k = 2) uncertainties U_j.

U_{Dij} is the expanded uncertainty of differences g_{ij}-g_j.

D_i is the final *DoE* computed according to Eq. 4 along with the expanded uncertainty U_{Di} (computed from U_{Dij} values, assuming statistical independence of D_{ij} values).

The constant value 980,836,900.0 µGal was subtracted from the gravity values.

Gravimeter i	Site j	g_{ij} /µGal	U_{ij} /µGal	g_j /µGal	U_j /µGal	D_{ij}=g_{ij}-g_j /µGal	U_{Dij} /µGal	D_i /µGal	U_{Di} /µGal
FG5-215H	CA	50.52	4.28	52.80	2.67	-2.28	5.05		
FG5-215H	DA	40.62	4.28	41.34	2.64	-0.71	5.03		
FG5-215H	EA	49.14	4.28	49.60	2.67	-0.47	5.04	-1.15	2.91
FG5-242	DA	39.99	5.42	41.34	2.64	-1.35	6.03		
FG5-242	EA	48.11	4.82	49.60	2.67	-1.49	5.51		
FG5-242	FA	59.43	5.02	59.93	2.66	-0.50	5.68	-1.11	3.31
FG5X-221	DA	42.14	4.62	41.34	2.64	0.80	5.32		
FG5X-221	EA	50.36	4.62	49.60	2.67	0.76	5.33		
FG5X-221	FA	61.79	4.62	59.93	2.66	1.86	5.33	1.14	3.08
FG5X-254	FA	57.92	4.52	59.93	2.66	-2.01	5.25		
FG5X-254	DA	38.93	4.48	41.34	2.64	-2.41	5.20		
FG5X-254	CA	51.34	4.78	52.80	2.67	-1.46	5.48	-1.98	3.06
IMGC-02	FA	52.85	10.57	59.93	2.66	-7.08	10.90		
IMGC-02	CA	57.73	11.16	52.80	2.67	4.94	11.48		
IMGC-02	DA	40.76	11.03	41.34	2.64	-0.58	11.34	-1.12	6.49

The final *DoE* with uncertainty at the 95% confidence level is presented in Table 12 and Figure 3. All the gravimeters participating at EURAMET.M.G-K3 Key Comparison are in equivalence.

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

Table 12. Degrees of Equivalence (*DoE* according to Eq. 4) of the NMI/DI gravimeters participating in the KC. The uncertainty U_{DoE} is the minimum uncertainty U_{Dij} of the 3 differences from Table 11. It represents the expanded uncertainty at 95% confidence.

OFFICIAL RESULTS EURAMET.M.G-K3 KEY COMPARISON		
Gravimeter	Degree of Equivalence	
	DoE /µGal	U_{DoE} (k = 2) /µGal
FG5-215H	-1.2	5.0
FG5-242	-1.1	5.5
FG5X-221	1.1	5.3
FG5X-254	-2.0	5.2
IMGC-02	-1.1	10.9

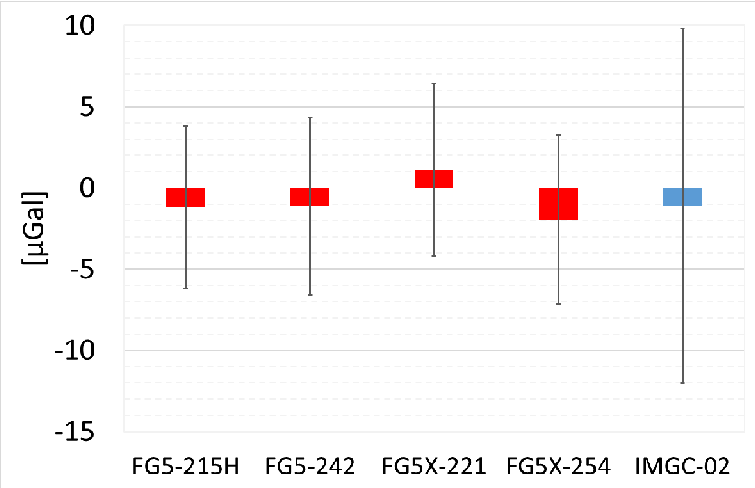

Figure 3. Degrees of Equivalence (*DoE*) of the NMI/DI gravimeters participating in the KC calculated from the difference between the gravimeter measurements and the KCRV for the correspondent pillar. The error bars represent the expanded uncertainties (U_{DoE}) of the *DoE* at 95% confidence.

8. Conclusions

Sixteen gravimeters were compared within the framework of the regional EURAMET.M.G-K3 key comparison and Additional Comparison. Five gravimeters were operated by different NMIs and DIs, these instruments participated at the EURAMET.M.G-K3 key comparison. Four of them were used to link the regional comparison to the CCM.G.K2.2017 by means of the linking converter computed as weighted average of *DoE* as documented in Wu et al. (2020) for those gravimeters.

Non-NMI/DI gravimeters participating in the Additional Comparison did not contribute to the definition of KCRV. Nevertheless, their observations were used 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 KCRV. The final *DoE* were estimated by the weighted mean of the differences between the observations at reference height and the KCRV. In case of KC gravimeters, the weights used in the adjustment and in the estimation of the *DoE* were computed from: 1) uncertainties provided by the operators, 2) the contribution of the VGG to the transfer to the comparison reference height of 1.250 m, and 3) the uncertainty of the linking converter.

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

In conclusion, the *DoE* of the 5 KC gravimeters are within the range of -2.0 and +1.1 μGal. For the gravimeters participating in the Additional Comparison (elaborated in Annex B), the *DoE* are between -8.9 μGal and +2.6 μGal.

All the gravimeters participating in EURAMET.M.G-K3 Key Comparison are in equivalence. By comparing Tables 6 and 12, the long-term stability of the 4 instruments participating in both key comparisons is demonstrated (Figure4).

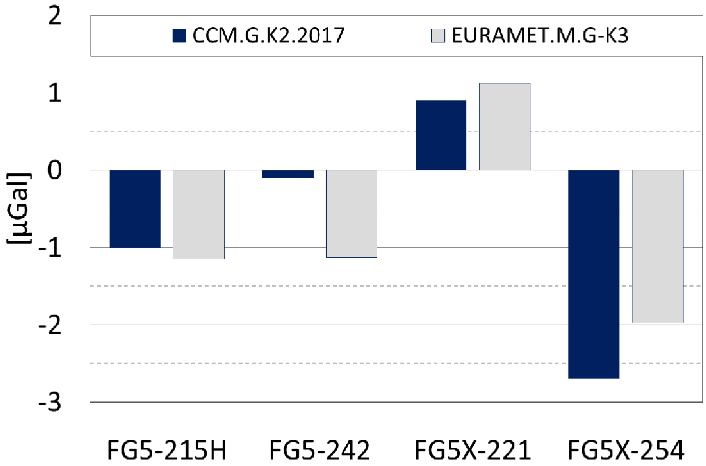

Figure 4. Joint presentation of the Degrees of equivalence of CCM.G.K2.2017 and EURAMET.M.G-K3

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Annex A: Gravity as a function of height (vertical gravity gradients)

To determine Vertical Gravity Gradients (VGGs) measurements were carried out with 3 Scintrex CG-5, 1 SCINTREX CG-6 and 2 LaCoste&Romberg model G gravimeters (with LRFB-300 feedback) at 2 or 3 different vertical levels above the sites, not only during the period of the comparison, but also over the last 8 years.

All relative measurements were organized in such a way that in the upper position the sensor of the relative gravimeter was preferably positioned exactly to the reference height of 1.250 m above the marker. Such a line-up was chosen to optimize the transfer of the AG measurements to the reference height. The lower positions varied depending on the kind of instrument, used tripods and also on the specific purpose of the particular campaign.

All gravity differences measured above the same pillar are referred to the reference height of 1.250 m. The VGG was obtained from these differences by a weighted least-squares adjustment, forcing the gravity value to zero at the reference height (cf. Figure A1).

The gravity as a function of height above the 4 sites was approximated by a linear function. The corresponding constant values (VGGs as derivatives of linear functions) including standard uncertainties are shown in Table 2. Second order approximations of the gravity as a function of height could not improve the accuracy of the transfer corrections.

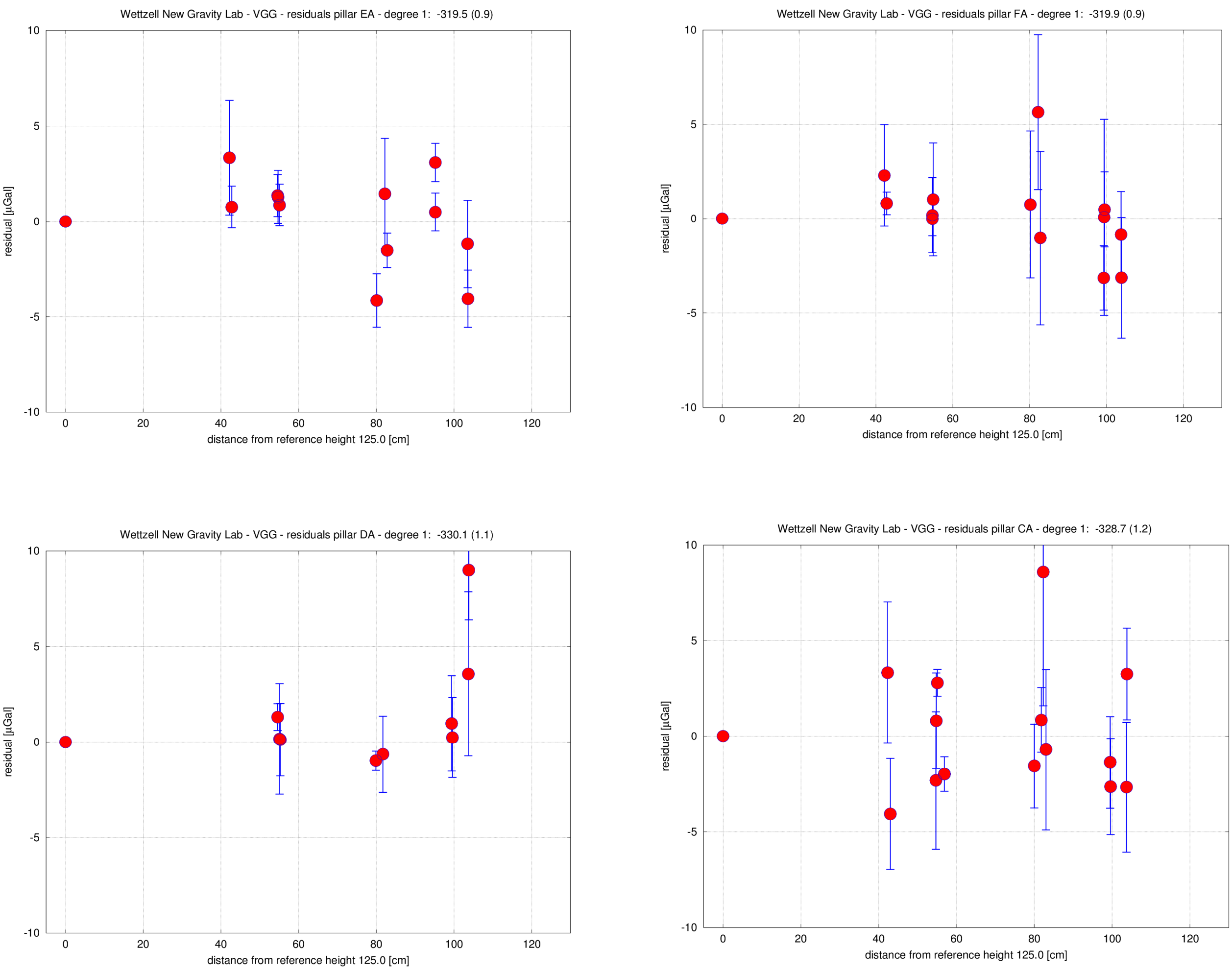

Figure A1. Results of relative gravity measurements to determine the gravity as a function of height (and consequently vertical gravity gradients) at the 4 comparison sites. Residuals of gravity differences (from measurement at the reference height of 1.250 m) are shown.

Annex B: Additional comparison

The aim of the Additional comparison was to link the European absolute gravimeters not belonging to NMI/DI to the result of the CCM.G-K2.2017 Key Comparison through the KCRV determined at EURAMET.M.G-K3 key comparison. No new adjustment has been performed. The results presented below originating from the adjustment described in section 7. KCRVs from Table 10 have been used to calculate *DoE* from the eq. (4).

Table B1. List of all the absolute gravity measurements (NMI/DIs are in yellow field, already shown as Table 4). The constant value 980,836,900.0 µGal is subtracted.

$\boldsymbol{g_{raw}}$: raw gravity data with standard uncertainty $\boldsymbol{u_{raw}}$ declared by the participants, $\boldsymbol{g_{raw}}$ are corrected for all the known geophysical (tides, atmospheric pressure and polar motion effects, gravity as a function of height (here denoted as vertical gravity gradient) and instrumental effects (speed-of light correction, laser beam diffraction **DC**, self-attraction **SAC**, etc.), $\boldsymbol{g_{raw}}$ were reported at the desired measurement height **H** above the pillar using gradient $\mathbf{VGG_1}$
$\boldsymbol{dg_{ref}}$: gravity difference between reported height of raw gravity data and 1.250 m. * The reported measurement height slightly doesn't corresponds with the reference instrumental height. To compute the transfer correction $\boldsymbol{dg_{ref}}$, we have used a reference height of FG5 and FG5X of 1.22 m and 1.27 m, respectively and also $\mathbf{VGG_1}$ for FG5-202, FG5-206, FG5-218 and FG5X-233.
g: gravity values transferred to the reference height of the comparison (1.250 m) using final gradients VGG_2 and corrected for gravity variations SGC based on measurement of superconducting gravimeter.
u: the standard uncertainty of g computed as root mean square of three components: u_{raw} , the transfer error to the reference height of the comparison and 0.2 µGal due to SG based corrections (SGC).
$\boldsymbol{u_{har}}$: harmonized standard uncertainties (see Section 7.1), computed as u but the contribution from u_{raw} of non NMI/DIs which are below 2.13 µGal were changed to 2.13 µGal. The uncertainty of the participating A10 gravimeter was harmonized to 12 µGal due to the instrument producer brochure (Microg LaCoste 2019) and the transfer to 1.250 m.

Gravi-meter	Site	Average Time	#Drops	H /cm	VGG_1 /µGal·m^{-1}	SAC /µGal	DC /µGal	g_{raw} /µGal	u_{raw} /µGal	VGG_2 /µGal·m^{-1}	dg_{ref} /µGal	SGC /µGal	g /µGal	u /µGal	u_{har} /µGal
FG5-215H	CA	23/04/2018 23:32	2250	122.29	-330.0	-1.73	2.1	60.04	2.13	-328.7	-8.91	-0.61	50.52	2.14	2.14
FG5-215H	DA	24/04/2018 21:21	2000	122.59	-330.0	-1.73	2.1	49.10	2.13	-330.1	-7.96	-0.52	40.62	2.14	2.14
FG5-215H	EA	25/04/2018 20:04	2200	122.42	-320.0	-1.73	2.1	57.69	2.13	-319.5	-8.24	-0.31	49.14	2.14	2.14
FG5-242	DA	11/06/2018 23:44	2875	121.00	-330.0	-1.5	1.4	51.8	2.7	-330.1	-13.20	1.39	39.99	2.71	2.71
FG5-242	EA	12/06/2018 18:42	3586	121.00	-320.0	-1.5	1.4	59.5	2.4	-319.5	-12.78	1.39	48.11	2.41	2.41
FG5-242	FA	13/06/2018 22:34	2994	121.00	-320.0	-1.5	1.4	70.6	2.5	-319.9	-12.80	1.63	59.43	2.51	2.51
FG5X-221	DA	23/04/2018 20:25	2148	126.40	-330.0	-1.2	1.4	38.2	2.3	-330.1	4.62	-0.68	42.14	2.31	2.31
FG5X-221	EA	24/04/2018 20:08	2249	126.50	-320.0	-1.2	1.4	46.1	2.3	-319.5	4.79	-0.53	50.36	2.31	2.31
FG5X-221	FA	25/04/2018 19:59	2175	126.50	-320.0	-1.2	1.4	57.3	2.3	-319.9	4.80	-0.31	61.79	2.31	2.31
FG5X-254	FA	02/05/2018 18:36	2189	127.70	-320.0	-1.4	1.6	49.79	2.25	-319.9	8.64	-0.51	57.92	2.26	2.26
FG5X-254	DA	04/05/2018 19:29	2098	127.75	-330.0	-1.4	1.6	30.50	2.23	-330.1	9.08	-0.65	38.93	2.24	2.24
FG5X-254	CA	05/05/2018 08:34	598	127.75	-330.0	-1.4	1.6	43.19	2.38	-328.7	9.04	-0.89	51.34	2.39	2.39
IMGC-02	FA	11/06/2018 23:08	471	47.43	-320.0	0.7	4.43	299.6	5.0	-319.9	-248.15	1.40	52.85	5.29	5.29
IMGC-02	CA	12/06/2018 17:51	537	47.77	-330.0	0.7	4.43	310.2	5.0	-328.7	-253.86	1.39	57.73	5.58	5.58
IMGC-02	DA	13/06/2018 22:35	553	47.73	-330.0	0.7	4.43	294.2	5.0	-330.1	-255.07	1.63	40.76	5.51	5.51

FG5-101	FA	12/06/2018 23:22	1500	123.00	-320.0	-1.43	2.00	61.3	3.0	-319.9	-6.40	1.35	56.25	3.01	3.01
FG5-101	CA	13/06/2018 23:10	1400	123.00	-330.0	-1.43	2.00	56.2	3.0	-328.7	-6.57	1.63	51.26	3.01	3.01
FG5-101	EA	14/06/2018 20:53	1500	123.00	-320.0	-1.43	2.00	51.7	3.0	-319.5	-6.39	1.49	46.80	3.01	3.01
FG5-202	CA	02/05/2018 18:17	2254	125.00*	-330.0	-1.70	2.10	56.8	2.1	-328.7	-9.86	-0.51	56.33	2.11	2.14
FG5-202	DA	03/05/2018 19:27	2112	125.00*	-330.0	-1.70	2.10	43.7	2.1	-330.1	-9.90	-0.50	43.20	2.11	2.14
FG5-202	EA	04/05/2018 18:17	2059	125.00*	-320.0	-1.70	2.10	52.6	2.1	-319.5	-9.59	-0.65	51.97	2.11	2.14
FG5-206	FA	14/05/2018 22:34	1376	125.00*	-320.0	n.a.	n.a.	56.8	2.4	-319.9	-9.60	0.00	56.80	2.41	2.41
FG5-206	CA	15/05/2018 13:59	680	125.00*	-330.0	n.a.	n.a.	48.2	2.4	-328.7	-9.86	-0.23	48.01	2.41	2.41
FG5-206	DA	16/05/2018 21:08	1859	125.00*	-330.0	n.a.	n.a.	36.9	2.4	-330.1	-9.90	0.04	36.94	2.41	2.41
FG5-218	CA	14/05/2018 21:00	2400	100.00*	-330.0	-1.36	1.20	127.71	2.0	-328.7	-9.86	-0.04	45.21	2.01	2.14
FG5-218	DA	15/05/2018 21:00	2400	100.00*	-330.0	-1.36	1.20	119.10	2.0	-330.1	-9.90	-0.08	36.52	2.01	2.14
FG5-218	EA	16/05/2018 21:00	2520	100.00*	-320.0	-1.36	1.20	124.16	2.0	-319.5	-9.59	0.02	44.19	2.01	2.14
FG5-234	CA	24/04/2018 23:19	2600	121.14	-330.0	-1.50	1.00	65.59	1.90	-328.7	-12.69	-0.49	52.41	1.91	2.14
FG5-234	DA	25/04/2018 19:04	1800	121.27	-330.0	-1.50	1.00	54.05	1.90	-330.1	-12.31	-0.18	41.56	1.91	2.14
FG5-234	FA	26/04/2018 13:20	2100	121.24	-320.0	-1.50	1.00	71.82	1.89	-319.9	-12.03	-0.06	59.73	1.90	2.14
FG5-238	DA	14/05/2018 19:26	2000	121.60	-330.0	-1.50	1.20	52.1	3.3	-330.1	-11.22	-0.02	40.86	3.31	3.31
FG5-238	EA	15/05/2018 22:23	1800	122.10	-320.0	-1.50	1.20	59.2	3.2	-319.5	-9.27	-0.06	49.87	3.21	3.21
FG5-238	FA	16/05/2018 23:54	1600	121.50	-320.0	-1.50	1.20	70.9	3.3	-319.9	-11.20	0.06	59.76	3.31	3.31
FG5-301	DA	16/04/2018 23:19	1300	122.00	-330.0	-1.43	1.10	53.8	3.1	-330.1	-9.90	-2.06	41.84	3.11	3.11
FG5-301	EA	17/04/2018 22:26	1600	122.00	-320.0	-1.43	1.10	61.7	3.1	-319.5	-9.59	-2.32	49.80	3.11	3.11
FG5-301	FA	18/04/2018 22:58	1600	122.00	-320.0	-1.43	1.10	73.1	3.1	-319.9	-9.60	-2.22	61.28	3.11	3.11
FG5X-220	EA	23/04/2018 22:06	1673	125.00	-320.0	-1.20	1.10	49.52	2.45	-319.5	0.00	-0.64	48.88	2.46	2.46
FG5X-220	FA	24/04/2018 20:12	2140	125.00	-320.0	-1.20	1.10	58.33	2.45	-319.9	0.00	-0.53	57.80	2.46	2.46
FG5X-220	CA	25/04/2018 19:58	1899	125.00	-330.0	-1.20	1.10	51.48	2.45	-328.7	0.00	-0.31	51.17	2.46	2.46
FG5X-233	EA	16/04/2018 21:57	1200	120.00*	-320.0	-1.50	1.00	62.65	2.4	-319.5	6.39	-2.05	44.59	2.41	2.41
FG5X-233	FA	17/04/2018 19:09	1400	120.00*	-320.0	-1.50	1.00	74.17	2.4	-319.9	6.40	-2.33	55.84	2.41	2.41
FG5X-233	CA	18/04/2018 19:34	1350	120.00*	-330.0	-1.50	1.00	68.48	2.4	-328.7	6.57	-2.35	49.60	2.41	2.41
FG5X-247	CA	17/04/2018 22:04	3300	125.00	-330.0	n.a.	n.a.	54.05	2.65	-328.7	0.00	-2.32	51.73	2.66	2.66
FG5X-247	DA	18/04/2018 22:04	3300	125.00	-330.0	n.a.	n.a.	42.36	2.00	-330.1	0.00	-2.25	40.11	2.01	2.14
FG5X-247	FA	16/04/2018 22:04	3300	125.00	-320.0	n.a.	n.a.	60.43	2.51	-319.9	0.00	-2.04	58.39	2.52	2.52
A10-020	CA	16/05/2018 19:29	7200	67.83	-330.0	-0.60	1.20	231.6	4.7	-328.7	-187.92	-0.01	43.67	5.05	12.14
A10-020	EA	14/05/2018 19:19	7680	67.83	-320.0	-0.60	1.20	219.9	4.6	-319.5	-182.66	-0.08	37.16	4.79	12.07
A10-020	FA	15/05/2018 20:15	7680	67.83	-320.0	-0.60	1.20	237.8	4.7	-319.9	-182.89	-0.11	54.80	4.87	12.07

Table B2. Consistency check: Comparison of measured gravity values g_{ij} (along with uncertainties u_{ij}) with reference values g_j (along with standard deviations σ_{gj}) by means of compatibility index E_n (see eq. 3 in section 7.2). 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	$u(g_{i,j})$ /µGal	g_j /µGal	$\sigma(g_j)$ /µGal	$g_{i,j}$ - g_j /µGal	E_n	σ_{rep} /µGal
FG5-215H	CA	50.52	2.14	52.80	0.44	-2.28	-0.90	
FG5-215H	DA	40.62	2.14	41.34	0.39	-0.71	-0.28	
FG5-215H	EA	49.14	2.14	49.60	0.43	-0.47	-0.18	0.98
FG5-242	DA	39.99	2.71	41.34	0.39	-1.35	-0.45	
FG5-242	EA	48.11	2.41	49.60	0.43	-1.49	-0.54	
FG5-242	FA	59.43	2.51	59.93	0.43	-0.50	-0.17	0.54
FG5X-221	DA	42.14	2.31	41.34	0.39	0.80	0.30	
FG5X-221	EA	50.36	2.31	49.60	0.43	0.76	0.29	
FG5X-221	FA	61.79	2.31	59.93	0.43	1.86	0.70	0.62
FG5X-254	FA	57.92	2.26	59.93	0.43	-2.01	-0.77	
FG5X-254	DA	38.93	2.24	41.34	0.39	-2.41	-0.93	
FG5X-254	CA	51.34	2.39	52.80	0.44	-1.46	-0.53	0.48
IMGC-02	FA	52.85	5.29	59.93	0.43	-7.08	-1.30	
IMGC-02	CA	57.73	5.58	52.80	0.44	4.94	0.86	
IMGC-02	DA	40.76	5.52	41.34	0.39	-0.58	-0.10	6.01
FG5-101	FA	56.25	3.01	59.93	0.43	-3.68	-1.12	
FG5-101	CA	51.26	3.01	52.80	0.44	-1.54	-0.47	
FG5-101	EA	46.80	3.01	49.60	0.43	-2.80	-0.85	1.07
FG5-202	CA	56.33	2.11	52.80	0.44	3.53	1.41	
FG5-202	DA	43.20	2.11	41.34	0.39	1.86	0.75	
FG5-202	EA	51.97	2.11	49.60	0.43	2.36	0.95	0.86
FG5-206	FA	56.80	2.41	59.93	0.43	-3.13	-1.14	
FG5-206	CA	48.01	2.41	52.80	0.44	-4.79	-1.74	
FG5-206	DA	36.94	2.41	41.31	0.39	-4.40	-1.60	0.87
FG5-218	CA	45.21	2.01	52.80	0.44	-7.59	-3.14	
FG5-218	DA	36.52	2.01	41.34	0.39	-4.82	-2.00	
FG5-218	EA	44.19	2.01	49.60	0.43	-5.41	-2.24	1.46
FG5-234	CA	52.41	1.91	52.80	0.44	-0.39	-0.17	
FG5-234	DA	41.56	1.91	41.34	0.39	0.22	0.09	
FG5-234	FA	59.73	1.90	59.93	0.43	-0.20	-0.09	0.31
FG5-238	DA	40.86	3.31	41.34	0.39	-0.48	-0.14	
FG5-238	EA	49.87	3.21	49.60	0.43	0.27	0.08	
FG5-238	FA	59.76	3.31	59.93	0.43	-0.17	-0.05	0.38
FG5-301	DA	41.84	3.11	41.34	0.39	0.50	0.15	
FG5-301	EA	49.80	3.11	49.60	0.43	0.19	0.06	
FG5-301	FA	61.28	3.11	59.93	0.43	1.35	0.40	0.60
FG5X-220	EA	48.88	2.46	49.60	0.43	-0.72	-0.26	
FG5X-220	FA	57.80	2.46	59.93	0.43	-2.13	-0.76	
FG5X-220	CA	51.17	2.46	52.80	0.44	-1.63	-0.58	0.71
FG5X-233	EA	44.59	2.41	49.60	0.43	-5.01	-1.82	
FG5X-233	FA	55.84	2.41	59.93	0.43	-4.09	-1.49	
FG5X-233	CA	49.60	2.41	52.80	0.44	-3.19	-1.16	0.91
FG5X-247	CA	51.73	2.66	52.80	0.44	-1.07	-0.36	
FG5X-247	DA	40.11	2.01	41.34	0.39	-1.23	-0.51	
FG5X-247	FA	58.39	2.52	59.93	0.43	-1.54	-0.54	0.24

A10-020	CA	43.67	5.05	52.80	0.44	-9.13	-1.75	
A10-020	EA	37.16	4.79	49.60	0.43	-12.44	-2.50	
A10-020	FA	54.80	4.87	59.93	0.43	-5.13	-1.02	3.66

Table B3. Biases of NMI/DIs (yellow marked) and non-NMI DIs related to the approach and used weights.

Gravimeter	δ /µGal	σ /µGal
FG5-215H	-1.15	0.48
FG5-242	-1.11	0.59
FG5X-221	1.14	0.52
FG5X-254	-1.98	0.53
IMGC-02	-1.12	1.44
FG5-101	-2.67	0.84
FG5-202	2.58	0.64
FG5-206	-4.11	0.70
FG5-218	-5.94	0.64
FG5-234	-0.12	0.64
FG5-238	-0.12	0.90
FG5-301	0.68	0.86
FG5X-220	-1.49	0.71
FG5X-233	-4.10	0.70
FG5X-247	-1.28	0.70
A10-020	-8.93	3.13

Table B4. *DoE* of all participating instruments determined according to Eq. 4.

g_{ij} : are the measured gravity values transferred to 1.250 m with expanded uncertainty U_{ij}.

g_j : are the KCRVs with associated expanded (k = 2) uncertainties U_j.

U_{Dij} : is the expanded uncertainty of differences g_{ij}-g_j computed based on non harmonized uncertainties of gravimeters.

D_i : is the final *DoE* computed according to Eq. 4 along with the expanded uncertainty U_{Di} , computed from U_{Dij} values, assuming statistical independence of D_{ij} values.

The constant value 980,836,900.0 µGal was subtracted from the gravity values.

Gravimeter i	Site j	g_{ij} /µGal	U_{ij} /µGal	g_j /µGal	U_j /µGal	$D_{ij}=g_{ij}$-g_j /µGal	U_{Dij} /µGal	D_i /µGal	U_{Di} /µGal
FG5-215H	CA	50.52	4.28	52.80	2.67	-2.28	5.05		
FG5-215H	DA	40.62	4.28	41.34	2.64	-0.71	5.03		
FG5-215H	EA	49.14	4.28	49.60	2.67	-0.47	5.04	-1.15	2.91
FG5-242	DA	39.99	5.42	41.34	2.64	-1.35	6.03		
FG5-242	EA	48.11	4.82	49.60	2.67	-1.49	5.51		
FG5-242	FA	59.43	5.02	59.93	2.66	-0.50	5.68	-1.11	3.31
FG5X-221	DA	42.14	4.62	41.34	2.64	0.80	5.32		
FG5X-221	EA	50.36	4.62	49.60	2.67	0.76	5.33		
FG5X-221	FA	61.79	4.62	59.93	2.66	1.86	5.33	1.14	3.08
FG5X-254	FA	57.92	4.52	59.93	2.66	-2.01	5.25		
FG5X-254	DA	38.93	4.48	41.34	2.64	-2.41	5.20		
FG5X-254	CA	51.34	4.78	52.80	2.67	-1.46	5.48	-1.98	3.06
IMGC-02	FA	52.85	10.57	59.93	2.66	-7.08	10.90		
IMGC-02	CA	57.73	11.16	52.80	2.67	4.94	11.48		
IMGC-02	DA	40.76	11.03	41.34	2.64	-0.58	11.34	-1.12	6.49

FG5-101	FA	56.25	6.01	59.93	2.66	-3.68	6.58		
FG5-101	CA	51.26	6.01	52.80	2.67	-1.54	6.58		
FG5-101	EA	46.80	6.01	49.60	2.67	-2.80	6.58	-2.67	3.80
FG5-202	CA	56.33	4.28	52.80	2.67	3.53	5.00		
FG5-202	DA	43.20	4.28	41.34	2.64	1.86	4.98		
FG5-202	EA	51.97	4.28	49.60	2.67	2.36	4.99	2.58	2.88
FG5-206	FA	56.80	4.82	59.93	2.66	-3.13	5.51		
FG5-206	CA	48.01	4.82	52.80	2.67	-4.79	5.51		
FG5-206	DA	36.94	4.82	41.34	2.64	-4.40	5.50	-4.11	3.18
FG5-218	CA	45.21	4.28	52.80	2.67	-7.59	4.83		
FG5-218	DA	36.52	4.28	41.34	2.64	-4.82	4.81		
FG5-218	EA	44.19	4.28	49.60	2.67	-5.41	4.83	-5.94	2.78
FG5-234	CA	52.41	4.29	52.80	2.67	-0.39	4.67		
FG5-234	DA	41.56	4.28	41.34	2.64	0.22	4.65		
FG5-234	FA	59.73	4.28	59.96	2.66	-0.20	4.64	-0.12	2.69
FG5-238	DA	40.86	6.62	41.34	2.64	-0.48	7.12		
FG5-238	EA	49.87	6.41	49.49	2.67	0.27	6.95		
FG5-238	FA	59.76	6.61	59.93	2.66	-0.17	7.13	-0.12	4.08
FG5-301	DA	41.84	6.22	41.34	2.64	0.50	6.75		
FG5-301	EA	49.80	6.21	49.60	2.67	0.19	6.76		
FG5-301	FA	61.28	6.21	59.93	2.66	1.35	6.76	0.68	3.90
FG5X-220	EA	48.88	4.92	49.60	2.67	-0.72	5.59		
FG5X-220	FA	57.80	4.92	59.93	2.66	-2.13	5.59		
FG5X-220	CA	51.17	4.92	52.80	2.67	-1.63	5.60	-1.49	3.23
FG5X-233	EA	44.59	4.82	49.60	2.67	-5.01	5.51		
FG5X-233	FA	55.84	4.82	59.93	2.66	-4.09	5.50		
FG5X-233	CA	49.60	4.82	52.80	2.67	-3.19	5.51	-4.10	3.18
FG5X-247	CA	51.73	5.32	52.80	2.67	-1.07	5.95		
FG5X-247	DA	40.11	4.28	41.34	2.64	-1.23	4.81		
FG5X-247	FA	58.39	5.04	59.96	2.66	-1.54	5.70	-1.28	3.13
A10-020	CA	43.67	10.09	52.80	2.67	-9.13	10.44		
A10-020	EA	37.16	9.58	49.60	2.67	-12.44	9.94		
A10-020	FA	54.80	9.74	59.93	2.66	-5.13	10.10	-8.93	5.86

All KC measurements reaching compatibility index below 2.0, therefore they are consistent with declared uncertainties. All measurements of FG5-218 and also one of A10-20 in the Additional Comparison showed to be inconsistent with declared uncertainties due to the larger bias of these gravimeters at all the measured sites. Since these gravimeters are not contributing directly to the definition of the reference, uncertainties were harmonized (for determination of KCRVs) and also due to the fact that they show short-term reproducibility of 1.5 µGal and 3.7 µGal respectively, we kept these measurements for determination of gravity differences.

The consistency of *DoE* along with declared uncertainties can be seen in Table B5. Inconsistency has been detected for the FG5-218 gravimeter.

Table B5. Degrees of Equivalence (*DoE* according to Eq. 5) of all gravimeters participating in the KC (yellow) and Additional Comparison. The uncertainty U_{DoE} is the minimum uncertainty U_{Dij} of the 3 differences from Table B4. It represents the expanded uncertainty at 95% confidence, computed based on declared uncertainties of participating gravimeters.

RESULTS EURAMET.M.G-K3 KEY COMPARISON AND ADDITIONAL COMPARISON		
Gravimeter	Degree of Equivalence	
	DoE /µGal	U_{DoE} /µGal
FG5-215H	-1.2	5.0
FG5-242	-1.1	5.5
FG5X-221	1.1	5.3
FG5X-254	-2.0	5.2
IMGC-02	-1.1	10.9
FG5-101	-2.7	6.6
FG5-202	2.6	5.0
FG5-206	-4.1	5.5
FG5-218	-5.9	4.8
FG5-234	-0.1	4.6
FG5-238	-0.1	7.0
FG5-301	0.7	6.8
FG5X-220	-1.5	5.6
FG5X-233	-4.1	5.5
FG5X-247	-1.3	4.8
A10-020	-8.9	9.9

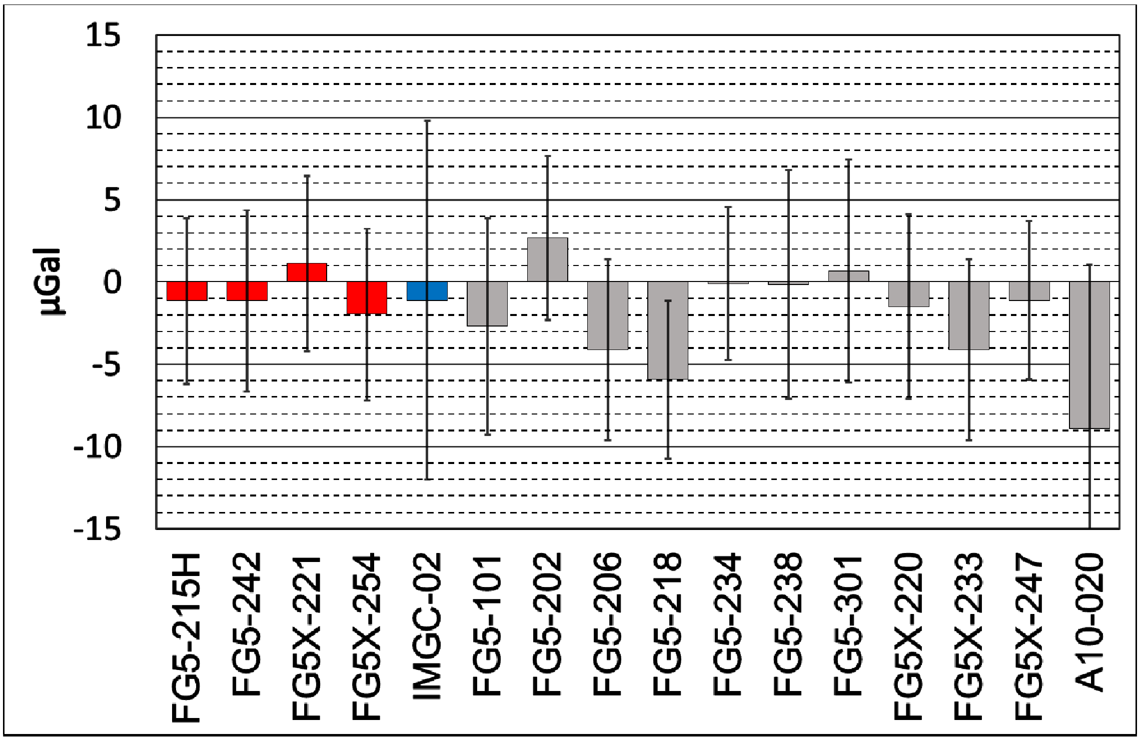

Figure B1. Degrees of equivalence of the gravimeters (linked to the CCM.G-K2.2017). The values for gravimeters of NMI/DIs are highlighted in red (participant of CCM.G-K2.2017) or blue. The error bars represent their expanded uncertainties (U_{DoE} with k = 2 in Table B5).

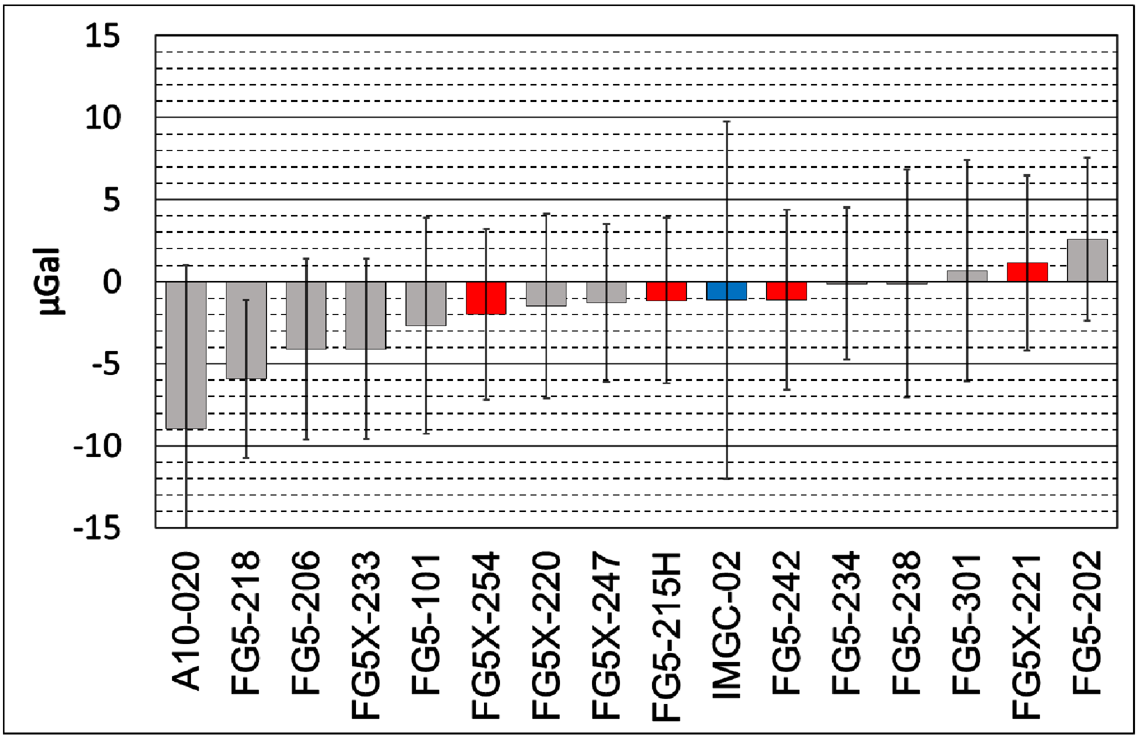

Figure B2. Degrees of equivalence of the gravimeters (linked to the CCM.G-K2.2017). The values for gravimeters of NMI/DIs are highlighted in red (participant of CCM.G-K2.2017) or blue. The error bars represent their expanded uncertainties (U_{DoE} with k = 2 in Table B5). The gravimeters have been rearranged according to the size of the deviation.