Consultative Committee on Mass and Related Quantities
(CCM)
Working Group on Gravimetry
(WGG)

Comparison of Absolute Gravimeters
SIM.M.G-K1 Key Comparison and Pilot Study

Table Mountain Geophysical Observatory (TMGO)
Boulder, Colorado

Pilot laboratory: NIST-Gaithersburg

Technical Protocol

IMPORTANT DEADLINES

We would like to present the results of the comparison as soon as possible. For that, we count on your collaboration to respect the different deadlines.

15 August 2016	Approbation of the Technical Report by all the SIM.M.G-K1 participants.
1 September 2016	Deadline for sending the completed form of **annex A** to the Local Organisation (derek.vanwestrum.noaa.gov) and the Pilot Laboratory (david.newell@nist.gov)
28-30 September 2016	Vertical gravity gradient measurements at TMGO
3-14 October 2016	Comparison of absolute gravimeters at TMGO
15 November 2016	Presentation of the results by the participants to the Local Organisation (derek.vanwestrum.noaa.gov) and the Pilot Laboratory (david.newell@nist.gov) (**Annex B**)
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15 January 2017	Draft A (confidential) presented to the participants
15 April 2017	Deadline for comments on Draft A
15 May 2017	Draft B (public) and publication in Metrologia “Technical Supplement”

Content

1. Introduction

The Regional Key Comparison of Absolute Gravimeters, SIM.M.G-K1 and Pilot Study, will be conducted at the Table Mountain Geophysical Observatory (TMGO), near Boulder, Colorado. The goals of the comparison are the validation of the Calibration and Measurement Capabilities (CMCs) published in the Key Comparison Database (KCDB) and to allow the operators to verify the proper operation of their absolute gravimeters by quantitative measurement of the degree of equivalence with respect to the other participating gravimeters**.** All agencies with absolute gravimetric capabilities are welcome to participate in the comparison.

The comparison is organized in accordance with the CIPM MRA-D-05 of the Consultative Committee on Mass and Related Quantities (CCM). It will be linked to the results of either the CCM.G-K1 or CCM.G-K2 comparison (formerly ICAG-2009 and ICAG-2013, respectively) through several measurements that will be carried out by absolute gravimeters that have participated in either comparison.

Only National Metrology Institutes (NMIs) that are signatories of the CIPM Mutual Recognition Arrangement (CIPM MRA), and laboratories officially designated by those institutes (DIs), can participate in the Key Comparison aspect of the project. Only their measurements can contribute to the evaluation of the Key Comparison Reference Values (KCRVs), and only their degrees of equivalence can be published in the Key Comparison Data Base (KCDB). However**, non-designated institutes are welcome (and encouraged!) to participate** in the comparison as well. All of the results–including those from non-NMI/DIs–will be the subject of a scientific publication in Metrologia.

Dr. David Newell of NIST will serve as the representative of the pilot laboratory, and Dr. Derek van Westrum has agreed to serve as the host of the local organizing committee.

2. Participants

The list of the participants who have registered so far is given in Table 1. In total, 14 absolute gravimeters from 14 institutes will take part in the comparisons including 2 different types of instruments.

Table 1. List of the 21 participants to SIM.M.G-K1 and Pilot Study

#	Country	Institution	Gravimeter	NMI or DI	Operator(s)	E-mail
1	USA	NIST-Gaithersburg	FG5-204	YES	David Newell	david.newell@nist.gov
2	USA	NOAA-NGS	FG5X-102	NO	Derek van Westrum Jeff Kanney	derek.vanwestrum@noaa.gov jeff.kanney@noaa.gov
3	Canada	National Research Council, Canada	FG5-105	YES	Jacques Liard Jason Silliker	jacques.liard@nrc-cnrc.gc.ca Jason.silliker@nrcan-rncan.gc.ca
4	Luxembourg	University of Luxembourg	FG5X-216	YES	Olivier Francis	olivier.francis@uni.lu
5	USA	Micro-g LaCoste	FG5X#302	NO	Brice Lucero	brice@microglacoste.com
6	Italy	INGV	FG5-238	NO	Filippo Greco Antonio Pistorio	filippo.greco@ct.ingv.it antonio.pistorio@ct.ingv.it
7	Netherlands	TU Delft	FG5-234	NO	Rene Reudink	r.h.c.reudink@tudelft.nl
8	Russian Federation	Institute of Automation and Electrometry, Siberian Branch of the Russian Academy of Sciences	GABL-PM	NO	Egor Nazarov Dmitry Nosov Igor Sizikov	nazarov@gmail.com
9	Mexico	CENAM & National University of Mexico	FG5X-252	YES	Alfredo Esparza Ramirez Jorge Arzate	aeparza@cenam.mx
10	Brazil	Observatorio Nacional	FG5-223	NO	Mauro Andrade de Sousa	mauro@on.br
11	Italy	Agenzia Spaziale Italiana	FG5-218	NO	Domenico Iacovone Francesco Baccaro	domenico.iacovone@e-geos.it francesco.baccaro@e-geos.it
12	Canada	National Resources, Canada	FG5-236	NO	Joe Henton	joe.henton@nrcan-rncan.gc.ca
13	USA	National Geospatial Intelligence Agency	FG5-107	NO	Robert D Wheeler	robert.d.wheeler@nga.mil
14	Germany	Federal Agency for Cartography and Geodesy	FG5-301	NO	Reinhard Falk Axel Ruelke	reinhard.falk@bkg.bund.de axel.ruelke@bkg.bund.de
15						
16						
17						
18						

3. Measurand

The measurand is the mean free-fall acceleration at the reference height corrected for gravimetric Earth tides, atmospheric and polar motion effects on gravity. Corrections are made in compliance with the International Earth Rotation and Reference Systems Service (IERS) conventions [1] and IAGBN (International Absolute Gravity Base-station Network) processing standards [2]. It means applying corrections for

- the gravimetric Earth tides to obtain "zero-tide" values for gravity,
- the polar motion effect, estimated from the coordinates of the Celestial Ephemeris Pole relative to the IERS Reference Pole,
- the effect of atmospheric mass variations using an admittance factor of -0.3 μGal/hPa on the difference between the normal air pressure [3] and measured air pressure at the station.

The required geographical coordinates and elevation of the measuring sites (stations), as well as the observed tidal parameters are listed in Annex D. The polar motion coordinates are published by the IERS at http://maia.usno.navy.mil.

The reported time of the measurement shall be the average of the times of the observations contributing to the measurement.

Throughout the duration of the comparison, changes in both atmospheric pressure and local gravity (using a Superconducting gravimeter, GWR CT-024) will be continuously monitored. The relevant corrections will be applied to the measurand by the pilot laboratory. All relevant information concerning the measurements and corrections will be made available to the participants after the comparison (draft A).

The vertical gravity gradient (VGG) at each TMGO site is described as a function of the height z by a second degree polynomial $g(z) = a\,z^2 + b\,z + c$. Thus, the vertical gravity gradient (VGG) at the specific height is $\gamma(z) = 2a\,z + b$ with parameters a, b given in Annex D. The participants have to provide the value of VGG in Annex B, which was used within the solution of equation of motion and for transferring g to the measurement height. To avoid any possible problems, we recommend reporting g in the reference instrumental height (distance between benchmark and the effective position of free-fall, ≈1.21 m for the FG5 and ≈1.27 m for the FG5-X), where g is invariant on VGG used in the equation of motion. In a second step provided by the pilot laboratory, the second order vertical gravity change will be used to transfer the g-values from the instrumental reference heights to the comparison reference height of 1.3 m.

4. Methods of measurement

Details concerning the instrumentation and methods of the absolute measurements should be described by each participant (Annex A). This information is mandatory for the KC participants.

5. Program of the measurements

A 9-station gravity network is proposed for all the measurements. Each gravimeter should measure at four gravity stations. The comparison will be organized in two sessions each with measurements occurring over four nights. The first session will be composed of eight instruments, and the second session six instruments.

The optimal measurement schedule has been prepared by Dr. Dru Smith (NOAA-NGS) according to [6]. In designing an optimal schedule, the following conditions have been imposed: 1) an instrument shall not occupy the same pier more than once, 2) the number of missing meter-to-meter comparisons shall be minimized, 3) the number of times any two instruments observe on the same pier more than once shall be evenly distributed among all the instruments (to the extent possible).

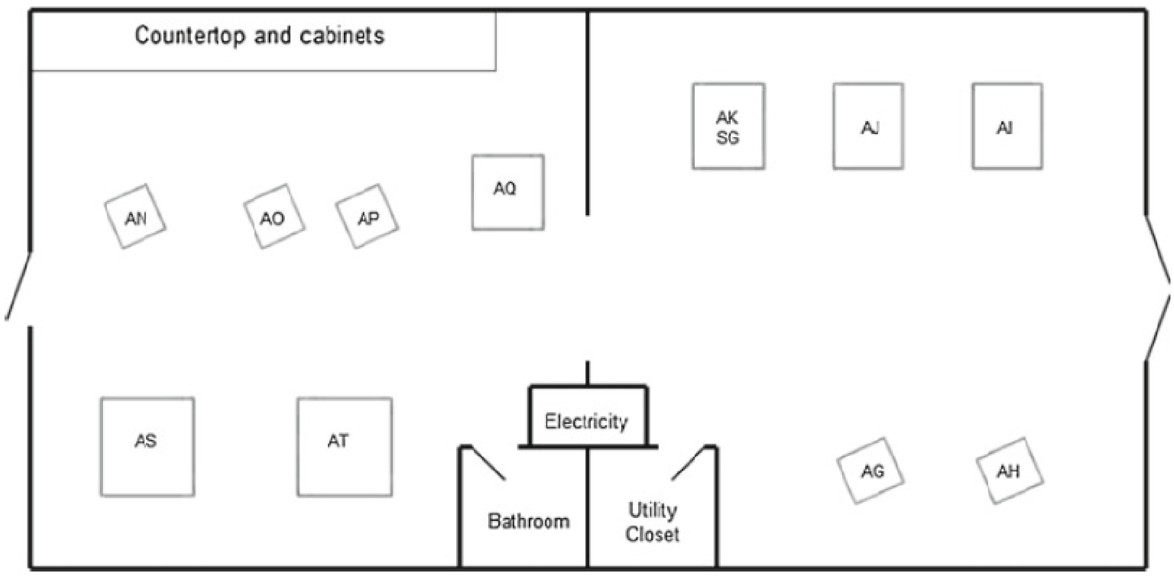

Figure 1. A. Schematic of the comparison site at TMGO. Note that pier AK is permanently occupied by the SG, and piers AN and AP will be avoided for reasons of spatial convenience.

6. Measurement timetable

The measurement timetable is given in Table 2. Assembly of the instruments of a particular gravimeter between stations have to be realized till 11 am.

Table 2. Measurement schedule. Note that the schedule is necessarily subject to change if an instrument(s) becomes unavailable for some reason. The NMI/DI instruments are shaded light brown.

	Date start end / Pier	3/10 4/10	4/10 5/10	5/11 6/11	6/10 7/10	10/10 11/10	11/10 12/10	12/11 13/11	13/10 14/10
	AG	FG5X-252	FG5-231	GABL-PM	FG5X-216	FG5-107	FG5X-102		FG5-236
	AH	FG5-223	FG5X-252	FG5-231	FG5-218	FG5-236	FG5-107	FG5-105	FG5X-302
	AI	FG5-301	FG5-223	FG5X-252	GABL-PM	FG5X-302	FG5-236	FG5-204	
	AO	FG5-238	FG5-301	FG5-223	FG5-231		FG5X-302	FG5X-102	
	AJ	FG5X-216	FG5-238	FG5-301	FG5X-252			FG5-107	FG5-105
	AQ	FG5-218	FG5X-216	FG5-238	FG5-223	FG5-105		FG5-236	FG5-204
	AS	GABL-PM	FG5-218	FG5X-216	FG5-301	FG5-204	FG5-105	FG5X-302	FG5X-102
	AT	FG5-231	GABL-PM	FG5-218	FG5-238	FG5X-102	FG5-204		FG5-107

Table 3. Quantity of pier co-occupations. NMI/DI instruments are shaded light brown.

	FG5X-252	FG5-223	FG5-301	FG5-238	FG5X-216	FG5-218	GABL-PM	FG5-231	FG5-105	FG5-204	FG5X-102	FG5-107	FG5-236	FG5X-302
FG5X-252	0	2	2	1	2	1	2	2	2	1	1	3	3	2
FG5-223	0	0	2	2	1	2	1	2	2	2	1	1	3	3
FG5-301	0	0	0	2	2	1	2	1	2	2	2	1	1	3
FG5-238	0	0	0	0	2	2	1	2	2	2	2	2	1	1
FG5X-216	0	0	0	0	0	2	2	1	3	2	2	2	2	1
FG5-218	0	0	0	0	0	0	2	2	3	3	2	2	2	2
GABL-PM	0	0	0	0	0	0	0	2	1	3	3	2	2	2
FG5-231	0	0	0	0	0	0	0	0	1	1	3	3	2	2
FG5-105	0	0	0	0	0	0	0	0	0	2	1	2	2	2
FG5-204	0	0	0	0	0	0	0	0	0	0	2	1	2	2
FG5X-102	0	0	0	0	0	0	0	0	0	0	0	2	1	2
FG5-107	0	0	0	0	0	0	0	0	0	0	0	0	2	1
FG5-236	0	0	0	0	0	0	0	0	0	0	0	0	0	2
FG5X-302	0	0	0	0	0	0	0	0	0	0	0	0	0	0

7. Data report

All participants must provide the absolute measurement results for every measured point (pier) in the table format given in Annex B. The operators are responsible for processing their own gravity data, including the application of corrections for all known instrumental effects. They will then submit final *g*-values for all the measured sites at their own preferred height above the benchmark together with the vertical gravity gradient that they employed. Finally, the operators will provide the combined standard uncertainty of final *g*-values. Dr. David Newell and Dr. Derek van Westrum will be responsible for reducing the submitted gravity values to a common height (1.3 m) using the measured vertical gravity gradients at each pier.

8. Uncertainty evaluation

"*A result from a participant is not considered complete without an associated uncertainty, and is not included in the draft report unless it is accompanied by an uncertainty supported by a complete uncertainty budget*" [4].

Uncertainty of measurements should be estimated **(mandatory for KC participants**) according to the GUM [5]. The calculation of uncertainty can be divided in two steps:

1. uncertainty budget of the instrument that includes, at least, the following influence parameters:
   - Laser frequency
   - Rb-clock frequency
   - Gravity gradient measurement
   - Misalignments in the verticality of the laser beam correction
   - Imperfect collimation and cosine error effect
   - Verticality
   - Residual gas pressure
   - Diffraction effects
   - Glass wedges
   - Corner cube rotation
   - Air gap modulation
   - Inhomogeneous magnetic field
   - Apparatus gravity attraction effect
   - Electrostatics effect
   - Temperature changes
   - Beam divergence correction
   - Phase shifts in fringe counting and timing electronics
   - Choice of the initial and final scaled fringes effect
   - Reference height

   Other possible effects:
   - Laser frequency reproducibility/stability
   - Beam shear effect
   - Photodetection and fringe counting electronics effect
   - Finite speed of light effect
   - Optical effects
   - Radiation Pressure effect
   - Whichever other contribution characterized from the participant laboratory

2. measurement uncertainty in a specific site that includes, at least, the following influence parameters:

- Instrumental uncertainty (as results of the first step in the uncertainty calculation)
- Uncertainty in air pressure correction (admittance factor)
- Air pressure measurement effect
- Earth tide evaluation

- Ocean loading correction evaluation
- Polar motion correction evaluation
- Groundwater effect
- Coriolis acceleration effect
- Floor (instrument) recoil effect
- Gravity gradient (transfer to 1.3 m)
- Typical standard deviation of measurements

From the influencing quantities X_i , measurement deviations Δx_i and uncertainties in the form of standard deviation s_i (type A) and a_i (type B) are considered:

- standard uncertainty:

note: k_a depends on the type of statistical distribution (2 for U distribution, 3 for rectangular , 6 for triangular, etc.)

$$u^2(x_i) = s_i^2 \vee \frac{a_i^2}{k_a} \quad (1)$$

- sensitivity coefficients:

$$c_i \approx \left.\frac{\Delta g}{\Delta x_i}\right|_{X_1=x_1,\ldots,X_N=x_N} \quad (2)$$

- single gravity deviation:

$$\Delta g_i = c_i \cdot \Delta x_i \quad (3)$$

- variances:

$$u^2(y_i) = c_i^2 u^2(x_i) \quad (4)$$

- combined standard uncertainty:

$$u(g) = \sqrt{\sum_{i=1}^{n} u^2(y_i)} \quad (5)$$

- sum of gravity deviations:

$$\Delta g = \sum_{i=1}^{n} \Delta g_i \quad (6)$$

- effective degrees of freedom, according to the Welch-Satterthwaite formula:

$$\nu_{eff} = \frac{u^4(y)}{\sum_{i=1}^{n} \frac{u_i^4(y)}{\nu_i}} \quad (7)$$

- coverage factor (p=level of confidence):

$$k = f(\nu_{eff}, p) \quad (8)$$

- expanded standard uncertainty:

note: $|\Delta g|$ is the calculated error. If it is not corrected, at least it should be included in the estimation of uncertainty. See F.2.4.5 in [2].

$$U(g) = k \cdot u(g) + |\Delta g| \quad (9)$$

- relative expanded standard uncertainty:

$$U_{rel}(g) = \frac{U(g)}{g} \quad (10)$$

An example of calculation of uncertainty is given in annex C. It contains the unified budget of uncertainty for FG5-type gravimeters, as result of the analysis done in previous comparisons.

All participants are requested to estimate (e.g. based on their long-term experience with a gravimeter) the long-term reproducibility of the measurements. It can be understood as a parameter which describes the degree of consistency of an AG after several years. The reproducibility is defined [5] as a closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement. It includes random errors (e.g. setup error, errors of applied corrections for tides or atmosphere) but also errors which may cause systematic effects over a few months (e.g. in connection with the interferometer alignment, such as collimation or fringe size effect). This information would be helpful for a possibility to separate the systematic and stochastic part of the uncertainty and by such a way to improve the approach of the least-squares adjustment.

9. Frequency measurements during the comparison

TMGO (with the kind assistance of nearby Micro-g LaCoste, Inc.) can provide assistance in the determination of

- Frequency calibration (GPS-10 MHz and/or 1PPS, traceable to NIST)
- Laser wavelength calibration (632nm nominal wavelength, traceable to NIST)
- Laser beam width determination (diffraction correction)

. Depending on the quantity and nature of such assistance requests, arrangements prior to the comparison may be necessary. Participants interested in such assistance are asked to contact Derek van Westrum well in advance of the comparison.

10. Results elaboration and link to either the Key Comparison of 2009 or 2013

The results of the comparison will be the Comparison Reference Values with their uncertainties evaluated using all the measurements performed by all the gravimeters participating at the comparison linked to the results of either the CCM.G-K1 or CCM.G-K2 comparison.

The data processing will be based on a weighted least square adjustment including the gravity differences measured by all gravimeters (PS and KC). The observation equation is

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

with the non-weighted condition in the first approach

$$\sum_i \delta_i = d$$

and with the weighted condition in the second approach

$$\sum_i w_i \, \delta_i = d \, .$$

In the first approach, weights w_{ik} ($w_{ik} = u_o^2/u_{ik}^2$ where u_o is the unit weight) based on the uncertainty budget of the observations will be applied to the measured values g_{ik}. In the second approach, weights $w_i = u_o^2/u_i^2$ will be also applied on the biases δ_i, where u_i is computed as root mean square of u_{ik} for a gravimeter i. The link to either the CCM.G-K1 or CCM.G-K2 will be provided by the linking converter d representing the non-weighted/weighted mean of DoEs at the CCM.G-K1 or CCM.G-K2 of the linking participants. The final DoEs of the gravimeters participating at the RMO KC will be calculated from the difference between the gravimeter measurements and the CRVs.

The results related to the two approaches for constraining the condition will be presented to the participants in the Draft A.

Consequently, the participants will decide which will be the more appropriate method and it will be implemented in the Draft B report.

Since the comparison strive for a blind test type of measurement, **participants cannot communicate their results, neither to other participants nor officially on any other way before the issue of the Draft A.**

Once the draft B of the report on KC is published all the results of the comparison will be made public.

11. Visitor and Transportation Logistics

Questions regarding travel to Boulder (letters of invitation, etc.) should be addressed to Derek van Westrum. Foreign nationals will need some extra time for permission to enter the TMGO site. It is requested that these processes be started as quickly as possible (something like at least two months before the comparison).

Questions regarding the logistics of instrumentation transportation (customs formalities, etc) should also contact Derek van Westrum. The name of a local shipping company or consignee who is used to deal with the customs formalities of this kind of equipment will be recommended on request.

12. References

[1] Petit G. and B. Luzum, IERS Conventions 2010, IERS Technical Note No. 36, 2010. ftp://maia.usno.navy.mil/conv2010/tn36.pdf

[2] Boedecker G. International Absolute Gravity Base-station Network (IAGBN). Absolute gravity observations data processing standards & station documentation. *BGI Bull. Inf.* 1988, Vol. 63, 51–57.

[3] US Standard Atmosphere, NASA-TM-X-74335, NOAA 77-16482, 1976.

[4] T. J. Quinn, Guidelines for CIPM key comparisons carried out by Consultative Committees, BIPM, Paris, 1 March 1999 with modifications by the CIPM in October 2003. http://www.bipm.org/utils/en/pdf/guidelines.pdf

[5] BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, Guide to the Expression of Uncertainty in Measurement; Edition 1993, corrected and reprinted 1995, ISO-GUM, International Organization for Standardization, Geneva, Switzerland,ISBN92-67-10188-9. http://www.bipm.org/en/publications/guides/gum.html

[6] Smith D.A., Saleh J., Eckl M. Optimizing an Absolute Gravimeter Comparison Schedule. http://www.ngs.noaa.gov/web/science_edu/presentations_library/files/agu_2013_poster.pdf

Annex A - Description of the absolute gravimeter

Manufacturer	
Model/Type	
s/n	
Method of the measurement of free-fall acceleration	
Approximated reference instrumental height*	
Vibration-isolation device	
Interferometer type	
Laser type	
Throw/drop length used during measurement, number of fringes acquired and fringes used for g-evaluation	
Software	
Length of the fringe signal cable (e.g. TTL cable)	
Add other information	

* (≈1.21 m for the FG5 and ≈1.27 m for the FG5-X), distance between benchmark and the effective position of free-fall, where g is invariant on vertical gravity gradient used in the equation of motion

Annex B - Report of measurement results

The g-values should be corrected for all known geophysical effects (tides, polar motion, atmospheric pressure, etc.) as well as for all instrumental effects (self-attraction, diffraction effects, etc.).
The g-value can be given for any desired height. However, reference instrumental height* is recommend to use.

Date	**Time (from÷to)**	**Gravimeter**	Operator/s	**Site**	#sets, #drops	g@ measure-ment height /µGal	Measure-ment height / cm	VGG / µGal m^{-1}	Long-term reproducibility /µGal	**Standard uncertainty /µGal**	Degrees of freedom

Indicate the value of the applied self-attraction correction and diffraction correction with the associated uncertainty

Date	Time (from÷to)	Gravimeter	Operator/s	Site	Self-attraction /µGal	$u_{Self-attraction}$ /µGal	Diffraction /µGal	$u_{Diffraction}$ /µGal

* (≈1.21 m for the FG5 and ≈1.27 m for the FG5-X), distance between benchmark and the effective position of free-fall, where g is invariant on vertical gravity gradient used in the equation of motion

Annex C - Example of calculation of uncertainty.

Example of instrumental uncertainty (unified for FG5s)

Note: table below is in MS-Excel® format. Double-click to open it. Light blue cells contain formulas that should not be modified

Example of instrumental uncertainty (unified for FG5s)

Influence parameters, x_i	Value	Unit	u_i or a_i	Type A, σ_i	Type B, a_i	Correction, Δg	Type of distribution	Equivalent variance	Sensitivity coefficients	Contribution to the variance	Degrees of freedom, ν_i	Equivalent standard uncertainty
Laser frequency		Hz	1,0E-01	1,0E-01			gaussian	1,0E-02	2,1E-08	4,4E-18	30	2,1E-09
Laser frequency reproducibility		Hz	1,0E-02	1,0E-02			gaussian	1,0E-04	2,1E-08	4,4E-20	30	2,1E-10
Rb-clock frequency		Hz	5,0E-04	5,0E-04			gaussian	2,5E-07	2,0E-06	1,0E-18	30	1,0E-09
Gravity gradient measurement		$m \cdot s^{-2} \cdot m^{-1}$	5,0E-12	5,0E-12			gaussian	2,5E-23	8,3E+02	1,7E-17	15	4,2E-09
Misalignments in the verticality of the laser beam correction	6,60E-09	$m \cdot s^{-2}$	±2,1E-09		2,1E-09	6,6E-09	rectangular	1,5E-18	1	1,5E-18	15	1,2E-09
Imperfect collimation and cosine error effect		$m \cdot s^{-2}$	1,0E-09	1,0E-09			gaussian	1,0E-18	1	1,0E-18	15	1,0E-09
Verticality		rad	4,8E-05		4,8E-05		rectangular	7,7E-10	1,41E-04	1,5E-17	15	3,9E-09
Residual gas pressure	2,0E-04	Pa	±2E-04		2E-04	3,6E-09	rectangular	1,3E-08	1,8E-05	4,3E-18	5	2,1E-09
Diffraction effects			±3,1E-10	3,1E-10			gaussian	9,6E-20	9,8E+00	9,2E-18	15	3,0E-09
Beam shear effect	unknown		unknown					0,0E+00		0,0E+00		0,0E+00
Glass wedges		rad		2,9E-05			gaussian	8,4E-10	-1,4E-04	1,6E-17	15	4,1E-09
Corner cube rotation		$rad \cdot s^{-1}$	±1E-02		1E-02		rectangular	3,3E-05	6,0E-07	1,2E-17	15	3,5E-09
Air gap modulation		mm	1,5E-07	1,5E-07			gaussian	2,3E-14	4,9E-02	5,4E-17	15	7,4E-09
Inhomogeneous magnetic field		T	±5E-05		5E-05		rectangular	8,3E-10	7,0E-05	4,1E-18	15	2,0E-09
Apparatus gravity attraction effect		$m \cdot s^{-2}$	±2E-09		2E-09		rectangular	1,3E-18	1	1,3E-18	10	1,2E-09
Electrostatics effect		$m \cdot s^{-2}$	1,0E-09	1,0E-09			gaussian	1,0E-18	1	1,0E-18	15	1,0E-09
Temperature changes		°C	±4E+00		4E+00		U	8,0E+00	7,0E-10	3,9E-18	10	2,0E-09
Diffraction effects	2E-08	$m \cdot s^{-2}$	1,10E-08	1,1E-08		2E-08	gaussian	1,2E-16	1	1,2E-16	10	1,1E-08
Index of refraction effect			negligible					0,0E+00		0,0E+00		0,0E+00
Phase shifts in fringe counting and timing electronics		s	±1E-08		1E-08		rectangular	3,3E-17	5,2E-01	9,0E-18	15	3,0E-09
Photodetection and fringe counting electronics effect			negligible					0,0E+00		0,0E+00		0,0E+00
Finite speed of light effect			negligible					0,0E+00		0,0E+00		0,0E+00
Choice of the initial and final scaled fringes effect		$m \cdot s^{-2}$	1,3E-08	1,3E-08			gaussian	1,7E-16	1	1,7E-16	15	1,3E-08
Optical effects			negligible					0,0E+00		0,0E+00		0,0E+00
Reference height		m	±1E-03		1E-03		rectangular	3,3E-07	3,0E-06	3,0E-18	30	1,7E-09
Radiation Pressure effect			negligible					0,0E+00		0,0E+00		0,0E+00
Others			negligible					0,0E+00		0,0E+00		0,0E+00
				Total correction		**3,02E-08**	**$m \cdot s^{-2}$**	Sum of variances		4,49E-16	$m^2 \cdot s^{-4}$	
				Combined standard uncertainty, u						2,1E-08	$m \cdot s^{-2}$	
				Degrees of freedom, ν_{eff} (Welch-Satterthwaite formula)						55		
				Confidence level, p						95%		
				Coverage factor, k (calculated with t-Student)						2,00		
				Expanded uncertainty (corrections applied), $U = ku$						**4,2E-08**	**$m \cdot s^{-2}$**	
				Relative expanded uncertainty (corrections applied), $U_{rel} = U/g$						**4,3E-09**		
				Expanded uncertainty (corrections not applied), $U = ku + ABS(\Delta g)$						**7,3E-08**	**$m \cdot s^{-2}$**	

Example of site dependent uncertainty (unified)

Note: table below is in MS-Excel® format. Double-click to open it. Light blue cells contain formulas that should not be modified

Influence parameters, x_i	Value	Unit	u_i or a_i	Type A, σ_i	Type B, a_i	Type of distribution	Equivalent variance	Sensitivity coefficients	Contribution to the variance	Degrees of freedom, ν_i	Equivalent standard uncertainty
Instrumental uncertainty	2,1E-08	$m \cdot s^{-2}$	2,1E-08	2,1E-08		gaussian	4,5E-16	1	4,5E-16	55	2,1E-08
Uncertainty in air pressure correction (admittance factor)	6,3E+00	hPa	6,0E-01		3,0E-01	rectangular	3,0E-02	3,2E-08	3,0E-17	15	5,5E-09
Air pressure measurement effect		$m \cdot s^{-2}$	±1E-09		1,0E-09	rectangular	3,3E-19	1	3,3E-19	30	5,8E-10
Earth tide evaluation		$m \cdot s^{-2}$	±1E-08		1,0E-08	rectangular	3,3E-17	1	3,3E-17	30	5,8E-09
Ocean loading correction evaluation		$m \cdot s^{-2}$	±0,5E-09		5,0E-09	rectangular	8,3E-18	1	8,3E-18	30	2,9E-09
Polar motion correction evaluation		$m \cdot s^{-2}$	±0,5E-11		5,0E-10	rectangular	8,3E-20	1	8,3E-20	30	2,9E-10
Groundwater effect	Unknown		Unknown				0,0E+00		0,0E+00		0,0E+00
Coriolis acceleration effect		$m \cdot s^{-2}$	±7,5E-09		7,5E-09	rectangular	1,9E-17	1	1,9E-17	15	4,3E-09
Floor (instrument) recoil effect		$m \cdot s^{-2}$	±2E-09		2,0E-09	rectangular	1,3E-18	1	1,3E-18	15	1,2E-09
Gravity gradient (transfer to 0.9 m)		$m \cdot s^{-2} \cdot m^{-1}$	5,0E-12	5,0E-12		gaussian	2,5E-23	8,3E+02	1,7E-17	30	4,2E-09
Typical standard deviation of measurements		$m \cdot s^{-2}$	5,0E-09	5,0E-09		gaussian	2,5E-17	1	2,5E-17	30	5,0E-09

Sum of variances	5,83E-16	$m^2 \cdot s^{-4}$
Combined standard uncertainty, u	2,4E-08	$m \cdot s^{-2}$
Degrees of freedom, ν_{eff} (Welch-Satterthwaite formula)	89	
Confidence level, p	95%	
Coverage factor, k (calculated with t-Student)	1,99	
Expanded uncertainty (corrections applied), $U = ku$	**4,8E-08**	$m \cdot s^{-2}$
Relative expanded uncertainty (corrections applied), $U_{rel} = U/g$	**4,9E-09**	
Expanded uncertainty (corrections not applied), $U = ku + ABS(\Delta g)$	**7,8E-08**	$m \cdot s^{-2}$
Relative expanded uncertainty (corrections not applied), $U_{rel} = U/g$	**8,0E-09**	

Annex D - Parameters of the TMGO site

The same geographical coordinates are used for all the sites:
Name of the station: Table Mountain Geophysical Observatory (TMGO)
Bench mark (pier) designations: AG, AH, AI, AJ, AN, AO, AP, AQ, AS, AT
Latitude: 40.1309 North
Longitude: 105.2327 West
Altitude: 1683 m

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

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

Thus, the vertical gravity gradient at the specific height is

$$\gamma(z) = 2a\,z + b\,.$$

A least-squares fit provides with the coefficients *a*, *b* and *c* as well as σ_a, σ_b and σ_{ab} (standard deviation and covariance). The results are presented in Table D1, but note that parameters may change slightly if/when the gradients are re-measured before the comparison. Not that the coefficient c is omitted as it is of no use.

Table D1. Parameters and associated uncertainties of the second degree polynomial for the vertical gravity gradient.

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	4.6	1.3	-322.3	1.7	2.2
AH	4.9	1.0	-318.4	1.3	1.3
AI	3.6	1.7	-310.4	2.1	3.6
AJ	1.1	1.1	-316.1	1.5	1.7
AN	3.6	1.3	-316.0	1.7	2.2
AO	3.3	1.2	-319.4	1.6	1.9
AP	0.6	1.8	-317.0	1.5	2.7
AQ	9.2	1.1	-332.5	1.4	1.8
AS	8.5	3.0	-330.0	4.0	12.0
AT	6.8	1.4	-329.2	1.9	2.7

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

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

and the associated uncertainty

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

These are the two formulas used to transfer the gravity values along the vertical from the reference instrumental height to the reference height of the comparison, 1.30 m.

Table D2. Observed tidal parameters at TMGO

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