NKG Comparison of Absolute Gravimeters NKG-CAG-2022 Additional Comparison

Onsala Space Observatory (OSO)
Lantmäteriet (LM), Sweden

Pilot laboratory

Finnish Geospatial Research Institute (FGI), Finland

Technical Protocol

Version 1.6

27 May 2022

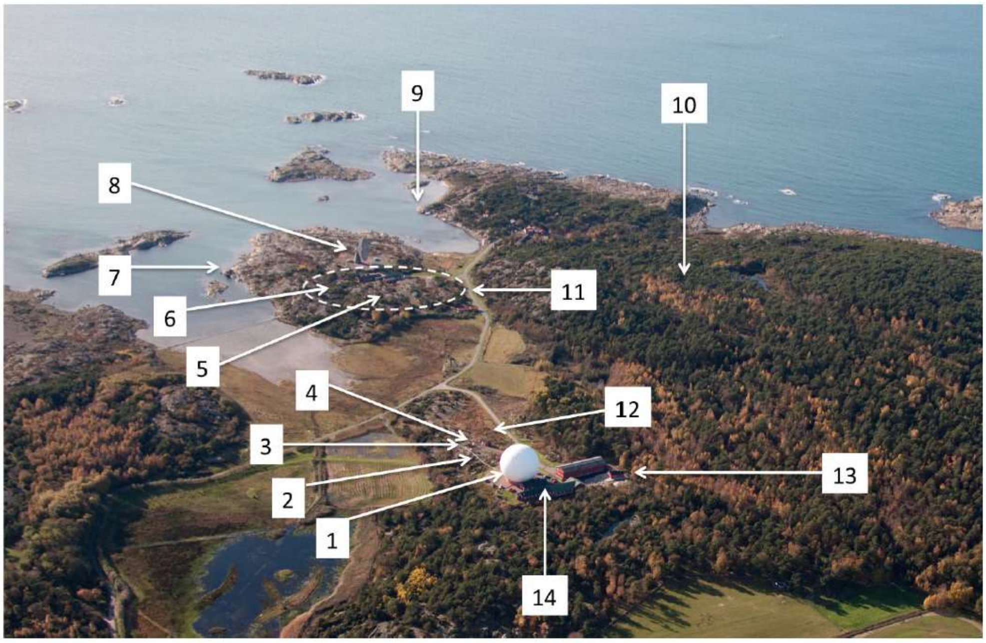

Fig. 1 Aerial photo of OSO: (1) the radome-enclosed 20 m radio telescope, (2) the microwave radiometer "Konrad", (3) the GNSS-station ONSA, (4) the microwave radiometer "Astrid', (5) the location of the northern telescope of the future Onsala Twin Telescope, (6) the location of the southern telescope of the future Onsala Twin Telescope, (7) the tide gauge station, (8) the 25 m radio telescope, (9) the GNSS-R based tide gauge, (10) the seismometer, (11) the six-station GNSS-array around the OTT, (12) the GNSS-station ONS1, (13) the gravimeter laboratory with the superconducting gravimeter, (14) the time and frequency laboratory.

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.

13.5.2022	Approbation of the Technical Protocol by all the NKG-CAG-2022 participants
29.5.2022	Deadline for sending the completed from of annex A to the Pilot Laboratory (Mirjam.Bilker-Koivula@nls.fi)
9.5. – 7.7.2022	Comparison at the Onsala Space Observatory
1.8.2022	Presentation of the results by the participants to the Local Organisation (Andreas.engfeldt@lm.se) and the Pilot Laboratory (Mirjam.Bilker-Koivula@nls.fi) (Annexes B and C)
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31.10.2022	Draft A (confidential) presented to the participants
2.12.2022	Deadline for comments on Draft A
31.1.2023	Draft B (in public form) presented

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1. Introduction

The Additional Comparison of Absolute Gravimeters, NKG-CAG-2022, will be organized under the umbrella of the Nordic Geodetic Commission at the Onsala Space Observatory in Sweden. The comparison will be organized as an Additional Comparison as described in §4.1.4 of the CCM -IAG Strategy for Metrology in Absolute Gravimetry [1]. The comparison will allow the operators to verify the proper operation of their absolute gravimeters and guarantee traceability to the SI. Due to limited space at the comparison site, participation in the comparison is by invitation only.

In order to guarantee traceability to the SI, the additional comparison will be linked to the EURAMET.M.G-K3 by means of joint participants of National Metrology Institutes (NMIs) that are signatories of the CIPM Mutual Recognition Arrangement (CIPM MRA), and laboratories officially designated by those institutes (DIs). Participation of a minimum of two NMI/DI's is required for the link to be established.

The results of the comparison will be subject of a publication in scientific journal and will be available at the International Database for absolute Gravity measurements (AGrav).

Mirjam Bilker-Koivula of FGI will serve as the representative of the pilot laboratory. Maxime Mouyen of OSO will serve as local organizer and Andreas Engfeldt as administrator.

2. Participants

The list of the participants that have announced their interest of participation so far is given in Table 1. In total, # absolute gravimeters (AGs) will take part in the comparison including # AGs of NMI/Dis.

TABLE 1. List of participants to NKG-CAG-2022.

* NMI or Designated Institute, ** participant of EURAMET.M.G-K3

Country	**Institution**	**Gravimeter**	*	**	**Participant**	**Operator(s)**
Sweden	Lantmäteriet, Gävle	FG5X-233	no	Yes	AG-1	Andreas Engfeldt
Finland	Finnish Geospatial Research Institute (FGI), National Land Survey of Finland (NLS), Helsinki	FG5X-221	yes	Yes	AG-2	Jyri Näränen Timo Saari (Mirjam Bilker-Koivula)
Germany	Leibniz-University Hannover	FG5X-220	no	Yes	AG-3	Ludger Timmen
Poland	Institute of Geodesy and Cartography (IGiK), Warszawa	A10-020 and AQG-B07	no no	Yes No	AG-4 AG-5	Przemyslaw Dykowski Marcin Sękowski
Germany	Federal Agency for Cartography and Geodesy (BKG), Frankfurt a.M.	FG5-301 and AQG-A02	no no	yes[1] no	AG-6 AG-7	Reinhard Falk Julian Glässel
Netherlands	Technical University of Delft	FG5(X)-234	No	No	AG-8	Rene Reudink
~~France~~	~~Universite de Montpellier~~	~~FG5-228~~ ~~?AQG-A01~~	~~No~~ ~~no~~	~~No~~ ~~No~~	~~AG-9~~ ~~AG-10~~	~~Nicolas Le Moigne~~ ~~X~~
France	University of Strasbourg	FG5-206	No	Yes	AG-11	Jean-Daniel Bernard
Norway	NMBU/Kartverket	FG5-226 FG5X-250	no no	No No	AG-12 AG-13	Vegard Ophaug Kristian Breili
Poland	Faculty of Geodesy and Cartography Warsaw University of Technology	FG5-230	no	No	AG-14	Marcin Rajner Tomasz Olszak

Great Britain	NERC	FG5-229	no	No	AG-15	Victoria Smith
Denmark	DTU Space	A10-019	no	No	AG-16	Hergeir Teitsson Gabriel Strykowski
Belgium	Royal Observatory of Belgium	FG5-202	no	Yes	AG-17	Stefaan Castelein Bert Frederick
Czech Republic	Pecny	FG5X-215H	yes	Yes	AG-18	Vojtech Palinkas Jakub Kostelecky
Germany	GFZ Potsdam	AQG-B02?	no	No	AG-19	Marvin Reich

[1]Changes have been made to the FG5-301 since the EURAMET.M.G-K3 comparison

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 Gravity Reference System and Frame processing standards [2]. Corrections are applied for

- the gravimetric Earth tides in the zero-frequency tide system,
- 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 [2] 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 https://www.iers.org/IERS/EN/DataProducts/EarthOrientationData/eop.html

The start and end time of the measurement of the observations which are contributing to the measurement shall be reported.

Throughout the duration of the comparison, changes in local gravity will be continuously monitored with the Superconducting gravimeter GWR SG 054. The relevant corrections will be applied to the measurand during the evaluation of results. All relevant information concerning the measurements and corrections will be made available to the participants after the comparison (draft A).

The gravity change along the vertical at each comparison site can be given as a function of the height z by a first degree polynomial $g(z) = \gamma z + g_0$. Thus, the vertical gravity gradient (VGG) at the site is described by the parameter γ. Preliminary values of the VGGs at each measurement location are given in Annex D. Participants in the comparison can contribute to the determination of a second degree polynomial determination of the VGG by doing gradient measurements with their own relative gravimeter during their visit at OSO. 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 final VGGs will be used to transfer the g-values from the instrumental reference heights to the comparison reference height of 1.25 m.

4. Methods of measurement

Details concerning the instrumentation and methods of the absolute measurements should be described by each participant (Annex A).

5. Program of the measurements

A 3-site gravity network is proposed for the measurements. Each gravimeter should measure at each of the three gravity sites (Figure 1 and Figure 2). A particular gravimeter can occupy the given site within 23 hours, starting at 11 am of the specified date and ending at 10 am of the next day (the remaining one hour is for gravimeter movements). The comparison will be organized in seven sessions each with measurements starting on Tuesday. Therefore, the measurements at three sites should be finished on Friday. In case of instrumental troubles, the local organizer can permit an additional re-measurement from Thursday to Friday. The measurements in week 25 will start on Monday June 20 and end on Thursday June 23, due to the Midsummer holiday on Friday June 24.

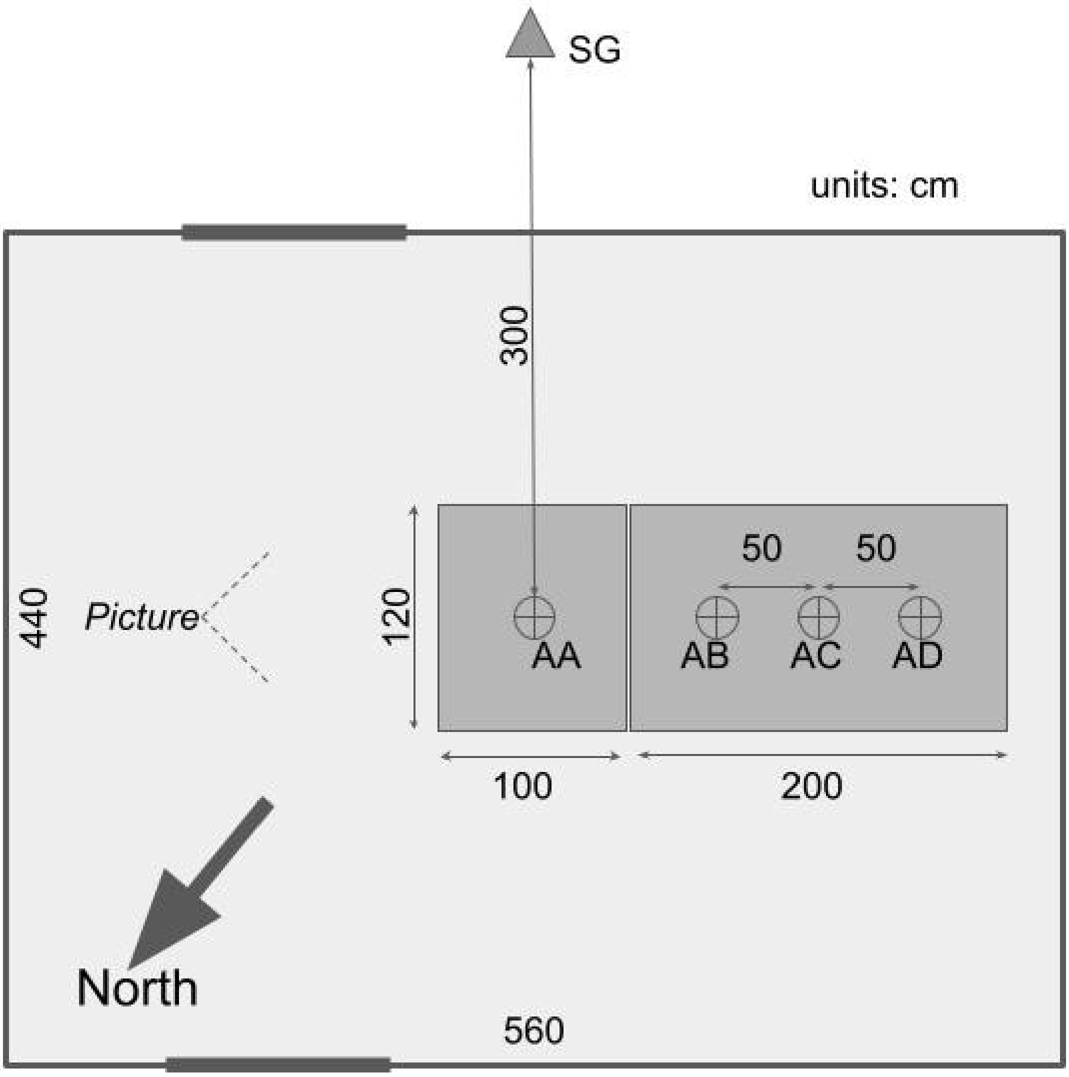

FIGURE 1. A sketch of the comparison site at OSO. Point AC will not be occupied in the comparison.

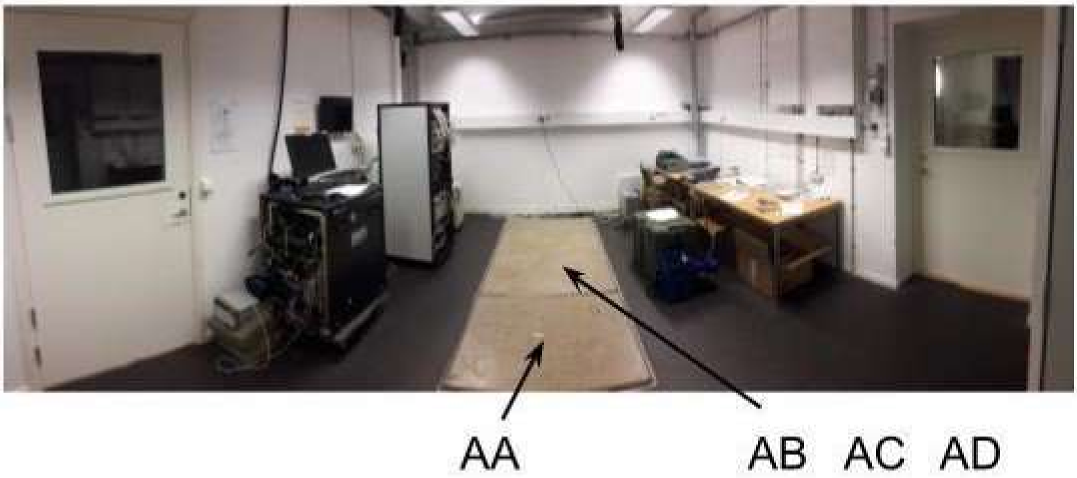

FIGURE 2. A photo of the comparison site at OSO. Notice that the table on the right side of the pillars will be removed before the comparison starts. Also notice that the point AC will not be used in the comparison.

6. Measurement timetable

The measurement timetable is given in Table .

TABLE 2. Measurement schedule. It may be subject to change

Date	Pillar	AA	AB	AD
Week 19				
09.05.2022	Monday			
10.05.2022	Tuesday	AG-1	-	AG-3
11.05.2022	Wednesday	AG-3	AG-1	-
12.05.2022	Thursday	-	AG-3	AG-1
13.05.2022	Friday			
Week 22				
30.05.2022	Monday			
31.05.2022	Tuesday	AG-11	AG-4	AG-5
01.06.2022	Wednesday	AG-5	AG-11	AG-4
02.06.2022	Thursday	AG-4	AG-5	AG-11
03.06.2022	Friday			
Week 23				
06.06.2022	Monday			
07.06.2022	Tuesday	AG-2	-	AG-18
08.06.2022	Wednesday	AG-18	AG-2	-
09.06.2022	Thursday	-	AG-18	AG-2
10.06.2022	Friday			
Week 24				
13.06.2022	Monday			
14.06.2022	Tuesday	AG-17	AG-16	AG-15
15.06.2022	Wednesday	AG-15	AG-17	AG-16
16.06.2022	Thursday	AG-16	AG-15	AG-17
17.06.2022	Friday			
Week 25				

20.06.2022	Monday	AG-13	AG-19	AG-12
21.06.2022	Tuesday	AG-12	AG-13	AG-19
22.06.2022	Wednesday	AG-19	AG-12	AG-13
23.06.2022	Thursday			
24.06.2022	Friday			
Week 26				
27.06.2022	Monday			
28.06.2022	Tuesday	AG-6	AG-7	AG-14
29.06.2022	Wednesday	AG-14	AG-6	AG-7
30.06.2022	Thursday	AG-7	AG-14	AG-6
01.07.2022	Friday			
Week 27				
04.07.2022	Monday			
05.07.2022	Tuesday	AG-8	~~AG-9~~	~~AG-10~~
06.07.2022	Wednesday	~~AG-10~~	AG-8	~~AG-9~~
07.07.2022	Thursday	~~AG-9~~	~~AG-10~~	AG-8
08.07.2022	Friday			

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. Mirjam Bilker-Koivula and Andreas Engfeldt will be responsible for reducing the submitted gravity values to a common height (1.25 m) using the measured vertical gravity gradients at each pier.

The deadline for submission of the results is 1.8.2022.

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*" [3].

Uncertainty of measurements should be estimated according to the GUM [4] where possible. The calculation of uncertainty can be divided in two steps:

1. <u>uncertainty budget of the instrument</u> that could include the following influence parameters:

- Laser frequency
- Rb-clock frequency
- Gravity gradient measurement
- 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 could include 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
- Coriolis acceleration effect
- Floor (instrument) recoil effect
- Gravity gradient (transfer to 1.25 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: $$c_i \approx \left.\frac{\Delta g}{\Delta x_i}\right|_{X_1=x_1,\dots,X_N=x_N} \quad (2)$$
- 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: $\nu_{eff} = \frac{u^4(y)}{\sum_{i=1}^{n} \frac{u_i^4(y)}{\nu_i}}$ (7)
- coverage factor (p=level of confidence): $k = f(\nu_{eff}, p)$ (8)
- expanded standard uncertainty:
  note: $|g|$ 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 **Fel! Hittar inte referenskälla.**. $U(g) = k \cdot u(g) + |\Delta g|$ (9)
- relative expanded standard uncertainty: $U_{rel}(g) = \frac{U(g)}{g}$ (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. In case a full uncertainty budget is not provided, the participant is requested to provide information on what the uncertainties and corrections given in Annex are based on (calculation, estimation, literature,…).

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 to separate the systematic and stochastic part of the uncertainty budget and to improve the approach of the least-squares adjustment.

9. Results elaboration and link to the EURAMET.M.G-K3

The results of the comparison will be the Comparison Reference Values, CRVs, for each site with their uncertainties evaluated using all the measurements performed by all the gravimeters participating at the comparison linked to the results of the EURAMET.M.G-K3 comparison.

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

$$g_{ik} = g_k + \delta_i + \varepsilon_{ik}, \quad (11)$$

with the 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}.

To obtain a unique solution for the comparison reference value, CRV, a weighted condition will be used:

$$\sum_i w_i \delta_i = d \quad (13)$$

where the weights $w_i = u_o^2/u_i^2$ will be 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 the EURAMET.M.G-K3 will be provided by the linking converter *d* representing the non-weighted/weighted mean of their Degrees of Equivalence, DoEs, at the CCM.G-K2.2017 of the linking participants. The final DoEs of the gravimeters participating at the comparison will be calculated from the difference between the gravimeter measurements and the CRVs.

The results 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.

10. Accommodation and travels

The Onsala Space Observatory is situated about 16 km south west of Kungsbacka and about 40 km south of Gothenburg (Göteborg) in Sweden and has the coordinates 57.39640 N and 11.92590 E. At the Space Observatory there are some options for accommodation, a little bit depending on if other researchers are staying there or not. There are two rooms which are like "normal" hotel standard and there is a house with three bedrooms and common bathrooms and kitchen and there is a house with very many bedrooms and common bathrooms and kitchen. Towels and bed linen cost extra and cleaning is not included in the price. In Gottskär (6 km east of Onsala), Kungsbacka and the southern part of Gothenburg (which means Mölndal), there are hotel rooms available for those who don't want to stay at the Space Observatory. For booking anything at the Space Observatory, please mail Maxime Mouyen. For booking the hotels, please do it yourself.

There are two ways to travel to Onsala Space Observatory. One is to go by the ferry boat (Stena Line) between Kiel and Gothenburg and then travel south via road 158 and then turn right in a roundabout toward Gottskär and later on turn right towards Råö. Another is to travel via Denmark to either Malmö or Helsingborg and then go by road E4 north and turn off at exit 59 (Kungsbacka S, Gottskär, Onsala) and follow the signs towards Onsala and later Mariedal and Råö.

11. References

[1] CCM-IAG Strategy for Metrology in Absolute Gravimetry, 2014. http://www.bipm.org/wg/CCM/CCM-WGG/Allowed/2015-meeting/CCM_IAG_Strategy.pdf

[2] Wziontek, H., Bonvalot, S., Falk, R. et al. (2021) Status of the International Gravity Reference System and Frame. J Geod 95, 7. https://doi.org/10.1007/s00190-020-01438-9US Standard Atmosphere, NASA-TM-X-74335, NOAA 77-16482, 1976.

[3] 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

[4] 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

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 FG5X), 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 be used.

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

Indicate the value of the applied self-attraction, diffraction or another (e.g. verticality, Coriolis) corrections with associated uncertainties

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

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
Groundw ater effect	Unknow n		Unknow n				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**	$\mathbf{m{\cdot}s^{-2}}$	
		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**	$\mathbf{m{\cdot}s^{-2}}$	
		Relative expanded uncertainty (corrections not applied), $U_{rel} = U/g$							**8.0E-09**		

Annex D Parameters of the Onsala Gravity Comparison site

Name of station: Onsala (ONS)
Benchmark (station) designations: AA, AB, AD
Latitude: 57.39640 N
Longitude: 11.92590 E
Altitude: 7.50 m

TABLE D. 1. Vertical gravity gradient, to be updated according to new measurements

Site	Vertical gravity gradient µGal/cm
Onsala AA	-3.160
Onsala AB	-3.160
Onsala AD	-3.120

TABLE D.2. Observed tidal parameters (from the observation result of the GWR SG 054 superconducting gravimeter)

```
TIDALPARAM=   .000000  .000000    1.00000    0.0000 M0S0 #tidal param.
TIDALPARAM=   .000001  .002400    1.16000    0.0000 LONG #tidal param.
TIDALPARAM=   .002401  .003450    2.91010  -24.8900 SA   #tidal param.
TIDALPARAM=   .003451  .005918    1.11735   -3.5400 SSA  #tidal param.
TIDALPARAM=   .005919  .008510    1.58376   -9.7100 STA  #tidal param.
TIDALPARAM=   .008511  .010960    1.77749   22.9300 SQA  #tidal param.
TIDALPARAM=   .010961  .044660    1.08405    1.1700 MM   #tidal param.
TIDALPARAM=   .044661  .080800    1.14242    0.0100 MF   #tidal param.
TIDALPARAM=   .080801  .115420    1.14761   -0.4200 MTM  #tidal param.
TIDALPARAM=   .115421  .250000    1.15726   -6.3100 MSQM #tidal param.
TIDALPARAM=   .250001  .870024    1.15095   -0.4800 SIG1 #tidal param.
TIDALPARAM=   .870025  .906320    1.14498   -0.3400 Q1   #tidal param.
TIDALPARAM=   .906321  .940490    1.14826    0.1200 O1   #tidal param.
TIDALPARAM=   .940491  .974190    1.15235    0.2200 M1   #tidal param.
TIDALPARAM=   .974191  .998030    1.15482    0.1500 P1   #tidal param.
TIDALPARAM=   .998031 1.000148    1.10669   -2.3300 S1   #tidal param.
TIDALPARAM=  1.000149 1.003653    1.14098    0.1400 K1   #tidal param.
TIDALPARAM=  1.003654 1.005625    1.26419    1.0400 PSI1 #tidal param.
TIDALPARAM=  1.005626 1.013692    1.17893   -0.2700 PHI1 #tidal param.
TIDALPARAM=  1.013693 1.044805    1.16117   -0.1000 J1   #tidal param.
TIDALPARAM=  1.044806 1.216400    1.15611    0.0100 OO1  #tidal param.
TIDALPARAM=  1.216401 1.837970    1.13158   -0.1500 3N2  #tidal param.
TIDALPARAM=  1.837971 1.872145    1.14168    1.5400 2N2  #tidal param.
TIDALPARAM=  1.872146 1.906465    1.18469    2.1000 N2   #tidal param.
TIDALPARAM=  1.906466 1.942756    1.19367    1.2700 M2   #tidal param.
TIDALPARAM=  1.942757 1.976930    1.18960   -0.4900 L2   #tidal param.
TIDALPARAM=  1.976931 2.003035    1.18677    0.3400 S2   #tidal param.
TIDALPARAM=  2.003036 2.182850    1.19937    0.2600 K2   #tidal param.
TIDALPARAM=  2.182851 3.333333    1.08563    1.0400 M3   #tidal param.
TIDALPARAM=  3.333334 4.000000    5.55860 -164.0800 M4   #tidal param.
```