Consultative Committee on Mass and Related Quantities (CCM)
Working Group on Gravimetry (WGG)
IAG Sub-Commission 2.1 "Gravimetry and Gravity networks"
Study Group 2.1.1 on Comparison of Absolute Gravimeters (SGCAG)

8th International Comparison of Absolute Gravimeters ICAG-2009

BIPM, 2009

CCM.G-K1 Key Comparison and Pilot Study
Pilot laboratory BIPM

Technical Protocol

Technical Protocol of the 8th ICAG-2009

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1. Introduction

The ICAG-2009 is organized in accordance with the proposal of the 3rd Joint Meeting of the CCM WGG and SGCAG 2.1.1 of the IAG on 24 August 2007.

ICAG-2009 consists in a unique comparison that includes a CIPM-Key (Comité International des Poids et Mesures) Comparison and a CIPM-Pilot Study.

The status of Key Comparison (KC) for ICAG-2009 was approved by the CCM. Only National Metrology Institutes that are signatories of the CIPM Mutual Recognition Arrangement (CIPM MRA) and laboratories officially designated by those institutes can participate in a Key Comparison, their measurements can contribute to the evaluation of the KCRVs (Key Comparison Reference Value) and their degrees of equivalence can be published in the Key Comparison Data Base (KCDB). Only results of absolute measurements will be used in the KC part of ICAG-2009 to evaluate the KCRVs. This Key Comparison is designated CCM.G-K1.

The meeting has nominated the BIPM as pilot laboratory. The members of the steering committee of the ICAG-2009 are: L. Vitushkin (BIPM), H. Baumann (METAS), M. Becker (IPG DTU), O. Francis (LU, ECGS), A. Germak (INRiM), Z. Jiang (BIPM), V. Palinkas (VUGTK/RIGTC), L. Robertsson (BIPM), H. Wilmes (BKG).

The steering committee held its 1st meeting in Sevres, 21 November 2008 at BIPM and the 2nd meeting in Prague, 11-12 May 2009.

One of the important reasons to support the key comparison status for the comparison of absolute gravimeters at the BIPM is that the absolute gravity measurements with relative uncertainty of less than 1 part in 10^8 are necessary in the watt-balance experiments currently being carried out at several metrology institutes. Such systems are the potential means for the realization of a proposed re-definition of the mass unit (kilogram) currently under intense discussion. Another reason is to establish and maintain a precise and consistent gravity reference system in SI units which can act as the global basis for geodetic and geophysical observations.

However, the steering committee has also taken steps to open ICAG-2009 to those participants who would be excluded from participation in a CCM.G-K1, or who do not wish to participate in it. The steering committee proposes therefore to accept in ICAG-2009 also other absolute gravimeters for participation in the Pilot Study only. The Pilot Study of ICAG-2009 will follow as closely as possible the rules of KCs (see website of the BIPM www.bipm.org/en/convention/mra) but certain procedural rules will be relaxed to allow a wider participation. The steering committee believes it is highly desirable for ICAG-2009 to include the absolute gravimeters of the best metrological quality, whether they belong to national metrology laboratories of the Regional Metrology Organizations (as defined by the CIPM MRA) or to other organizations.

Relative measurements needed to support comparisons among absolute gravimeters during the ICAG-2009 will be organized by Z.Jiang and M.Becker. Relative measurements will determine the gravity field distribution with a height above the benchmark at the gravity stations of the BIPM. A limited number of gravimeters will be invited to carry out the relative measurements.

The 1st draft of the Technical Protocol for the ICAGs was prepared by the CCM-WGG Discussion Group 2 (Moderator Alessandro Germak) and discussed at the 2nd Joint meeting of CCM-WGG and SGCAG. The present version of the Technical Protocol is the result of this discussion and later discussions by e-mail.

The first announcement on the organization of the 8th International Comparison of Absolute Gravimeters at the BIPM was circulated on 17 November 2008. The second announcement was circulated on 2nd June 2009.

The organization of the ICAG-2009, including the development of the technical protocol, has to attain the aims of key comparison (KC) [1]:

- the comparison tests all the principal techniques in the field;
- the results are clear and unequivocal;
- the results are robust;
- the results are easy to compare with those of corresponding comparisons carried out by regional metrology organizations; and
- overall, the comparisons are sufficient in range and frequency to demonstrate and maintain equivalence between the participating laboratories.

The technical protocol specifies in detail the procedure to be followed for the comparison [1].

2. Participants

Following the rules set up by the BIPM-CIPM [1], the participants should be chosen as follows:

"Participation in a CIPM key comparison is open to laboratories having the highest technical competence and experience, normally the member laboratories of the appropriate Consultative Committee. Those laboratories that are not members of a Consultative

Committee and not NMIs (National Metrology Institute) must be nominated by the designated national metrology institute referred to in paragraph 1.4. as being responsible for the relevant national measurement standards. In choosing participants, the Consultative Committees must take proper account of regional representation. The number of laboratories participating in CIPM key comparisons may be restricted for technical reasons".

For a KC, the CCM-WGG is responsible for choosing the participants according to the Guideline for KC. The criteria could be the claimed uncertainty of measurement, the traceability of all parameters to national standards and an adequate number of participants from each RMO (Regional Metrology Organisations).

For participation in a pilot study, the requirements are less stringent and participation can be from Associates of the General Conference on Weights and Measures (*Conférence Générale des Poids et Mesures*, CGPM), as well as from Members of the Metre Convention (*Convention du Mètre*). Pilot studies are not published in Annex B of the Key Comparison Database but can be published in the open literature or in the technical supplement to Metrologia. Even if there is no formal reference value in a pilot study, as this concept is reserved for Key Comparisons, its calculation is encouraged. Moreover, analysis of the results can be used to benchmark the performance of participants and can be used as evidence of calibration and measurement capabilities (CMCs) for laboratories which participate in the CIPM MRA in those cases where there has been no Key Comparison.

In view of the five gravity stations schedule for the absolute measurement at the BIPM in a limited time (not more than three weeks), the foreseen number of the participants in the ICAG-2009 is estimated at 26 (tab 1a, b). The final choice of the participants will be fixed by the steering committee.

Participants to the relative measurements are foreseen to be 10 (tab. 2).

To take part in the comparison, all participants are asked to fill the form in annex I and return it to the Pilot Laboratory.

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Table 1a. Preliminary list of participants to ICAG-2009

Key Comparison			
number	*Gravimeter*	*Institute*	*Country*
KC-1	FG5-108	BIPM	
KC-2	FG5-209	METAS	Switzerland
KC-3	FG5-211	CEM/IGN	Spain
KC-4	FG5-213	NMIJ/AIST	Japan
KC-5	FG5-215	VÚGTK/RIGTC	Czech Republic
KC-6	FG5-221	FGI	Finland
KC-7	FG5-224	CMS/ITRI	Chinese Taipei
KC-8	FG5-105	NRC	Canada
KC-9	FGL-103	KRISS	Rep. of Korea
KC-10	A10-005	TÜBITAK UME	Turkey
KC-11	IMGC-02	INRiM	Italy
KC-12	NIM-2	NIM	China
KC-13	JILAg-6	BEV	Austria
KC-14	SYRTE-CAG	SYRTE	France
Pilot Study			
number	*Gravimeter*	*Institute*	*Country*
PS-1	FG5-101	BKG	Germany
PS-2	FG5-102	NOAA	USA
PS-3	FG5-216	Univ. of Luxembourg	Luxembourg
PS-4	FG5-220	IfE	Germany
PS-5	FG5-228	Univ. Montpellier	France
PS-6	FG5-230	Warsaw Univ. of Technology	Poland
PS-7	FG5-233	Lantmäteriet	Sweden
PS-8	FG5-238	INGV	Italy
PS-9	A10-014	IPGP-IRD-IGN	France
PS-10	A10-020	Inst. of Geodesy and Cartography	Poland
PS-11	MPG-2	Max Planck Institute for Physics of Light	Germany

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Table 1b: Coordinates of participants to ICAG-2009

Nr. KC/PS	Organization	gravimeter	Contact Person/s	Address	Tel	Fax	E-mail	Country
KC-1	Bureau International des Poids et Mesures (BIPM)	FG5-108	Leonid Vitushkin Lennart Robertsson,	Pavillon de Breteuil 92132, Sèvres, France	+33 1 45 07 70 81 +33 1 45 07 70 53	+33 1 45 34 20 21	Lvitushkin@bipm.org, eluar@mail.ru ; Lroberts@bipm.org	
KC-2	Federal Office of Metrology (METAS), Switzerland	FG5-209	Henri Baumann	Lindenweg 50, 3003 Bern-Wabern	+41 31 32 33 243	+41 31 32 33 210	henri.baumann@metas.ch	Switzerland
KC-3	Spanish Metrology Centre (CEM/IGN), Spain	FG5-211	Nieves Medina	Head of Mass Division, C/Alfar 2, Tres Cantos, Madrid	+34918074789	+34918074807	mnmedina@cem.mityc.es	Spain
KC-4	National Metrology Institute of Japan/ National Institute of Advanced Industrial Science and Technology (NMIJ/AIST), Japan	FG5-213	Shigeki Mizushima	Mechanical Metrology Division, AIST Tsukuba Central 3, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8563	+81-29-861-4352	+81-29-861-4399	s.mizushima@aist.go.jp	Japan
KC-5	Geodetic Observatory Pecný (VÚGTK/RIGTC), Czech Republic	FG5-215	Vojtech Palinkas	Ondrejov 244, CZ-25165 Ondrejov	+420 323649235	+420 323649236	vojtech.palinkas@pecny.cz	Czech Republic
KC-6	Finnish Geodetic Institute (FGI), Finland	FG5-221	Jaakko Mäkinen Mirjam Bilker-Koivula	Geodeetinrinne 2 FIN-02430 Masala	+358 9 29555317 +358 9 29555218	+358 9 2955211	Jaakko.Makinen@fgi.fi Mirjam.Bilker@fgi.fi	Finland
KC-7	Center for Measurement Standards, Industrial Technology Research Institute (CMS/ITRI), Chinese Taipei	FG5-224	Chiungwu Lee	Bldg. 16, 321 Kuang Fu Rd., Sec. 2, Hsinchu, Taiwan 300	+886 3 5743772	+886 3 5726445	JohnLee@itri.org.tw	Chinese Taipei
KC-8	National Research Council of Canada Institute for National Measurement Standards (NRC), Canada	FG5-105	Dave Inglis, Jacques Liard, Ian Robinson	Campus, 1200, Montreal Road, Ottawa Natural Resources Canada (NRCAN-RNCAN) Geodetic Survey Division, 615 Booth, Ottawa, Ontario, K1A 0E9	+1-613-993-9384 +1 613 992 4889	+1-613-990-6439 +1 613 995 3215	Dave.Inglis@nrc-cnrc.gc.ca Jacques.liard@nrcan.gc.ca	Canada
KC-9	Korea Research Institute of Standards and Science (KRISS), Rep. Korea	FGL-103	In-Mook Choi	1 Doryong, Yuseong, Daejeon, 305-340	+82-42-868-5117	+82-42-868-5679	mookin@kriss.re.kr	Rep.Korea
KC-10	Ulusal Metroloji Enstitüsü (UME/TÜBİTAK), Turkey	A10-005	Baki Karaboce	Gebze Yerleşkesi, P.K.54 41470 Gebze Kocaeli	+90 262 6795000/3102	+90 262 6795001	baki.karaboce@ume.tubitak.gov.tr	Turkey
KC-11	Istituto Nazionale di Ricerca Metrologica (INRiM), Italy	IMGC-02	Alessandro Germak Giancarlo D'Agostino	Strada delle cacce, 73 I-10135 Torino	+39 011 3919 924 +39 011 3919 919	+39 011 3919 926	A.Germak@inrim.it G.Dagostino@inrim.it	Italy
KC-12	National Institute of Metrology (NIM), China	NIM-2	Wangxi Ji	Bei San Huan Dong Lu 18# Beijing 100013		+86-10-64226352	wxji@nim.ac.cn, areal4u@yahoo.com	China
KC-13	Bundesamt für Eich- und Vermessungswesen (Federal Office of Metrology and Surveying) (BEV), Austria	JILAg-6	Diethard Ruess Christian Ullrich	Schiffamtsgasse 1-3, 1020 Wien	+43-1-21110-3211 mobile: +43-676-8210-3211 +43-1-21110-3205	+43-1-21110-2224	diethard.ruess@bev.gv.at christian.ullrich@bev.gv.at	Austria

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KC-14	Systèmes de Référence Temps-Espace SYRTE, France	Cold Atom Gravimeter/SYRTE	Franck Pereira Dos Santos	SYRTE - CNRS UMR8630 Observatoire de Paris, 61 av. de L'Oservatoire 75014 Paris	+33 1 01 40 51 23 86	+33 1 43 25 55 42	franck.pereira@obspm.fr	France

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PS-1	Bundesamt für Kartographie und Geodäsie, Germany	FG5-101 (AXIS Instruments, upgraded by micro-g Lacoste)	Herbert Wilmes Reinhard Falk	Richard-Strauss-Allee 11, D-60598 Frankfurt/Main	+49-(0)69/6333-252	+49-(0)69/6333-425	herbert.wilmes@bkg.bund.de reinhard.falk@bkg.bund.de	Germany
PS-2	National Geodetic Survey (NOAA), USA	FG5-102	Daniel Winester Mark Eckl	Table Mountain Observatory 8600 North 39th St., Longmont, CO 80503, NGS41-SSMC3-Sta 8530 1315 East-West Highway Silver Spring, MD 20910	1-303-497-7405 1-303-713-3215 ext 117	1-303-497-7406 1-301-713-4175	Daniel.Winester@noaa.gov Mark.Eckl@noaa.gov	USA
PS-3	University of Luxembourg, Luxembourg	FG5-216	Olivier Francis	FTSC Campus Kirchberg, 6 rue Coudenhove-Kalergi, L-1359 Luxembourg	+352 46 66 44 6264	+352 46 66 44 5500	Olivier.francis@uni.lu	Grand-Duchy of Luxembourg
PS-4	IfE Institute für Erdmessung, Leibniz Universität Hannover (LUH), Germany	FG5-220	Ludger Timmen	Schneiderberg 50, 30167 Hannover	+49 511 762 3398	+49 511 762 4006	timmen@ife.uni-hanover.de	Germany
PS-5	Géosciences Montpellier Univ. Montpellier, France	FG5-228	Nicolas Le Moigne	- UMR 5243 CC 060 - Place Bataillon F-34095 Montpellier	+33 4 67 14 49 81	+33 4 67 14 36 42	nicolas.lemoigne@gm.univ-montp2.fr	France
PS-6	Department of Geodesy and Geodetic Astronomy,Warsaw Univeristy of Technology, Poland	FG5-230	Marcin Barlik	Department of Geodesy and Geodetic Astronomy, Warsaw University of Technology, 1 Pl. Politechniki, PL 00-661 Warsaw	+48 022 234 7237	+48 022 621 0052	m.barlik@gik.pw.edu.pl	Poland
PS-7	Lantmäteriet (Swedish mapping, cadastre and registry authority), Geodetic Research Division, Sweden	FG5-233	Jonas Ågren	Lantmäteriet Geodetic Resarch Division SE- 801 82 Gävle	+46 26 63 34 20	+46 26 61 06 76	jonas.agren@lm.se	Sweden
PS-8	National institute of Geophysics and Volcanology (INGV), Italy	FG5-238	Ciro Del Negro Greco Filippo	Piazza Roma 2, 95131, Catania	:+39 095 7165823 +39 095 7165827	+39 095 435811	delnegro@ct.ingv.it greco@ct.ingv.it	Italy
PS-9	Université Paris Diderot, Institut de Physique du Globe de Paris, Géophysique spatiale et planétaire – Bâtiment Lamarck (IPGP) Université de Toulouse (CNRS, IRD) Bureau Gravimétrique International Observatoire Midi-Pyrénées, France	A10-14	Michel Diament, Sylvain Bonvalot	Case 7011 35 rue Hélène Brion, 75025 Paris Cedex 13 URM5563/LMTG– 14avenue Edouard Belin, 314 Toulouse	+33 1 57 27 84 80 +33 5 61332651 (2980)	+33 1 57 27 84 82 +335 6125 3098	diament@ipgp.jussieu.fr bonvalot@ird.fr	France
PS-10	Institute of Geodesy and Cartography Geodesy and Geodynamics Department, Poland	A10-20	Jan Krynski Marcin Sekowski	27 Modzelewskiego St. 02-670 Warsaw	+48 22 3291904 +48 22 3291905	+48 22 3291950	jan.krynski@igik.edu.pl msek@igik.edu.pl	Poland
PS-11	Max Planck Institute for Physics of Light, Germany	MPG-2	L.J.Wang S. Svitlov Sergiy	Max Planck Institute for the Science of Light Günther-Scharowsky-Str. 1, Building 24 D-91058 Erlangen	+49 (0) 9131 68 77 200 +49 (0) 9131 68 77 227	+49 (0) 9131 68 77 299 +49 (0) 9131 68 77 209	lwan08540@yahoo.com lwan@optik.uni-erlangen.de Sergiy.Svitlov@mpl.mpg.de Svitlov@physik.uni-erlangen.de	Germany

Table 2: Preliminary list of the institutes which have declared their participation in the relative measurements of ICAG-2009

No.	Institute	Grv	No.	Operator
1	BIPM	Scintrex CG5	080240348	Laurent TISSERAND,Zhiheng JIANG zjiang@bipm.org
2	Department of Meteorology and Geophysics	Scintrex CG5	?	Bruno Meurers bruno.meurers@univie.ac.at
3 4	University of Luxembourg	Scintrex CG5	021210008 021210010	Olivier Francis Olivier.francis@uni.lu
5	LNE-SYRTE	Scintrex CG5	050210105	Sébastien Merlot sebastien.merlet@obspm.fr
6 7	BRGM	Scintrex CG5/3	CG3#245 CG5#028	Philippe Jousset/ p.jousset@brgm.fr Pajot Gwendoline/ g.pajot@brgm.fr Fabriol Hubert/ h.fabriol@brgm.fr Carnec Claudie/ c.carnec@brgm.fr
8	Finnish Geodetic Institute	Scintrex CG5	31110052	Jaakko Mäkinen Jaakko.Makinen@fgi.fi Mirjam Bilker-Koivula Mirjam.Bilker@fgi.fi
9	IPGD Angewandte Gravimetrie	ZLS Burris	B-25	Matthias Becker becker@ipg.tu-darmstadt.de Richard Schulz office@angewandte-gravimetrie.de Karin Schulz
10	RIGTC, Geodetic Observatory Pecny	ZLS Burris	B-20	Vojtech Palinkas vojtech.palinkas@pecny.cz

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 according to the Resolution 16 of the 18th General Assembly of the IAG 1983 to obtain "zero-tide” values for gravity [3].

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

Preliminary gradients to correct the results to the common reference height of 0.9 m, calculated by the BIPM, will be available for the absolute measurements.

The BIPM will provide the coordinates and elevation of the measuring sites (stations), tidal and ocean loading parameters, nominal air pressure, gravity gradients and barometric correction factor (Annex H).

The BIPM will measure continuously time series of atmospheric pressure at the BIPM sites during the comparison. Information on these measurements will be available during the comparison to the Pilot Study participants and after the comparison (draft A) to the Key-Comparison participants.

4. Methods of measurement

The methods of absolute measurements and measuring instruments used by the participants should be described by each participant (Annex A). This information is mandatory for the KC participants.

The measuring instruments and methods of evaluation used by the participants of the relative measurements should be described by each participant (Annex E).

5. Measurand stability

The gravimeter FG5-108, belonging to the BIPM, performed permanent measurements over almost one month during the ICAG-2001 and ICAG-2005. The observed variations of g-value measured by FG5-108 were within 1 μGal and that demonstrates the stability of gravity field at the BIPM. Nevertheless the BIPM will perform the additional measurements to monitor the stability of gravity field. It is planned that FG5-108 will perform the measurements at three stations in the frame of ICAG-2009 and then it can be installed at station A or A2 for some nightly measurements throughout the comparison.

6. Programme of the measurements

6.1 Absolute measurements

At its 2nd meeting on 11-12 May 2009 in Prague the Steering Committee proposed to optimize the gravity network of the BIPM to obtain a homogeneous coverage of all the gravity stations by multiple measurements.

A 5-stations gravity network is proposed for all the measurements. It means that all the gravimeters will be divided into groups of five gravimeters. Each gravimeter should measure at three gravity stations (table 3). All the stations are at the site B in the Pavillon du Mail.

We will have one-day breaks between all the three-day measurements by each group of five gravimeters. The breaks would be used to fix the problems that can happen with the gravimeters, allow to compensate for lost nights due to possible earthquakes or other disturbances and for the measurements at a fourth gravity station for those who wish to measure at one more station.

Table 3. Example of the schedule of absolute measurements for the first and second groups of gravimeters G# at the gravity stations S# in the frame of the five station program.

S1	S2	S3	S4	S5	day	date
G1	G2	G3	G4	G5	Day 1	14 Sept, Mon
G5	G1	G2	G3	G4	Day 2	15 Sept, Tue
G3	G4	G5	G1	G2	Day 3	16 Sept, Wed
					Day 4	17 Sept, Thu
G6	G7	G8	G9	G10	Day 5	18 Sept, Fri
G10	G6	G7	G8	G9	Day 6	19 Sept, Sat
G9	G10	G6	G7	G8	Day 7	20 Sept, Sun
					Day 8	21 Sept, Mon
G11	G12	G13	G14	G15	Day 9	22 Sept, Tue
G14	G15	G11	G12	G13	Day 10	23 Sept, Wed
G12	G13	G14	G15	G11	Day 11	24 Sept, Thu
					Day 12	25 Sept, Fri
G16	G17	G18	G19	G20	Day 13	26 Sept, Sat
					Day 14	27 Sept, Sun
					Day 15	28 Sept, Mon
					Day 16	29 Sept, Tue
G21	G22	G23			Day 17	30 Sept, Wed
					Day 18	1 Oct, Thu
					Day 19	2 Oct, Fri
					Day 20	3 Oct, Sat

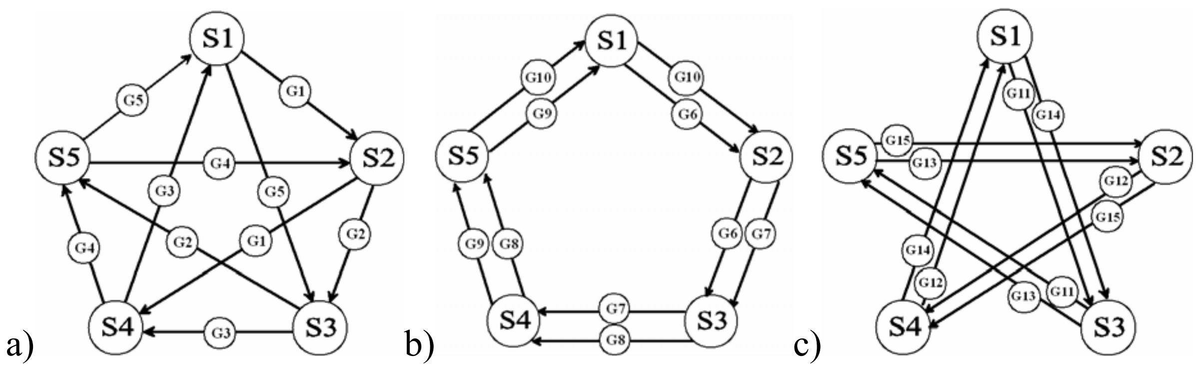


Fig. 1a – 1c. Links and gravity stations measured by the gravimeters G1–G15 according to the schedule in Table 3.

Links and gravity stations in Table 3 and in Fig. 1a – 1c are only the examples. Other appropriate schemes can be applied in the comparison following the real situation with the gravimeters (late arrivals, damages, malfunctions, etc.).

<u>*6.2 Relative measurements*</u>

The first aim of the relative measurements is to determine the vertical gravity gradient at the stations for the KC. The gradients are to be computed between the heights of 0.3 m, 0.9 m and 1.3 m and will be performed at the stations B, B1, B2, B3, B5, B6 on site B, the station A on site A and the stations WB1 and WB2 on site WB, totally 9 stations (Annex F).

The main relative gravity campaign (RGC) will be organized before and after the absolute measurements of the ICAG-2009 (see Table 3). In order to supply the preliminary gradients to the ICAG09 measurement campaign, at least 4 gravimeters should come and perform the measurements before mid-Sept.

7. Measurement timetable

Table 4. Distribution of the absolute gravimeters by groups (last update: 12.08.2009)

Group #	Date	Gravimeter				
	5-10 Sept	**NIM-II** NIM (KC)				
	8-10 Sept	**FG5-228** Univ. Montpellier (PS)	**A10-004** IPGP-IRD-IGN (PS)			
Group 1	14-16 Sept	**FGL-103** KRISS (KC)	**SYRTE** SYRTE (KC)	**FG5-213** NMIJ/AIST (KC)	**FG5-215** VÚGTK/RIGTC (KC)	**FG5-209** METAS (KC)
Group 2	18-20 Sept	**JILAg-6** BEV (KC)	**A10-005** TÜBITAK (KC)	**FG5-224** CMS/ITRI (KC)	**FG5-211** CEM/IGN (KC)	
Group 3	22-24 Sept	**FG5-105** NRC (KC)	**FG5-101** BKG (PS)			
Group 4	26-28 Sept	**MPG-2** Max Plank Inst. (PS)	**FG5-220** IfE (PS)	**FG5-216** Luxemburg Univ. (PS).	**FG5-102** NOAA (PS)	**FG5-230** WUT (PS)
Group 5	30 Sept – 2 Oct	**FG5-233** Lantmäteriet (PS)	**FG5-238** INGV (PS)	**A10-020** IGC (PS)	**IMGC-02** INRiM (KC)	**FG5-221** FGI (KC)

Notations:
KC: Key Comparison
PS: Pilot Study

Notes:
- SYRTE will make the tests of the gravimeter CAG in the Salle B from 3 September 2009.
- FG5-108 (BIPM) will perform the measurements in the frame of Key Comparison at three stations before 14 September or after 2 October.

Table 5. Schedule of the ICAG-2009 relative measurements *(last update: 15.06.2009)*

No. #	Institute/ Operator	Grv	Full Schedule	1st Period *	2nd Period **
1	BIPM Laurent TISSERAND, Zhiheng JIANG	Scintrex CG5	Yes	July 1-3	
2	Department of Meteorology and Geophysics Bruno Meurers	Scintrex CG5	Yes	Oct 5-7	Aug. 1-14
3/4	University of Luxembourg Olivier Francis	Scintrex CG5	No	July 6-10	
5	LNE-SYRTE Sébastien Merlet	Scintrex CG5	Yes	Oct 5-7	Aug. 1-14
6/7	BRGM *** Philippe Jousset, Pajot Gwendoline Fabriol Hubert, Carnec Claudie	Scintrex CG3 CG5	Yes	Oct 5-9	June & July *** Aug. 1-14
8	Finnish Geodetic Institute Jaakko Mäkinen Mirjam, Bilker-Koivula	Scintrex CG5	Yes	Oct 3-5	
9	IPGD, Matthias Becker Angewandte Gravimetrie, Richard Schulz, Karin Schulz	ZLS Burris	Yes	July 29 – Aug 1	
10	RIGTC, Geodetic Observatory Pecny Vojtech Palinkas	ZLS Burris		July 27-28	Sept 11-13

* 1st choice: measurement period proposed by the operator himself.
** 2nd choice: measurement period possibly arranged with BIPM (if you make this choice, please fix a three days' period and contact *zjiang@bipm.org*)
*** Perform precision levelling

8. Data report

All participants to the absolute measurement comparison are asked to fill the data sheet given in annex B with the results of calibration of their reference standards (laser and clock) (mandatory for the KC participants).

All participants should give the absolute measurement results for every measured point (station) in the table format given in annex C (mandatory for all participants).

All participants should give the relative measurement results for every measured point (station) in the table format given in annex G.

The dead line for submission of the results to the Pilot lab is 6 weeks after the measurements [1].

9. 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*" [1].

The participants should give information for the motion equation used in the software for least-square *g*-calculation. In addition, it is necessary to provide to the Pilot Laboratory the type of software used for tides calculation.

Uncertainty of measurements should be estimated (mandatory for KC participants) according to the GUM [2]. 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

Others 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 0.9 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: $$u^2(x_i) = s_i^2 \vee \frac{a_i^2}{k_a} \quad (1)$$
  note: k_a depends by the type of statistical distribution (2 for U distribution,, 3 for rectangular , 6 for triangular, etc.)
- 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: $$\nu_{eff} = \frac{u^4(y)}{\sum_{i=1}^{\nu} \frac{u_i^4(y)}{\nu_i}} \quad (7)$$
- coverage factor (p=level of confidence): $$k = f(\nu_{eff}, p) \quad (8)$$
- expanded standard uncertainty: $$U(g) = k \cdot u(g) + |\Delta g| \quad (9)$$
  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].
- relative expanded standard uncertainty: $$U_{rel}(g) = \frac{U(g)}{g} \quad (10)$$

An example of calculation of uncertainty is given in annex D. It contains the unified budget of uncertainty for FG5-type gravimeters, as result of the analysis done in the previous comparison (ICAG-2005) and accepted by the international community.

9.1 Frequency measurements during ICAG2009

The BIPM offers frequency measurements service during the ICAG2009 both of stabilized lasers and the Rb clocks. There will be 2 “first-come-first-served” tables available in room B for booking a “slot” for those measurements: one for the laser and one for the Rubidium clock. Please find a slot that suites you and book by gravimeter name and operator. The contact person for the Rb clock measurements is Laurent Tisserand while it is Lennart Robertsson for the laser frequency measurements.

The Rb reference frequency will be measured in place in room B using a phase/frequency meter provided by the TFG section and referenced to the distributed BIPM 10 MHz reference frequency. Measurement duration of about 30 minutes is foreseen. This allow for the measurements of the frequency and also the short term stability for addition indication that the clock performance is as expected.

The frequency of the stabilized lasers will be measured in the laser labs and the operators that want to have their frequency measured will need to bring the interferometer or, if they prefer, possibly only the laser itself to that lab. Due to possible technical complications we need some margin with these measurements and we plan to measure only one laser per day. If on the other hand, some measurements are made faster the possibility might appear to measure 2 lasers some days. Contact to Lennart Robertsson to know if additional free slots are available.

10. Results elaboration

10.1 Absolute measurements

The results of ICAG-2009 will be the Comparison Reference Values with their uncertainties evaluated using all the measurements performed by all the gravimeters participating in ICAG-2009.

The results of all the measurements (including the results of the measurements of the gravimeters participating in KC) will be processed together. Only a subset of all the data obtained using the AG participating in the KC will be used for the evaluation of the KC reference value. It will be used to calculate the compatibility between the laboratories participating to the KC and to verify the declared uncertainty as support to the Calibration Measurement Capabilities (CMC).

The symmetric scheme of the measurement plan allows the calculation of the reference values in different but easy ways. Median, arithmetic mean or weighted mean will be calculated and choose in order to have the minimum uncertainty in the reference value but also taking into the account possible correlated data, over- or underestimated uncertainties, etc.

Combined adjustment with the relative measurement will also be calculated in order to verify if the relative measurements can be useful to decrease the uncertainty of the reference value.

The Pilot Laboratory will process the data in different ways and the results will be presented in the Draft A report. 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 ICAG-2009 will be made public.

10.2 Relative measurements

Detailed explanations about the data elaboration are given in Annex F.

11. Transportation of the instrumentation and customs' formalities

Attached to the second announcement dated 2nd June 2009, two annexes were circulated in order to give instruction and, for the Pilot Laboratory, receive information related to the transportation of the instrumentation and customs' formalities (doc. procedures_ADM_ADM-DOU-F-12 and procedures_ADM_ADM-DOU-P-03).

12. References

[1] 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

[2] 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, ISBN 92-67-10188-9 http://www.bipm.org/en/publications/guides/gum.html

[3] International Earth Rotation and Reference Systems Service, IERS Conventions (2003), Dennis D. McCarthy and Gérard Petit (eds.), IERS Technical note No. 32, http://www.iers.org/documents/publications/tn/tn32/tn32.pdf

Annex A - Description of the absolute gravimeter

Manufacturer	
Model/Type	
s/n	
Year of fabrication/ Year of last factory service/date of last service by owner	
Method of the measurement of free-fall acceleration:	
Approximated reference height	
vibration-isolation device	
interferometer type	
Laser type	
Photo-detection board type	
Throw/drop length used during measurement, number of fringes acquired and fringes used for g-evaluation	
Mass of gravimeter and mass of electronics	
Software	
Add other information	
Picture	

Annex B - Results of the calibration of the laser frequency and verification of the clock frequency

Instrument	*Manufacturer*	*Model/Type*	*s/n*	*Date of calibration*	*Calibration value*	*Uncertainty (p=95%)*	*Coverage factor, k*
Laser							
Iodine cell							
Clock							

Annex C - Report of measurement results

Date	*Time (from÷to)*	*Gravimeter*	*Operator/s*	*Site*	*#sets, #drops*	Z_{ref}/mm	*gravity gradient/* $10^{-8}m\cdot s^{-2}/m$	*g @* $Z_{ref}/10^{-8}m\cdot s^{-2}$	*st. dev.* $/10^{-8}m\cdot s^{-2}$	$u/10^{-8}m\cdot s^{-2}$	*Degrees of freedom*	*Picture of the AG at the site*

Note: Z_{ref} is the instrumental reference height at corresponding site

Annex D - 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

Influence parameters, x_i	Value	Unit	u_i or a_i	Type A, □$_i$	Type B, a_i	Correction, □g	Type of distribution	Equivalent variance	Sensitivity coefficients	Contribution to the variance	Degrees of freedom, □$_i$	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, □$_{eff}$ (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), $U = ku + ?$□$g?$				**7.3E-08**	**$m{\cdot}s^{-2}$**
Relative expanded uncertainty (corrections not applied), $U_{rel} = U/g$				**7.4E-09**	

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	ms^{-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		ms^{-2}	±1E-09		1,0E-09	rectangular	3,3E-19	1	3,3E-19	30	5,8E-10
Earth tide evaluation		ms^{-2}	±1E-08		1,0E-08	rectangular	3,3E-17	1	3,3E-17	30	5,8E-09
Ocean loading correction evaluation		ms^{-2}	±0,5E-09		5,0E-09	rectangular	8,3E-18	1	8,3E-18	30	2,9E-09
Polar motion correction evaluation		ms^{-3}	±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		ms^{-2}	±7,5E-09		7,5E-09	rectangular	1,9E-17	1	1,9E-17	15	4,3E-09
Floor (instrument) recoil effect		ms^{-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)		$ms^{-2}{\cdot}m^{-1}$	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		ms^{-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	ms^{-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**	**ms^{-2}**
Relative expanded uncertainty (corrections applied), $U_{rel} = U/g$	**4,9E-09**	
Expanded uncertainty (corrections not applied), $U = ku + ?\Delta g?$	**7,8E-08**	**ms^{-2}**
Relative expanded uncertainty (corrections not applied), $U_{rel} = U/g$	**8,0E-09**	

Annex E - Description of the relative gravimeter and data evaluation

1	Manufacturer:	
2	Number of Instrument	
3	Method of reading:	
4	Calibration factor for conversion to milligal: ($\delta g \times$ calibration factor)	
5	Calibration line used for determining the calibration factor	
6	Date of calibration	
7	Periodical errors as defined below or with the correction formula (period, amplitude and phase):	
8	Top-to-beam height difference of gravimeter /mm:	
9	Owner and observer(s):	
11	Date of issue:	
10	Remarks:	

Annex F – ICAG-2009 relative gravity measurement and data processing strategy

Notation:

1 Gal = 1 cm s^{-2} = 1000 mGal

AG: Absolute gravimeter

RG: Relative gravimeter

g: Absolute gravity acceleration value in μGal (minus a constant value of 980 900 000 μGal)

δg: Difference of *g*

δg/δH: Vertical gradient

RGC: Relative Gravity Campaign co-organized with the ICAG

MSE: Mean square error given by a least-squares adjustment

Site, Station and Point : A site is comprised of one or several stations horizontally located in a isolated indoor laboratory. There are three sites: A, B and WB (cf. Figure 1F): A station is comprised of three or four points vertically aligned and benchmark fixed (cf. Figures 1B, 1C); A point is the location of 30 or 90 or 100 or 130 cm above the benchmark of a station (cf. Figure 1A)

KC: Key Comparison

PC: Pilot Comparison

Simple schedule: the minimum measurement schedule deigned for the KC

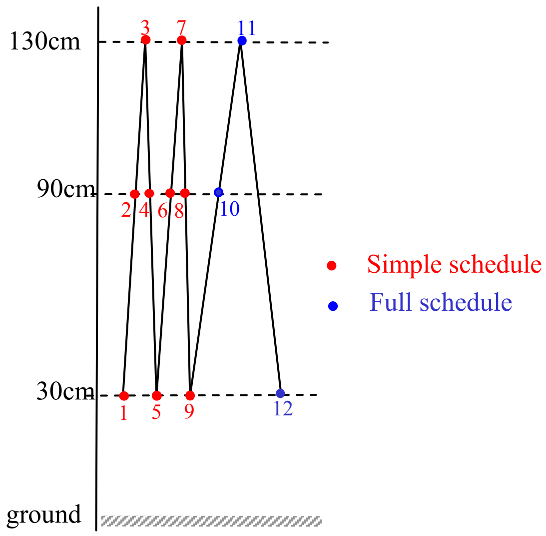
Full-schedule: designed for the PC and related scientific studies with more redundant measurements and closure constraints

Design of the vertical and horizontal δg measurement schedules

The measurement schedule is designed to achieve the lowest possible uncertainty in *δg* under the BIPM laboratory condition. They are following a scheme which has a closure based sequence with short and symmetrical time-distance intervals so as to minimize influence of the uncertainties due to gravimeter zero-drift, re-setting up, displacement and environmental influences etc . Fixed level tripods are used for the vertical *δg* measurements to avoid the errors in the height measure. The main point of a station is defined at 90 cm vertically above the ground surface benchmark to reduce the near ground non-linearity variation in *g*. The RGs were always set up to be oriented to the north. The RG sensor is close to the measured point to keep the eccentricity reduction smallest. There are two categories of the measurements schedules: the *simple* and the *full*. The first is designed for the KC and the second for the PC and the further precise gravimetry studies where more redundant measurements and closure constraints are required. Raw digital recordings without any analytic corrections, such as the Earth tide, zero-drift corrections etc. should be supplied to BIPM before leaving from BIPM.

Vertical δg ties

Figure 1A presents the schedule for the vertical *δg* measurement at a station. It is realized with the help of a set of BIPM-designed fixed-level tripods. There are 9 occupations at a station in the simple-schedule and 12 occupations in the full one. This should be carried out on the 9 stations A, B, B1, B2, B3, B5 and B6 (except for B4) as well as WB1, WB2. There are totally 81 occupations in the simple-schedule and 108 occupations for the full one. A point of 100 cm in height will be added on the station WB2 to coincide the reference height of the BIPM watt balance. But this will be made only by the specially scheduled RGs.

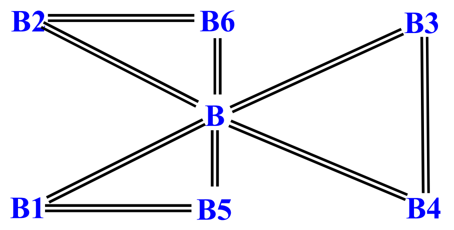


No.	1	2	3	4	5	6	7	8	9	10	11	12
Point/cm	30	90	130	90	30	90	130	90	30	90	130	30

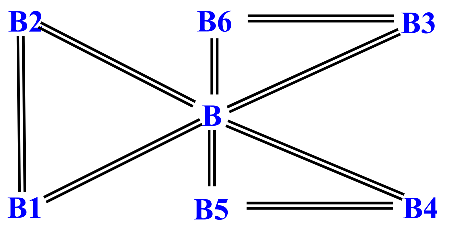
Figure 1A Vertical *δg* measurements at a station. There are 9 occupations in the simple-schedule and 12 occupations in the full-schedule. The vertical *δg* measurements should be carried out at the stations A, WB1 and WB2 as well as the 6 stations on site B. There are totally 81 occupations for the simple-schedule and 108 occupations for the full one. A point of 100 cm in height will be measured only by the specially scheduled RGs on the station WB2 to coincide the reference height of the watt balance.

Horizontal δg ties

On B site (Figure 1B): Horizontal *δg* grid measurement at site B performed on the height of 90 for the simple-schedule and 30, 90 and 130 cm for the full-schedule. There are two schemata: the odd-schema is for the odd-numbered gravimeters (1,3,5,7 and 9) in Table 1b and the even-schema is for the even-numbered gravimeters (2,4,6,8 and 10) in Table 1b. For a RG, there are 10 occupations in the simple-schedule and 30 occupations in the full-schedule.

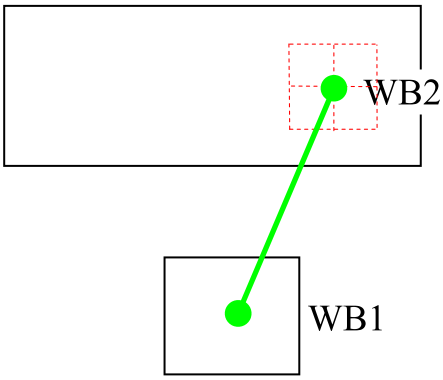


Odd-schema for the odd # (Tab. 1b):
B,B1,B5,B,B2,B6,B,B3,B4,B.
10 occupations separately at 30/90/130 cm



Even-schema for the even # (Tab. 1b):
B,B1,B2,B,B3,B6,B,B4,B5,B.
10 occupations separately at 30/90/130 cm

Figure 1B Horizontal δg grid measurement schedule at site B performed separately on each height of 30, 90 and 130 cm for full-schedule and only the 90 cm for the simple schedule. There are two schemata: the odd-schema is for the odd-numbered gravimeters (1,3,5,7 and 9) in Table 1b and the even-schema is for the even-numbered gravimeters (2,4,6,8 and 10) in Table 1b. Totally there are 30 occupations for gravimeter.



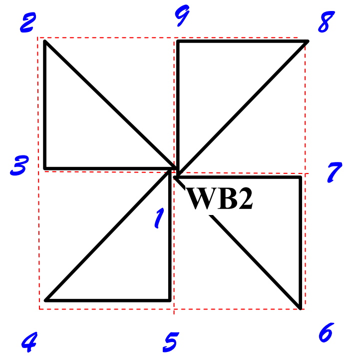
No.	1	2	3	4	5	6	7
Stations	WB1	WB2	WB1	WB2	WB1	WB2	WB1

Figure 1C Horizontal δg tie measurement schedule at site WB. WB1 is the gravity station and WB2 is the BIPM watt balance location. The simple-schedule requires 7 occupations between the two points of 90 cm in height. The full-schedule requires 5 occupations on each height of 30, 90 and 130 cm, totally 15 occupations. The tie on 100 cm in height is to be measured only by the specially scheduled RGs.

On WB site (Figure 1C): Horizontal δg tie at site WB is measured between WB1 and WB2. WB1 is gravity station and WB2 is the future BIPM watt balance location of which the reference height is about 1 m (not decided yet at present). There are 7 occupations on the height of 90 cm for the simple-schedule. To strengthen the absolute g value transfer and reduce the gradient effects, in the full-schedule the δg is measured on the heights of 30, 90, 100 and 130 cm with 5 occupations on each height, there are totally 20 occupations.

On WB2 station (Figure 1D): The horizontal δg grid measurements are scheduled on the station WB2. There are two schemata: the odd-schema (Figure 1D) is for the odd-numbered RG (number 1,3,5,7 and

9) in the Table. 1b. and it is consisted of the triangles 123,145,167, 189 and closed to 1. The even-schema is for the even-numbered gravimeters (2,4,6,8 and 10), which is consisted of the triangles 134,156,178, 192 and closed to 1. The cells of the grid are of 0.5 m². There are totally 40 occupations and to be measured only by the specially scheduled gravimeters.



Odd-schema	1	2	3	1	4	5	1	6	7	1	8	9	1
Even-schema	1	3	4	1	5	6	1	7	8	1	9	2	1

Figure 1D The Odd-schema of the horizontal δg grid measurement schedule on the station WB2 on the heights of 30, 90, 100 and 130 cm. There are two schemata: the odd-schema is for the odd # RG (Tab. 1b) consisted of the triangles 123,145,167, 189 and closed to 1. The even-schema is for the even # (Tab. 1b) consisted of the triangles 134,156,178, 192 and closed to 1. A cell of the grid is of 0.5 m². There are 40 occupations measured only by the specially scheduled gravimeters.

On WB site (Figure 1E): To investigate the gravity variation on the WB site, a grid consisted of the gravity profiles is to be measured. The horizontal δg is measured on the knots of the grid of which the cell is of 2×2 m² and 100 cm above the ground in the BIPM watt balance laboratory. The grid is consisted of 4 independent schedules: the two blue and two red closed ties as illustrated in Figure 1E. The blue and red circles are the starting and closing points of the measuring circles. There are totally 40 occupations. This measurement is to be organised only for the special scheduled RGs.

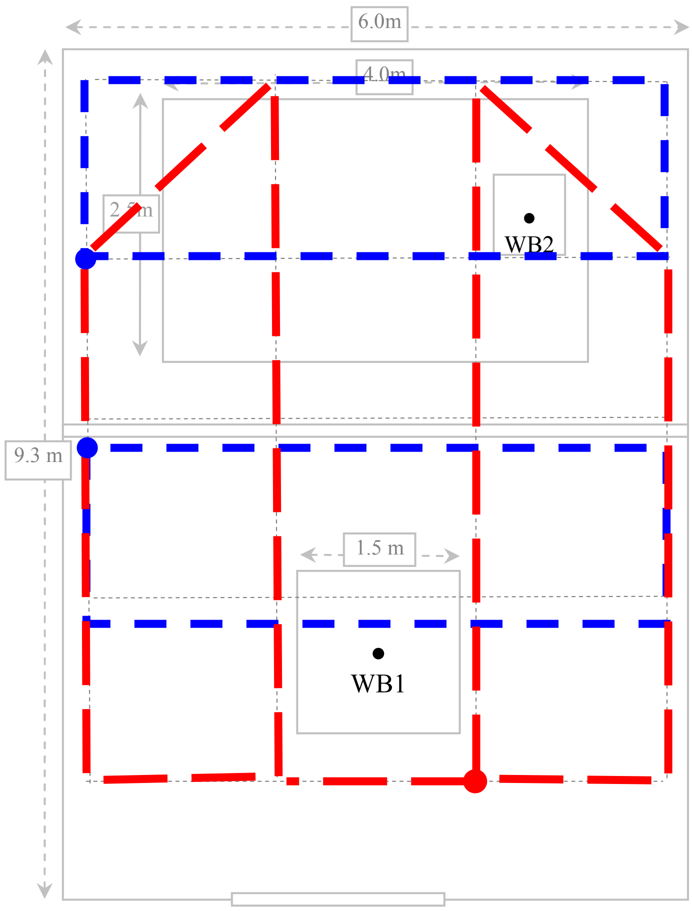
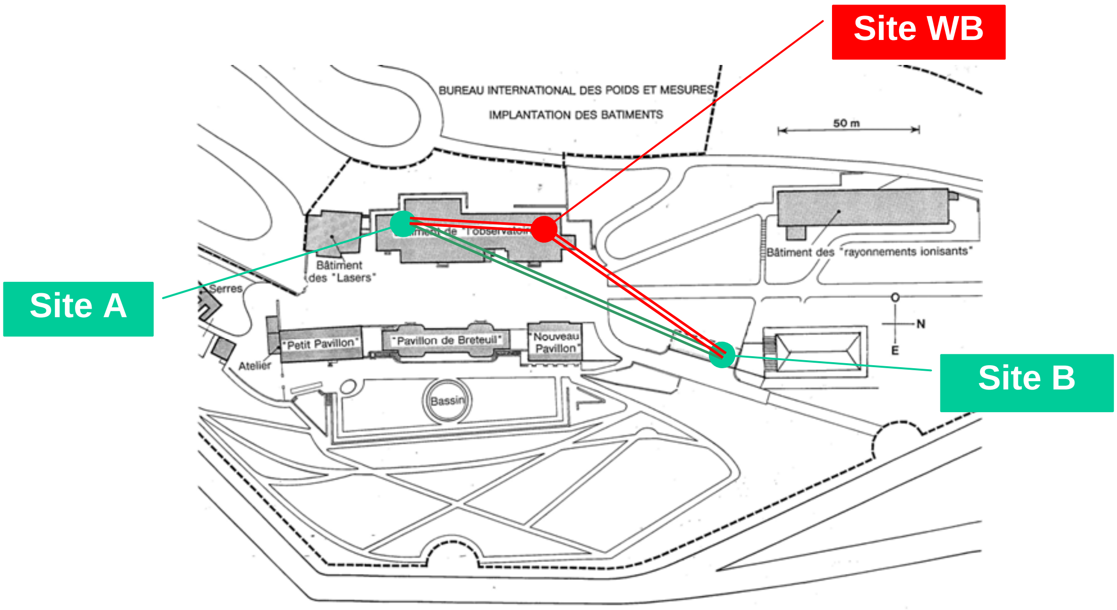


Figure 1E Horizontal δg measured on the knots of the grid of which the cell is of 2×2 m² and 100 cm above the ground in the BIPM watt balance laboratory. The measurement schedule is consisted of the two blue and two red closed ties. The blue and red circles are the starting and closing points of the measuring circles. There are totally 40 occupations. This is only for the special scheduled RGs.

Outdoor ties between the sites A, B and WB (Figure 1F): Outdoor horizontal δg measurement scheduled between the sites A, B and WB on the height of 90 cm for the simple-schedule and on the heights of 30, 90 and 130 cm for the full-schedule. There are 10 occupations for the simple-schedule and 21 occupations for the full-schedule with 7 occupation on each height.



No.	1	2	3	4	5	6	7	8	9	10
Site	B	A	WB1	B	WB1	A	B	A	WB1	B

Figure 1F Outdoor horizontal δg measurement scheduled between the sites A, B and WB on the height of 90 cm for the simple-schedule and on the heights of 30, 90 and 130 cm for the full-schedule. There are 10 occupations for the simple-schedule and 21 occupations for the full-schedule.

Table 1 shows the total numbers of the occupations in the different schedules. A printed schedule will be distributed for the operator of every gravimeter. Schedule must be exactly followed.

Table 1. The total occupation numbers in the simple and full-schedules

δg	Simple-schedule	Full-schedule	Special schedule /100cm
Vertical δg (Fig. 1A)	81	108	-
Horizontal δg at B (Fig. 1B)	9	27	-
Horizontal δg between WB1 and WB2 (Fig. 1C)	7	15	7
Horizontal δg at WB2 (Fig. 1D)	-	-	40
Horizontal δg at WB (Fig. 1E)	-	-	40
Outdoor δg between A,B and WB (Fig. 1F)	10	21	-
Total	107	171	87

Data processing strategy for the KC

The Earth-tide and zero-drift free measurements. For each horizontal or vertical individual indoor or outdoor schedule, a zero-drift model is set which has a maximum life of $p \leq 2.5$ hours and contains minimum $n \geq 3$ closures. A normal zero-drift model is a 2-order polynomial determined by a least-squares adjustment. Suppose $R_{q,p}(t_k)$ is the reading of the RG q at time epoch t_k during period p, t_o is its starting reading epoch, n is the total number of the closing readings and $D_{q,p}(t_k)$ is the zero-drift model expressed by a polynomial:

$$R_{q,p}(t_k) = R_{q,p}(t_o) + D_{q,p}(t_k),\ k = 1, 2, 3 \ldots n.$$

Here, $D_{q,p}(t_k) = \mathrm{A}_{q,p}(t_o) + \mathrm{B}_{q,p} \times (t_k - t_o) + \mathrm{C}_{q,p} \times (t_k - t_o)^2$. $\mathrm{A}_{q,p}(t_o)$ is the zero drift at t_o and can be set to zero in our case. Therefore 2 unknowns are to be determined, $\mathrm{B}_{q,p}$ and $\mathrm{C}_{q,p}$. For $n \geq 2$, the solution is optimal and unique using the least-squares method. In abnormal cases, such as zero-drift jumps, schedule interruption, etc., the initial 2-order zero-drift model is degraded into several linear regressions ($\mathrm{C}_{q,p}$ set to zero) and cut off into several sub-drift-periods. As given above, the number of triangle and go-back closures n is mainly greater than 2, e.g. the schedule of the grid on WB2 (Figure 1D) contains 4 closures. With the redundant closures, the measurement error is greatly reduced in zero-drift modeling. After the zero-drift corrections, a particular closure may not be usually different from zero. The residuals can be used for the measuring uncertainty analysis for an individual RG q over a particular operating period p. This can be used for the relative δg observation weighting in the network adjustment.

The linear vertical gradient between 30 to 90 cm and 90 to 130 cm supplied for the KC is computed using the vertical g-difference δg over the corresponding height differences: $\delta g/\delta H$. The vertical g-difference δg here is the simple mean value of the Earth-tide and zero-drift free measurements. Outliers bigger than 3σ (three times the standard deviation) will be rejected. The number of the rejected measurements should not be more than 10 % of the total measurements.

Uncertainty evaluation

Uncertainties are estimated for the gravity difference δg measured at the BIPM in-door air-conditioned laboratory condition, i.e. small δg, small and symmetric distances between the points, height fixed tripods, carefully designed closing measurement schedule.

Table 2 presents the uncertainty budget of a δg obtained by one measure of one RG. The total uncertainty is estimated to be 4 μGal. Assuming the measurements of the gravimeter are independent, the uncertainty of the mean value of the M×N measured δg is $4.0/\sqrt{(\mathrm{M}\times\mathrm{N})} \leq 2$ μGal with the number of RGs $\mathrm{M} \geq 4$ and the number of measurement of a RG $\mathrm{N} \geq 1$.

For the simple-schedule of a vertical δg, we have $\mathrm{M}\times\mathrm{N} \geq 16$, that is, the uncertainty of the gradient correction $\leq 4.0/\sqrt{(\mathrm{M}\times\mathrm{N})}/0.4\mathrm{m} \leq 2.5$ μGal/m.

Table 2. Uncertainty estimation of per δg per gravimeter

No.	Sources of the uncertainty	Uncertainty µGal	remark
1	*Resolution of gravimeter readout*	*0.5*	
2	*Scale factor*	*1.0*	
3	*Feedback and non-linearity*	*0.5*	
4	*un-levelling effect*	*1.5*	
5	*Temperature etc. environmental effects*	*1.5*	
6	*Transport/Displacement*	*1.0*	
7	*Atmosphere Pressure correction*	*0.1*	
8	*Eccentricity of gravimeter sensor*	*1.5*	
9	*Tidal corrections*	*0.5*	
10	*Zero-drift correction*	*1.5*	
11	*Others*	*2.0*	
	TOTAL	4.0 µGal	

Data processing strategy for the PC and for the BIPM local gravity field study

As shown in Table 1, the full-schedule and the special schedule as well as the PC AGs give numerous redundant measurement data. This allows to performing various un-equal weight least square adjustments using rigorous methods. Depending on the input data set, at least three kinds of adjustment can be made, namely:

1. Adjustment with the absolute-only measurement data;
2. Adjustment with the relative-only measurements data. This is an unconstrained network adjustment with the fixed point at 90 cm of B site;
3. Combined adjustment with both relative and absolute data

Above the first two adjustments are independent and can be used to evaluate the uncertainty of each. By weighting or by using or without using the owner scales etc., various adjustments can also be defined. Detailed descriptions can be found in [1] and [2].

References

[1] Vitushkin, L, Becker M, Jiang Z, Francis O, van Dam T M, Faller J, Chartier J-M, Amalvict M, Bonvalot S, Debeglia N, Desogus S, Diament M, Dupont F, Falk R, Gabalda G, Gagnon C G L, Gattacceca T, Germak A, Hinderer J, Jamet O, Jeffries G, Käker R, Kopaev A, Liard J, Lindau A, Longuevergne L, Luck B, Maderal E N, Mäkinen J, Meurers B, Mizushima S, Mrlina J, Newell D, Origlia C, Pujol E R, Reinhold A, Richard Ph, Robinson I A, Ruess D, Thies S, van Camp M, van Ruymbeke M, de Villalta Compagni M F and Williams S (2002) Results of the Sixth International Comparison of Absolute Gravimeters ICAG-2001 *Metrologia* 39 407–24

[2] Z Jiang, M Becker, O Francis, A Germak, V Palinkas, P Jousset, J Kostelecky, F Dupont, C W Lee, C L Tsai, R Falk, H Wilmes, A Kopaev, D Ruess, M C Ullrich, B Meurers, J Mrlina, S Deroussi, L Métivier, G Pajot, F Pereira Dos Santos, M van Ruymbeke, S Naslin and M Ferry (2009) Relative Gravity Measurement Campaign during the 7th International Comparison of Absolute Gravimeters (2005) *Metrologia* 2009 in printing

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Annex G - ICAG-2009 relative gravimeter record sheet (general format)

Digital data recording file is required. Paper recording is not obliged.

Instrument________ Observer________________ Organisation
________________________Page___ of ___

Local time = UT + ____ Scale factor___________ Scale factor for voltmeter___________ mV/µGal

☐ Tie ☐ Gradient

Site_________Remarks____

Date (dd/mm/yyyy) _____/_____/2009

Point	Top cover height/mm	Time			Reading /C.U.	Voltmeter /mV	Tide /µGal	Readings /µGal	Note
		h	m	s					

Notes: If a point name is proposed, please always overwrite it is no matter if it is right or wrong. 3 readings/recordings are suggested for each occupation. Keep always the gravimeter in north-south direction. Please deliver a digital version of your data if possible which has the same information and with a format explanation.

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Annex H - Parameters of the sites of the BIPM gravity network

Table H.1. Preliminary gradient values to be updated according to the new measurements)

POINT NAME	A	A2	B	B1	B2	B3	B5	B6
NORTH LATITUDE	48.8294°	48.8294°	48.8294°	48.8294°	48.8294°	48.8294°	48.8294°	48.8294°
EAST LONGITUDE	2.2194°	2.2194°	2.2194°	2.2194°	2.2194°	2.2194°	2.2194°	2.2194°
POINT ELEVATION /m (*) Reference system : NGF	65.94	65.96	56.33	56.34	56.33	56.33	56.33	56.33
NOMINAL AIR PRESSURE /mbar	1005.4	1005.4	1006.5	1006.5	1006.5	1006.5	1006.5	1006.5
GRAVITY GRADIENT Height of 1.20 m µGal/m	300.0±1.3	298.2±1.3	295.9±1.3	284.7±1.3	279.4±1.3	290.6±1.3	295.3±1.3	286.3±1.3
BAROMETRIC CORRECTION FACTOR /µGal/mbar	300	300	300	300	300	300	300	300

Table H.2. Polynomial coefficients for gravity field distributions above the gravity stations of the BIPM.

Station	*a*	*b*	*c*
A	25980.8	-315.37	6.417
A2	25987.9	-319.80	9.000
B	28287.2	-300.10	1.750
B1	28276.0	-296.93	5.083
B2	28254.4	-289.60	4.250
B3	28274.3	-310.77	8.417
B5	28287.0	-297.33	0.833
B6	28263.0	-300.33	5.833

Table H.2 presents the polynomial coefficients of the second-order polynomials which describe the gravity field distribution $g(h)$ above the gravity stations measured during the ICAG-2005 by relative gravimeters.
Such distributions are described by the formula:

$$g(h) = a + bh + ch^2 ,$$

where h is the height above the gravity station and a, b and c are the polynomial coefficients obtained by least-square minimization.

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Parameters for evaluation of the tidal correction for BIPM

Tidal parameters generated using ETGTAB

TIDALPARAM= 0.000000 0.000001 1.000000 0.0000 DC #tidal param.
TIDALPARAM= 0.000002 0.249951 1.160000 0.0000 Long #tidal param.
TIDALPARAM= 0.721500 0.906315 1.154250 0.0000 Q1 #tidal param.
TIDALPARAM= 0.921941 0.974188 1.154240 0.0000 O1 #tidal param.
TIDALPARAM= 0.989049 0.998028 1.149150 0.0000 P1 #tidal param.
TIDALPARAM= 0.999853 1.216397 1.134890 0.0000 K1 #tidal param.
TIDALPARAM= 1.719381 1.906462 1.161720 0.0000 N2 #tidal param.
TIDALPARAM= 1.923766 1.976926 1.161720 0.0000 M2 #tidal param.
TIDALPARAM= 1.991787 2.002885 1.161720 0.0000 S2 #tidal param.
TIDALPARAM= 2.003032 2.182843 1.161720 0.0000 K2 #tidal param.
TIDALPARAM= 2.753244 3.081254 1.07338 0.0000 M3 #tidal param.
TIDALPARAM= 3.791964 3.937897 1.03900 0.0000 M4 #tidal param.

Ocean loading parameters from FES2004 model

SEVRES PARIS lat: 48.829 long: 2.219 alt: 66 m

Component	*Amplitude*	*Phase*
fM2 :	2.3052e-008	67.250
fS2 :	7.7898e-009	3.476e+001
fK1 :	3.6201e-009	61.861
fO1 :	2.0463e-009	169.012
fN2 :	4.9999e-009	87.023
fP1 :	1.1770e-009	62.656
fK2 :	2.0844e-009	32.641
fQ1 :	6.6837e-010	-139.592

the long wavelength coefficients by those provided by H.-G. Scherneck (Ocean tide loading provider)
http://www.oso.chalmers.se/%7Eloading/index.html

Mf	:	1.0100E-09	-22.9
Mm	:	6.6000E-10	-18.2
Ssa	:	6.6000E-10	-3.2

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Annex I – Information from the participants

Lab name: ____

____

Operators: ____

____

Address: ____

____

Tel. : ____________________

Fax. : ____________________

e-mail: ____________________

I have read the Technical Protocol and I agree to participate in

☐ *CCM.G-K1 Key Comparison*

or

☐ *Pilot Study*

following this TP in particular and MRA instructions for participation in Key Comparisons in general.

Date: ___________

Signature: ______________________________