Metrologia

PAPER

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To cite this article: Z Jiang *et al* 2012 *Metrologia* **49** 666

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Metrologia 49 (2012) 666–684 doi:10.1088/0026-1394/49/6/666

The 8th International Comparison of Absolute Gravimeters 2009: the first Key Comparison (CCM.G-K1) in the field of absolute gravimetry

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Received 24 May 2012, in final form 3 August 2012
Published 5 October 2012
Online at stacks.iop.org/Met/49/666

Abstract
The 8th International Comparison of Absolute Gravimeters (ICAG2009) took place at the headquarters of the International Bureau of Weights and Measures (BIPM) from September to October 2009. It was the first ICAG organized as a key comparison in the framework of the CIPM Mutual Recognition Arrangement of the International Committee for Weights and Measures (CIPM MRA) (CIPM 1999). ICAG2009 was composed of a Key Comparison (KC) as defined by the CIPM MRA, organized by the Consultative Committee for Mass and Related Quantities (CCM) and designated as CCM.G-K1. Participating gravimeters and their operators came from national metrology institutes (NMIs) or their designated institutes (DIs) as defined by the CIPM MRA. A Pilot Study (PS) was run in parallel in order to include gravimeters and their operators from other institutes which, while not signatories of the CIPM MRA, nevertheless play important roles in international gravimetry measurements. The aim of the CIPM MRA is to have international acceptance of the measurement capabilities of the participating institutes in various fields of metrology. The results of CCM.G-K1 thus constitute an accurate and consistent gravity reference traceable to the SI (International System of Units), which can be used as the global basis for geodetic, geophysical and metrological observations of gravity. The measurements performed afterwards by the KC participants can be referred to the international metrological reference, i.e. they are SI-traceable.

The ICAG2009 was complemented by a number of associated measurements: the Relative Gravity Campaign (RGC2009), high-precision levelling and an accurate gravity survey in support of the BIPM watt balance project. The major measurements took place at the BIPM between July and October 2009. Altogether 24 institutes with 22 absolute gravimeters[32] and nine relative gravimeters participated in the ICAG/RGC campaign.

This paper is focused on the absolute gravity campaign. We review the history of the ICAGs and present the organization, data processing and the final results of the ICAG2009.

After almost thirty years of hosting eight successive ICAGs, the CIPM decided to transfer the responsibility for piloting the future ICAGs to NMIs, although maintaining a supervisory role through its Consultative Committee for Mass and Related Quantities.

(Some figures may appear in colour only in the online journal)

Acronyms and notation

AG:	absolute gravimeter
AG(k):	absolute gravimeter of laboratory k in International Comparison of Absolute Gravimeters (ICAG) 2009
BIPM:	International Bureau of Weights and Measures
CCM:	Consultative Committee for the Mass and Related Quantities
CCM.G-K1:	Designation of the Key Comparison component of ICAG2009
CIPM:	International Committee for Weights and Measures
CIPM MRA:	Mutual Recognition Arrangement of national measurement standards and of calibration and measurement certificates issued by national metrology institutes (NMIs) [1]
CMC:	calibration and measurement capability
ICAG2009:	The 8th ICAG consisting of a KC and a PS, which took place in 2009
KC:	CIPM Key Comparison in the context of the CIPM MRA
PS:	Pilot Study (not constrained by the rules of the CIPM MRA)
RG:	relative gravimeter
RGC:	Relative Gravity Campaign
TP:	Technical Protocol of the 8th ICAG2009 [2]
KCDB:	The Key Comparison Database of the CIPM MRA, where KC results are maintained
KCRV:	Key Comparison Reference Value(s). In the case of CCM.G-K1 they are the G_j values at the stations calculated at a height 0.9 m above the benchmark, obtained in the final data processing from the measurements of the KC participants
CRV:	Comparison Reference Value(s) of the ICAG2009, i.e. a set of G values calculated at height $h = 0.9$ m above the benchmark from the measurements of all participants.
SAE:	self-attraction effect due to the mass distribution of an AG apparatus

[32] One of the 22 AGs was ultimately withdrawn.

SAC: self-attraction correction
DC: diffraction correction due to a curved wave front of a laser beam used in AGs with laser interferometers
h_{jk}: reference height of AG(k) at station j
1 Gal 1×10^{-2} m s^{-2} (the default unit used in this paper is µGal)
σ: sample standard deviation
g^m_{jk}: measured absolute acceleration due to gravity by AG(k) at station j at h_{jk}, $j = 1, 2, 3$ (in µGal minus a constant value of 980 900 000)
g_{jk}: g^m_{jk} transferred to the reference height of the comparison (0.9 m)
u_{jk}: standard uncertainty of g_{jk} reported by the participants
u_k: root mean square of u_{jk} for AG(k)
U_k: expanded uncertainty ($k = 2$), corresponding approximately to 95% confidence: $U_k = 2u_k$
w_{jk}: statistical weight of g_{jk}
G_j: adjusted g value at station j (in µGal minus a constant value of 980 920 000)
δ_k: offset of the AG(k), used to represent the difference of the measurements of an AG(k) from the CRV in the least-squares adjustment
D_k: Degree of Equivalence (DoE) of the AG(k), defined as the deviation of the result of a particular laboratory from the KCRV or CRV computed as the weighted mean value of the $g_{jk} - G_j$ and the expanded uncertainty associated with this datum
S_k: standard uncertainty of the D_k from the least-squares adjustment
$\delta g, \delta G$: difference of g or G

1. Introduction

The 1st International Comparison of Absolute Gravimeters (ICAG) of the International Association of Geodesy (IAG) and the accompanying Relative Gravity Campaign (RGC) were held at the BIPM in 1981 [7]. Since then, successive ICAGs/RGCs have been organized at the BIPM every four years. In accordance with the decision taken in August 2007 at the Joint Meeting of the Working Group on Gravimetry of the Consultative Committee for the Mass and Related Quantities (CCM WGG) and the Study Group on Comparisons of Absolute Gravimeters SGCAG 2.1.1 of the IAG, the ICAG2009 was defined as the comparison of absolute gravimeters (AGs) that includes a CIPM Key Comparison (KC) and CIPM Pilot Study (PS). Only national metrology institutes (NMI) that are signatories of the CIPM MRA (Mutual Recognition Arrangement of national measurement standards and of calibration and measurement certificates issued by NMIs [1]) and laboratories officially designated by those institutes can participate in the KC part designated as CCM.G-K1 (designation of the KC component of ICAG2009). The PS part is organized for institutes that are not involved in the CIPM MRA.

The ICAG2009 was performed in accordance with the Technical Protocol (TP) [2] approved by the Steering Committee (SC) after its two meetings held in Sèvres (December 2008) and Prague (May 2009) and based on previous experience [7–15].

The BIPM, acting as the pilot laboratory, organized the full measurement campaign at its headquarters in Sèvres (France), and evaluated the final results of ICAG2009, that is the KC CCM.G-K1 and the PS (figure 4). The results of CCM.G-K1 were approved by the participants in 2011 and were later submitted to the Consultative Committee for the Mass and Related Quantities (CCM) which gave final approval in February 2012. A final report of the KC is made available on the BIPM Key Comparison Data Base (KCDB) [16].

Several activities took place associated with ICAG2009, and for some of them results have already been published:

- RGC2009, whose result have been published in 2011 [15],
- precise levelling at the BIPM between 2001 and 2009 to monitor the stations' height variations, with results published in 2011 [17],
- estimation of the self-attraction correction (SAC) for AG measurements, whose results have been published in the BIPM Report 2012/01 [3] and used in the final evaluation of the ICAG2009 [16],
- measurements of Earth tides at BIPM of which the final result was published in [36],
- AG and RG gravity measurements to support the BIPM watt balance project, preliminary result will be published in [45].

After eight ICAGs hosted by the BIPM for over 28 years, the CIPM, in consultation with the International Association of Geodesy (IAG), decided to stop the activity of the BIPM hosting the ICAGs, and has requested volunteer NMIs of Member States to continue the organization of further ICAGs. Both the CIPM and the IAG have agreed that organization will still be made within the Working Group on Gravimetry of the CIPM Consultative Committee for Mass and Related Quantities (CCM).

One of the aims of the ICAGs is to create an appropriate basis for accurate absolute gravimetry needed especially in metrology and geosciences. This will be used to establish a new global absolute gravity reference at the µGal level which fulfils the requirements of IAG's 'Global Geodetic Observing System (GGOS)', see [33], and which is necessary for the study of changes in the Earth's gravity field. In a common initiative of the two IAG Working Groups JWG 2.1 'Techniques and Metrology in Absolute Gravimetry' and JWG 2.2 'Absolute gravimetry and absolute gravity reference system' a new International Gravity Reference System shall be realized [22] which replaces the current IAG gravity reference system IGSN71, see [34].

1.1. Background of the ICAG2009 and CCM.G-K1

ICAG2009 has aimed to serve two different communities with seemingly different priorities. The geosciences community is primarily interested in making correct gravimetric measurements suitable for geodesy and geophysics. The NMI community emphasizes correct uncertainty analyses, leading to results that are traceable to the International System of Units (SI), and ultimately to recognition of their measurement capabilities by international peers.

Since 1999, a mechanism has been in place for NMIs to achieve their goals through the CIPM MRA [1]. A part of the requirements for international recognition involves participation in so-called ‘Key Comparisons’ (KCs) [1, 37] in order to support claimed measurement capabilities. The rules governing KCs are very restrictive [37] and exclude much of the geoscience community from participation. To solve this dilemma, we have organized ICAG2009 in such a way that NMIs or their designated institutes (DIs) have participated in ICAG2009 following the strict rules of the CIPM MRA [37]. Results from this group form the basis for CCM.G-K1, the first CIPM KC in gravimetry. The geosciences community also participated in ICAG2009 in what we have called a PS. Participants in the PS made all the same measurements but were not constrained by all rules governing a KC. The purpose of the following report is to analyse and compare the results of all participants—those who participated in the KC and those who participated in the PS. We believe that the fusion of these results, as shown in detail below, has considerably benefited our knowledge of absolute gravimetry. The KC results, important to the NMI and DI participants, are published in a separate report [16].

The comparison of the AGs is the only way to realize the metrological calibration of the instruments or determine the degrees of equivalence (DoEs) between instruments. In addition to the ICAGs, Regional Comparisons of Absolute Gravimeters are regularly organized, such as those in Walferdange in Europe in 2011 (namely EURAMET.M.G-K1) and as planned in Beijing in Asia in 2015.

The most recent previous ICAG, ICAG2005, was piloted by BIPM and organized as a PS that would aim towards becoming a KC for ICAG2009. Accordingly, a Steering Committee (SC) was established. One of its major responsibilities was to draft the Technical Protocol [2] following the guidelines of the CIPM MRA for organizing KCs [37]. The membership of the SC for ICAG2009 was composed of H Baumann (METAS), M Becker (IPGD), O Francis (UL), A Germak (IMGC/INRiM), V Pálinkáš (VUGTK/RIGTC), H Wilmes (BKG), L Vitushkin, L Robertsson and Z Jiang (BIPM). The measurements and the evaluation of CCM.G-K1 were guided by the TP 2009 approved by the SC 2009. A Germak was responsible for drafting the TP, L Vitushkin for organizing the AG measurement and Z Jiang for organizing the relative gravimeter (RG) and levelling measurements, as well as for the considerable task of data processing. A working group on the strategy of the evaluation of the CCM-G.K1 was composed by the BIPM staff: F Arias, L Robertsson, R Davis and Z Jiang. The pilot laboratory was also responsible for drafting the draft A and B reports of the KC result, as described in [37]. Certain confidentiality rules must be followed and, not until the draft B report is approved by participants as well as the relevant Consultative Committee can results be presented at conferences and in publications [37].

1.2. History of the ICAGs at BIPM

The first ICAG took place at the BIPM between the end of 1981 and the beginning of 1982. All the participating AGs were prototypes developed at the participating institutes. The first serialized AG model, JILAg [38], participated in the second ICAG in 1985 and was the dominant model in the third ICAG in 1989 (table 1). The number of gravimeters of this type progressively decreased in the successive campaigns, following introduction of the FG5. The first FG5 [19] participated in the fourth ICAG in 1994. Since 2001, the FG5 model has become the dominant model with 10 of the total 15 AGs being FG5s in ICAG2009. IMGC is the only model that has participated in all the eight ICAGs. Unfortunately, the data of IMGC-2 were withdrawn from the final evaluation of ICAG2009 due to significant measurement errors caused by damage to a falling corner-cube.

The trend of the ICAGs over the last three decades is from a traditional geodesy-oriented calibration for relative and absolute gravimeters to a more general application in geosciences, including a worldwide reference system traceable to the SI through a rigorous metrology procedure, motivated by rapid developments in instrumentation and the introduction of the CIPM MRA [1]. There were several remarkable events through the course of the ICAGs: the first important step towards a commercially available AG was the JILAg, which appeared in 1989, and which was made in response to requests from a number of scientific organizations that the JILA makes available to them (rather than they having to develop it themselves) its absolute gravimetry technology. The construction of six JILAg instruments resulted in response to these requests. In 1994, an improved ‘in-line’ instrument, the FG5, became commercially available and marked a new epoch of the modern accurate gravimetry [20]; the first atomic AG in ICAG2009 introduced a completely new approach from traditional gravimeters with macroscopic objects; since 2001, the ICAGs have been moving towards metrological ‘KCs’ as defined in the context of the CIPM MRA and this has been fully realized within the 2009 ICAG. Accordingly, the organization, the measurement setup, the data processing method [44], the comparison strategy, etc have been adapted to this evolution. For instance, since 2005, the task of the RG calibration has no longer been mandated in the ICAGs. Site B built at the BIPM in the spring of 2001 was designed to allow the best metrological comparison conditions.

In the very first ICAG1981, the comparison data were collected from the AG measurements carried out over different years at BIPM. This experience demonstrated a necessity for a regular and rigorous plan for the AG comparisons. Accordingly, data collection for all ICAGs which followed was completed within three months. In addition, significant progress can be seen in the methodology of comparisons and data treatments: for ICAG1985 each AG carried out measurements for several days at different stations. Usually a station was only occupied by one AG so that comparisons between AGs were made indirectly, relying on knowledge of the gravity differences between the stations as measured by relative gravity meters (RG).

Table 1. Participating AGs in the eight ICAGs at BIPM[a]. (JILAg was the dominant model in 1989. Since 2001, the FG5 has taken that role. Together with the A10 and FGL, they are the three commercially produced models in ICAGs. Others are prototypes of the owner institutes. The information given on the first four ICAGs is from [10]).

1981–82 7 AG	1985 6 AG	1989 10 AG	1994 11 AG	1997 17 AG	2001 15 AG	2005 19 AG	2009 22 AG
IMGC, Italy	IMGC	IMGC	IMGC	IMGC	IMGC	IMGC-2	IMGC-2*
GABL, USSR	GABL	GABL		GABL	A10-b02*	GABL	CAG-1
JAEGER, BIPM	JAEGER, BIPM		JAEGER, Japan	NIM-2A	A10-03	A10-8	NIM-2
NIM, China	NIM-1	NIM-1		NIM-2B*		FGC-1	MPG-2
Hammond, USA	Zumberge, USA	NAO, Japan		ZZB		GABL-1	A10-05
Sakuma, static array		Sakuma, static array*				TBG-1	A10-14
Faller, USA	JILAg-1	JILAg-4					A10-20
		JILAg-2	JILAg-2	JILAg-2	JILAg-2	JILAg-2	
		JILAg-3	JILAg-3	JILAg-3			
		JILAg-5	JILAg-5	JILAg-5	JILAg-5		
		JILAg-6	JILAg-6	JILAg-6	JILAg-6	JILAg-6	JILAg-6
							FGL-103
			FG5-101	FG5-101	FG5-101	FG5-101	FG5-101
			FG5-102	FG5-103	FG5-103	FG5-108	FG5-102
			FG5-104	FG5-105	FG5-105	FG5-202	FG5-105
			FG5-107	FG5-107	FG5-108	FG5-206	FG5-209
			FG5-108	FG5-108	FG5-202	FG5-209	FG5-213
				FG5-202	FG5-204	FG5-211	FG5-215
				FG5-206	FG5-206	FG5-213	FG5-220
					FG5-209	FG5-215	FG5-221
					FG5-211	FG5-216	FG5-224
					FG5-213	FG5-221	FG5-228
					FG5-301*	FG5-224	FG5-230
						FG5-228	FG5-233
							FG5-238
	1st JILAg	5 JILAg	5 FG5	7 FG5	11 FG5	12 FG5	13 FG5

[a] Instruments marked with * participated in the comparison but the data were withdrawn from the final evaluation.

The comparisons before 2001 were calculated by first transferring all the AG measurements from different stations to a single one with the help of the RG ties and then comparing the mean values of each AG. Since ICAG2001, an experimental design requiring station-occupation for a half day and up to four stations for each AG was used so as to obtain an optimal link between AGs without the necessity of RG ties. This allows greater flexibility for data processing, such as AG-only, RG-only and combined AG–RG solutions, all obtained by least-squares adjustment [12].

ICAGs have triggered developments ranging from improved instrumentation to studies of factors which may cause systematic errors in a given AG. As examples, interested readers should refer to the discussions in sections 1.4 and 4.3 as well as to the studies published in [2–6, 19–21, 23, 26–28, 31, 38–40]. All these efforts are made by the joint and successful cooperation of the geoscientists and the metrologists. Progress in the precision of AG comparisons is evident in decreasing the scatter, from 13 µGal in ICAG1985 to 4 µGal in ICAG2009.

1.3. New technology involved in ICAG2009

There were three new AG models participating in the ICAG2009: MPG, FGL and CAG, see figures 1 and 6.

The AG measurements, in general, were based on the traditional free-fall or rise-and-fall methods, tracking a macroscopic object. Combination of different types of AGs or even different techniques is important for detecting potential biases. One remembers the famous International Gravity Standard Network 1971 (IGSN71) [32] which identified and corrected the bias of about 14 mGal (1.4×10^{-4} m s^{-2}) in the Potsdam-based system measured by a pendulum AG. It was confirmed by new generations of free-fall gravimeters.

With this in mind, the participation of the cold-atom absolute gravimeter (CAG-1) [18] from LNE-SYRTE (France) is an important milestone in ICAGs. The CAG-1 is the world's first transportable atom gravimeter. ICAG2009 marked the first successful 'field' test of the CAG-1 since it became operational in the summer of 2009. The standard uncertainty of the CAG-1 was about 6 µGal, dominated by wavefront aberration bias (4 µGal) [25]. Comparison of the two physically different methods of measuring gravity brings valuable information about possible biases caused by the technical realization of either method. Atom interferometry and the realization of cold-atom gravimeters introduce an important new technology for metrology in gravimetry.

Figure 1 illustrates the CAG-1 setup. A cold atomic cloud of ^{87}Rb is first prepared in a 3D magneto-optical trap. The cloud then falls when the lasers are switched off. Three Raman pulses separated by a time T allow separation, deflection and recombination of the wave packets, resulting in an atom interferometer. The phase difference accumulated along the two paths of the interferometer is given by $\Delta\Phi = -\boldsymbol{k}_{\mathrm{eff}} \cdot \boldsymbol{g}T^2$ in which $\boldsymbol{k}_{\mathrm{eff}} = \boldsymbol{k}_1 - \boldsymbol{k}_2$ is the effective Raman wave vector obtained. The Raman beams are generated by two extended

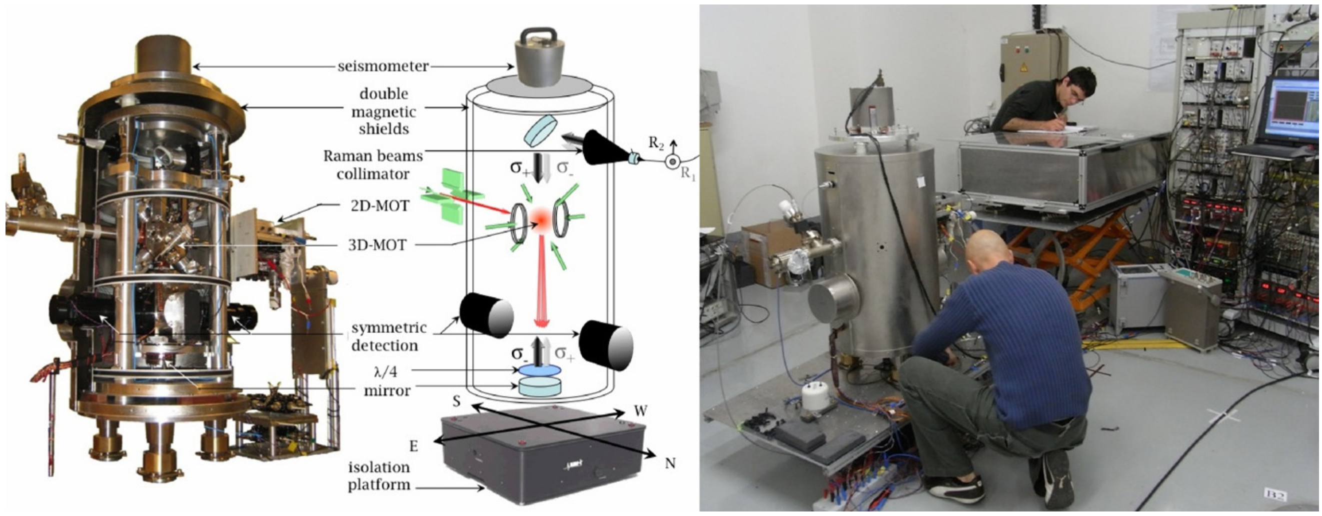


Figure 1. Left: picture and schematic diagram of the LNE-SYRTE cold-atom gravimeter (CAG-1) with the magnetic shields partially removed in the picture. Two pairs of counter-propagating lasers induce Raman transitions with an effective wave vector k_{eff}. Right: the setup of the CAG-1 during ICAG 2009 on site B. The drop chamber (protected from wind and acoustic noise by a wooden box during the measurements), the optical bench and the control electronics are visible.

cavity laser diodes R_1 and R_2 of frequency ω_1 and ω_2. In order to compensate for the gravity-induced Doppler shift, their frequency difference is swept according to $(\omega_2-\omega_1)(t) = (\omega_2-\omega_1)(0)+\alpha t$, adding αT^2 to the interferometer phase shift, which cancels for a perfect Doppler compensation: $\alpha_0 = \boldsymbol{k}_{\mathrm{eff}}\cdot\boldsymbol{g}$ [26]. Finally, the g measurement is a frequency measurement of the chirp α_0 steered onto the interferometer central fringe.

For the first time, a FGL and a MPG (Max-Planck Gravimeter) participated in the ICAG. The FGL was designed in 2005 and can be thought of as a combination of FG5 and A10 gravimeters. It uses a dropping chamber (7 cm dropping distance) and super-spring (with effective free period about 30 s) as does the A10. As in FG5, the Mach–Zender interferometer including an iodine-stabilized He–Ne laser is used. The MPG-2 is a transportable AG built on a classical free-fall scheme to measure the local gravity value. It uses a novel spring-preload mechanism to realize free-fall motion of the test mass, and uses digital fringe signal processing methods to retrieve the gravity value [40]. The combined standard uncertainty of the FGL-103 [39] and MPG-2 [40] are as given in table 7.

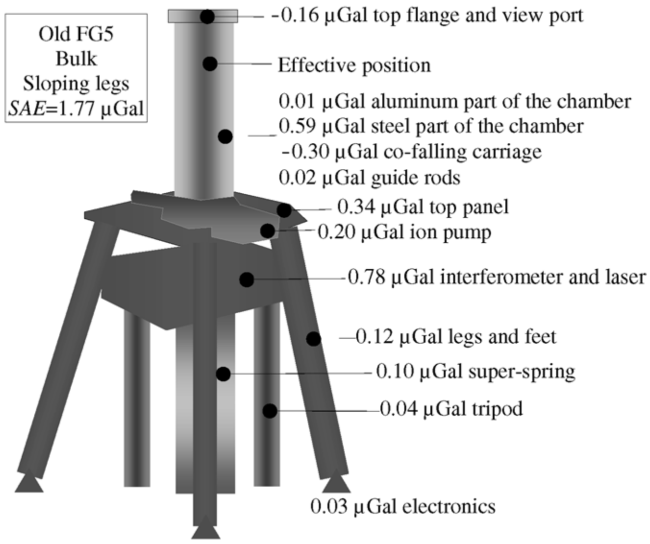


Figure 2. Values of the SAE at the effective position produced by the subcomponents of the old FG5 (bulk with sloping legs). The total SAE is 1.77 µGal according to [3, 4].

1.4. The SAC and the diffraction correction

The TP fully considered error sources based on the state-of-the-art of gravimetry measurements up to the first half of 2009, including the self-attraction effect (SAE) and diffraction effect as components in the total measurement uncertainty budget. Niebauer *et al* [19] indicate that the uncertainty of the SAC due to the SAE of the FG5 apparatus is 0.1 µGal, but do not indicate the value of the correction or its method of calculation. In 1996, Robertson [23] pointed out that the SAC for an FG5 might influence the g determination by about −1.3 µGal to −1.5 µGal along the free-fall trajectory but unfortunately this did not draw sufficient attention from the absolute gravimetry community. An effect larger than 1 µGal has also been obtained in the analysis of the uncertainty budget for the CAG [27]. Recent studies including eight corner-cube AGs [3, 4] show that the SAC is about one order of magnitude greater than what we believed it to be in the TP. This was confirmed with the calculation of the SAC for three AGs as published in [28]. To illustrate the amplitude of this effect, we detail the SAE caused by the different subcomponents of an old generation FG5 (bulk interferometer and dropping tripod with sloping legs as shown in figure 2). More details can be found in [4]. Finally, table 2 gives the values of the SAC for the different kinds of instruments used in the comparison. To remove any possible ambiguity, figure 3 displays the three different types of FG5 gravimeters referred to as New1, New2 and Old in the table. The SAC values in table 2 represent preliminary results of [3] at the time when the final evaluation of ICAG2009 was made. The final results [4] for FG5 are slightly, but insignificantly,

Table 2. The SAC values at the reference height of AGs applied in the final ICAG2009 evaluations (see figures 2 and 3).

Type of AG	Height/m	SAC/μGal	u_{SAC}/μGal
FG5 New1	1.21	−1.12	0.2
FG5 New2	1.22	−1.32	0.2
FG5 Old	1.22	−1.81	0.2
A10	0.67	−0.58	0.3
JILAg	0.84	−0.79	0.2
MPG-2	1.142	−1.35	0.2
FGL	0.814	−1.10	0.2
NIM-2	1.187	−1.17	0.2
CAG-1	0.82	−1.3	0.1

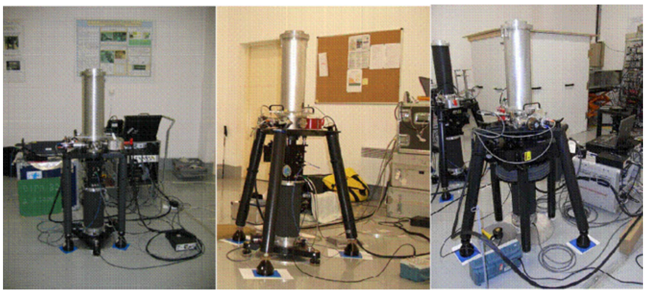


Figure 3. The three types of FG5 participating in ICAG2009. Left: FG5 type New1, fibre laser optic interferometer with tripod with straight legs. Middle: FG5 type New2, fibre laser optic interferometer with tripod with sloping legs. Right: FG5 type Old with bulk interferometer.

different from the preliminary values. As for CAG-1 [27] and NIM-2, the SAC were supplied by the owners.

The impact of the SAC on the evaluation of the offsets of the FG5 is not critical due to the predominance of the FG5 gravimeters (with similar SACs), enhanced by their high statistical weights in the least-squares adjustment. According to the results in [3], the difference between offsets calculated by applying or not the SAC can be expected to be less than 0.4 μGal for the FG5 and less than 2 μGal for other gravimeters. Hence, the changes are not very significant compared with their respective uncertainties. However, the offset uncertainty is directly affected by the uncertainty of the Comparison Reference Value of the ICAG2009 (CRV). Therefore, a significantly biased CRV cannot be used for accurate offset estimates. Liard *et al* [3] show that the impact of the SAC introduces an effect as big as 1.3 μGal on the Key Comparison Reference Value (KCRV). Any bias which reaches the μGal level or larger cannot be considered negligible in the context of the Global Geodetic Observing System or realization of the International Gravity Reference System where a consistency of observations at the level of 10^{-9} is required [33].

The SAE, due to the mass distribution of an AG apparatus, provokes a bias of about 1.3 μGal in the KCRV. The application of the SAC to the raw gravity data for the KC was rejected by most participants. The major cause was that during the approval procedure at the beginning of 2011, the SAE estimates were not known for all the AGs participating in the ICAG2009. To compensate for the non-consideration of the SAE, an enlarged uncertainty was given to the KCRVs [16]. Since the TP does not fix any constraint on the PS, we could apply the SAC in the PS evaluation and study its influence on the KCRV/CRV and on the offsets. Refer to [3, 4, 23, 27, 28] for further details on the SAC.

Another systematic error present in the AG measurements is the diffraction effect caused by the inherent curvature of the laser wave front used in laser interferometers as demonstrated in [5, 6]. The impact of the diffraction effect depends strongly on the waist of the laser beam of an individual AG, varying from about 1 μGal to 10 μGal among the AGs participating in 2009. The diffraction correction (DC), due to a curved wave front of a laser beam used in AGs with laser interferometers, was considered only for the prototype AGs, i.e. IMGC-2, MPG-2, NIM-2 and CAG-1. However, it is usually not considered in the commercialized AGs (only the owner of the FG5-221 had applied a DC = 1.4 μGal in the raw measurement data reported to the BIPM). According to [5] the DC can be estimated from the beam waist, and should have a constant value for a well aligned laser and interferometer of a particular AG type.

During a common meeting of the two IAG working groups JWG 2.1 and JWG 2.2 (Vienna, February 2012) [31], both groups recommended applying SAC and DC in all AG measurements. Based on the study of Van Westrum and Niebauer [5], the DC is 1.2 μGal for a 2.9 mm beam waist (defined as the radius at which the beam intensity is $1/e^2$ of its axial value). As JILAg, FG5, FG5-X, FGL and A10 use beams with very similar waists, the working groups recommended to apply such DC with a standard uncertainty of 0.5 μGal. Since the CAG waist is more than four times larger (12 mm) this effect reduces to 0.05 μGal.

In conformity with the TP the estimated values of the SACs and the DCs were not considered for the KC CCM.G-K1. Independent of the KC, we have recalculated the results of ICAG2009 with the aim of getting a solution in conformity with our current knowledge; since this solution is not constrained by the TP, the recommendation of the IAG JWGs on the application of the SAC and DC was taken into account. Different solutions of ICAG2009 are discussed in section 3. Evaluations of the SAC or the DC by the participants, whenever available, were preferred to the recommenced values. The reported uncertainties, which generally have already included contributions for SAC and DC, were not modified by new estimates. It would be relevant only in cases where the complete uncertainty budget of all gravimeters is available (mandatory only for KC participants). However, the available uncertainty budgets show that the uncertainties would be modified by less than for 10%, thus having negligible impact on the final results.

It is interesting to note that the absolute values of the SAC and the DC of the FG5s are similar in size but with opposite signs. Consequently, the CRV and KCRV should not be affected significantly, and this is also due to the fact that FG5s are given more than 90% of the total statistical weight in the adjustment.

2. The organization of the ICAG2009

The ICAG2009 consisted of two parts, the KC and the PS, see figure 4. The complete set of measurements for the KC

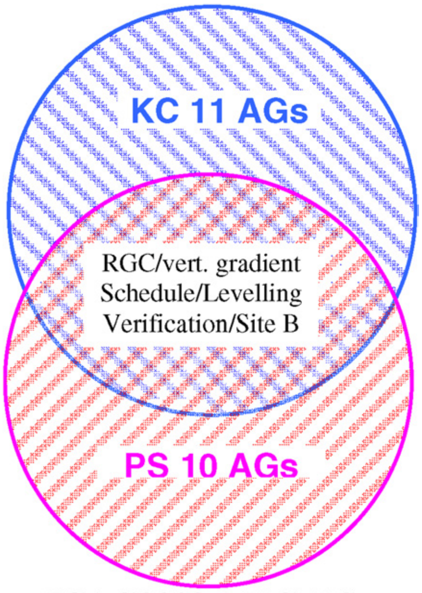


Figure 4. ICAG2009 is the combination of the KC and the PS sharing the same schedule and the results of the RGC2009 including the vertical gravity gradients, taking place during the same periods on the same stations, benefiting both from the clock and laser verification supplied by BIPM as well as the BIPM's administrative support.

and the PS was performed between August and October 2009 following the guidelines of the Scientific Committee and the Technical Protocol. There were 11 participants in the KC and 10 in the PS. Table 3 lists the participants of the ICAG2009. The results of RGC2009 [15], levelling [17] and frequency verifications were used in support of ICAG2009.

2.1. The ICAG2009 absolute gravity measurements

During the ICAG2009, there were five stations at site B: B, B1, B2, B5 and B6 (figure 5) occupied by the 21 AGs, among them 11 in the KC and 10 in the PS. Each AG had three overnight occupations at three different stations. In total, there were 63 AG determinations. Eight different AG models were used; see figures 1, 3 and 6. Table 4 gives the distribution of the occupations. There were 15 occupations at B, 14 at B1, 13 at B2, 9 at B5 and 12 at B6. The occupation homogeneity, especially that of the FG5s, is important for an optimal and robust solution of the KCRV/CRV and the offset of each AG.

Figure 7 shows the schedule of the ICAG2009 KC measurements. The number of occupations (N) and the number of stations (M) were such that we could organize a schedule allowing each AG to be directly compared on the same station to all the other participant instruments. To do this requires $M \leqslant 2N - 1$. As illustrated in figure 7, two generic instruments AG1 and AG2 have twice occupied a station (B in the figure). If M exceeds $2N - 1$, not all AGs can have a direct comparison with all the other AGs. The relationship $M = 2N - 1$ was used for the ICAG2009 with $N = 3$. The total number of the AGs is 22, of which the IMGC-2 was withdrawn from the final evaluation. The ratio of the number of AGs and M is between 4 and 5.

2.2. The frequency measurements during the ICAG2009

The BIPM offered a frequency-measurements service during the ICAG2009 for both stabilized lasers and Rb clocks. The Rb reference frequency was measured using a phase/frequency meter provided by the BIPM Time Department and referenced to the distributed BIPM 10 MHz reference frequency. The reference frequency was provided by a hydrogen maser clock traceable to UTC (Coordinated Universal Time) with a frequency stability of 2×10^{-15} at one hour averaging time. Table 5 is a summary of the frequency measurement results.

The laser frequencies of some AGs were measured. A BIPM reference laser, calibrated with an optical frequency comb system, was used as a reference for the beat frequency measurements. The frequency measurements are summarized in table 6 for iodine-stabilized lasers with saturated (S) and non-saturated (N) iodine cells. Δf(e) and Δf(f) are differences between determined frequencies for iodine peaks 'e' and 'f' and frequencies of 473 612 366 000 kHz and 473 612 353 000 kHz, respectively. The standard uncertainty of frequency measurements is estimated to be 5 kHz. The CAG-1 optical bench setup (or architecture) guarantees knowledge of the frequencies of the prototype extended cavity laser diode thanks to a saturated absorption spectroscopy signal in a ^{87}Rb vapour cell [29]. For all CAG-1 measurements, a calibration of the quartz frequency source used to lock the frequency chirp α_0 essential to the g determination was performed with the BIPM 10 MHz reference frequency. A standard uncertainty of 1 µGal was associated with this result for the CAG-1.

The verification results were provided to the participants. It was their decision to apply the parameters to their data reprocessing or to use their own calibration parameters.

3. Data processing

As defined in the Technical Protocol (TP) [2], the measurand is the mean value of the free-fall acceleration at the reference instrumental height corrected for

- the gravimetric Earth tides to obtain 'zero-tide' gravity values [41] based on the IAG resolution 16 of the 18th General Assembly (1983). In the TP, it is recommended to apply tidal parameters from [42] for a solid Earth model and ocean loading parameters given by [43] for FES2004 model,
- the atmospheric effects, with barometric admittance factor of -0.3 µGal hPa^{-1} recommended by the TP,
- the polar motion effects with respect to the IERS pole in compliance with [41].

The examples of the uncertainty given in [2] are 0.7 µGal and 0.6 µGal for tidal and atmospheric corrections, respectively. Meanwhile, according to the TP and the CIPM MRA [1], the participants are responsible for choosing which models to apply in order to correct their AG measurements and to estimate the associated uncertainties. Therefore BIPM, as the pilot laboratory, used the result reported by each participant, see table 7.

Table 3. Participants in the ICAG2009 (see the list in the authorship for the acronyms and the full names of the institutes).

No	AG	Participant/Institute	ICAG
1	FG5-105	D Inglis, NRC and J Liard, NRCan, Canada	KC
2	FG5-209	H Baumann , METAS, Switzerland	KC
3	FG5-213	S Mizushima, NMIJ/AIST, Japan	KC
4	FG5-215	V Pálinkáš, J Kostelecký, VÚGTK/RIGTC, Czech Rep.	KC
5	FG5-221	J Mäkinen, FGI, Finland	KC
6	FG5-224	C Lee, CMS/ITRI, Chinese Taipei	KC
7	FGL-103	I M Choi, KRISS, Rep. of Korea	KC
8	A10-5	B Karaboce, UME, Turkey	KC
9	NIM-2	W Ji, Q Wu, NIM, P. R. China	KC
10	JILAg-6	D Ruess, C Ullrich, BEV, Austria	KC
11	CAG-1	S Merlet, Q Bodart, F Pereira Dos Santos, LNE-SYRTE, France	KC
12	FG5-101	H Wilmes, R Falk, BKG, Germany	PS
13	FG5-102	D Schmerge, M Eckl, NOAA, USA	PS
14	FG5-220	L Timmen, IfE, Germany	PS
15	FG5-228	N Le Moigne, R Bayer, UM, France	PS
16	FG5-230	T Olszak, WUT, Poland	PS
17	FG5-233	J Ågren, Lantmäteriet, Sweden	PS
18	FG5-238	F Greco, C Del Negro, INGV, Italy	PS
19	A10-14	M Diament, S Deroussi, S Bonvalot, IPGP-IRD, France	PS
20	A10-20	J Krynski, M Sekowski, IGC, Poland	PS
21	MPG-2	L J Wang, H Hu, J Schäfer, S Svitlov, MPL, Germany	PS

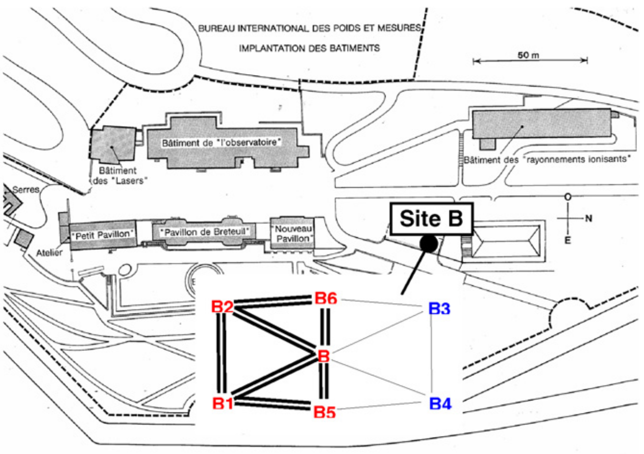


Figure 5. The five stations B, B1, B2, B5 and B6 at the BIPM B site were occupied by the 21 AGs during ICAG2009. Stations B3 and B4 were used as standby occupations.

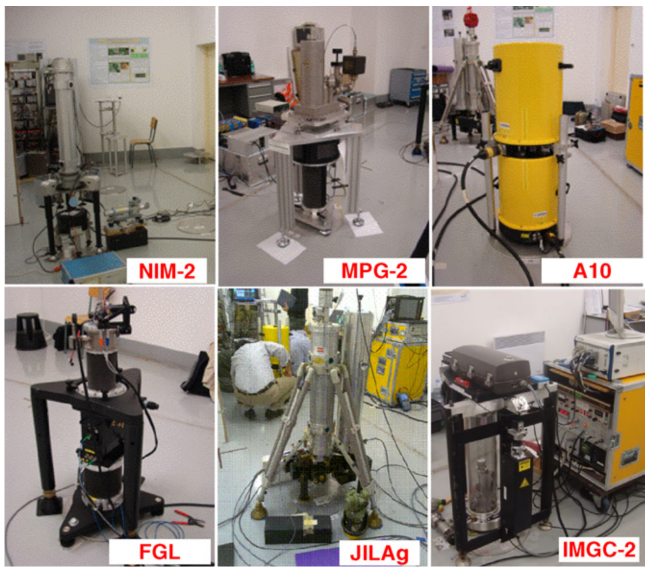


Figure 6. The six AG types participating in ICAG2009 in addition to the FG5s and CAG.

The AG raw data and the associated uncertainties were prepared and submitted by the participants till May 2010. For KC participants, a detailed uncertainty budget was required.

Table 7 lists the AG raw measurements at the reference heights and the uncertainties reported by the participants (columns 7, 8 and 9 of the table) as well as the g values corrected by the SAC and DC (column 13, here DC $= 0.0$ suggests the correction had been taken into account already by the participant in raw measured data reported to BIPM). The reported uncertainties were not modified by taking into account estimates of SAC and DC due to reasons explained in section 1.4.

The gravity values given in table 7 were transferred to the reference height of ICAG2009 ($h = 0.9$ m) using a second-order polynomial approximation for the gravity variations along the vertical determined at all stations during RGC2009 [15] (see table 8).

3.1. The mathematical model for the least-squares adjustments

In this section, we present a brief description of the mathematical model of the least-squares adjustments used in the evaluation.

We note that the measurements are processed together. This was not the case for the KC of ICAG2009, where according to the TP and the rules of the CIPM MRA, the KCRV is calculated only from the KC participants and is used to calculate the degrees of equivalence (see section 3.2.2) of the gravimeters with respect to the reference gravity values represented by the KCRVs.

In the following, CRV indicates the comparison reference values calculated from the measurements of all 21 AGs

Table 4. AG occupations for KC and PS.

AG	ICAG	B	B1	B2	B5	B6
NIM-2	KC	*		*		*
CAG-1	KC	*	*			*
JILAg-6	KC		*	*	*	
A10-5	KC	*	*			*
A10-14	PS	*		*		*
A10-20	PS		*	*		*
MPG-2	PS	*	*		*	
FGL-103	KC		*	*		*
FG5-105	KC	*	*			*
FG5-209	KC	*		*	*	
FG5-213	KC	*	*		*	
FG5-215	KC		*		*	*
FG5-224	KC			*	*	*
FG5-221	KC		*	*	*	
FG5-101	PS	*	*		*	
FG5-102	PS	*	*	*		
FG5-220	PS	*	*	*		
FG5-228	PS	*		*		*
FG5-230	PS	*		*		*
FG5-233	PS	*	*	*		
FG5-238	PS	*			*	*
FG5 #	39	10	8	8	7	6
FG5 KC #	18	3	4	3	5	3
FG5 PS #	21	7	4	5	2	3
KC+PS #	63	15	14	13	9	12

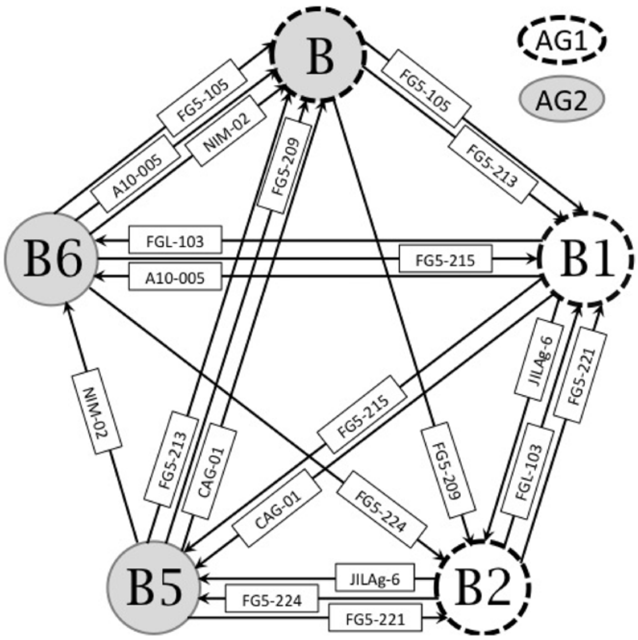


Figure 7. Schedule of the ICAG2009 KC measurements which allows that an arbitrary AG had a direct comparison on the same station with all the other AGs through its three occupations. As illustrated, AG1 and AG2 twice occupied station B. Similarly, an AG will occupy a station with any of other AG(k), $k = 1, 2, \ldots, 21$.

in ICAG2009. Depending on the methods and the data used, the CRV of the ICAG2009 is obtained using all the participating AGs and may not be unique and not constrained by the TP. It may be statistically the best solution. The

Table 5. Relative frequency deviation from the nominative frequency of the Rb clocks used in ICAG2009.

Gravimeter	ICAG2009	$\Delta f/f_{\mathrm{ref}}$	σ_{r}
FG5-213	KC	91.2×10^{-11}	9.0×10^{-11}
FG5-215	KC	27.4×10^{-11}	3.4×10^{-11}
FG5-221	KC	488.2×10^{-11}	3.7×10^{-11}
FG5-224	KC	-109.0×10^{-11}	5.4×10^{-11}
FG5-101	PS	185.7×10^{-11}	4.3×10^{-11}
FG5-102	PS	39.3×10^{-11}	1.5×10^{-11}
FG5-105	KC	8708.0×10^{-11}	4.0×10^{-11}
FG5-233	PS	2.8×10^{-11}	2.7×10^{-11}
FG5-238	PS	-57.3×10^{-11}	2.4×10^{-11}
A10-20	PS	21.9×10^{-11}	2.5×10^{-11}
MPG-2	PS	1.1×10^{-11}	1.2×10^{-11}

Table 6. The laser frequencies measured during the ICAG2009, Δf(e) and Δf(f) for the iodine peaks 'e' and 'f' relative to the offset frequencies 473 612 366 000 kHz and 473 612 353 000 kHz, respectively.

Gravimeter	ICAG2009	Laser type	Δf(e)/ kHz	Δf(f)/ kHz
FG5-209	KC	WEO-100-S	977.2	612.4
FG5-213	KC	WEO-100-N	996.1	633.3
FG5-215	KC	WEO-100-N	993.3	627.3
FG5-221	KC	WEO-100-S	958.0	596.2
FG5-224	KC	WEO-100-S	969.1	605.2
FG5-105	KC	WEO-100-N	792.0	432.0
FG5-101	PS	WEO-100-N	957.0	594.0
FG5-102	PS	WEO-100-N	974.0	610.5
FG5-220	PS	WEO-100-S	965.0	602.1
FG5-233	PS	WEO-100-S	963.9	599.3

symmetric scheme of the measurement allows the calculation of the CRV in different but easily managed ways in order to reach the minimum variance from least-squares adjustment. A combined adjustment with the RG measurements is also carried out to increase the precision of CRV.

Three least-squares adjustment models were applied using different data sets and parameters. The RG-only model and the results have been fully discussed and released, see [15]. Here we present only the other two models and analyse the results.

The *AG-only model* was used for the KC and ICAG (KC+PS) absolute gravity measurements. The observation equation for an AG(k) over station j reads

$$v_{jk} = g_{jk} - G_j + \delta_k. \qquad (3.1.1)$$

Here, g_{jk} is the AG(k) measured gravity value at the station j and transferred to 0.9 m, v_{jk} is the corresponding residual, G_j is the adjusted gravity value and δ_k the offset [30] of the AG(k). The reported uncertainties of individual measurements u_{jk} were used for deriving the respective weights w_{jk} ($w_{jk} = u_{\mathrm{o}}^2/u_{jk}^2$ where u_{o} is the unit weight).

The offset condition is that the sum of the weighted offsets equals zero:

$$\sum \boldsymbol{w}_k \delta_k = 0. \qquad (3.1.2)$$

Here, $\boldsymbol{w}_k = \sum w_{jk}/3$ for $j = 1, 2, 3$ is the average weight of particular AG and δ_k is the offset parameter for the AG(k). Unlike the earlier ICAGs, such as those of 2001 and 2005,

Table 7. AG raw measurements and corrected for the SAC and DC. Date (day/month) is the start day of the measurement in 2009. g^m_{jk} is the raw data measured at the reference height (h_{jk}) with the combined standard uncertainty u_{jk} submitted to BIPM by the participants; u_k is the root mean square of u_{jk}, h_k is the average reference height of AG(k); SAC is the self-attraction correction; DC is the diffraction correction; type *New* or *Old* is the FG5 type [3], *New1* for straight legs and *New2* for sloping legs; NA stands for not applicable and g + SAC + DC is the g_{jk} corrected by the SAC and DC.

N	Date	AG (k)	Inst.	ICAG	Type	Stn$_j$	g^m_{jk} /µGal	u_{jk} /µGal	h_{jk} /m	u_k /µGal	h_k /m	SAC /µGal	DC /µGal	g + SAC + DC /µGal
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
	6/9					B2	27 928.1	6.6	1.1870	6.7	1.1870	−1.17	0.7	27 929.63
1	7/9	NIM-2	NIM	KC	NA	B6	27 915.7	7.4	1.1870			−1.17		27 917.23
	10/9					B	27 949.3	6.0	1.1870			−1.17		27 950.83
	11/9					B1	28 026.5	6.1	0.8160	6.3	0.8168	−1.30	0.0	28 025.20
2	15/9	CAG-1	LNE-SYRTE	KC	NA	B6	28 027.3	6.7	0.8178			−1.30		28 026.00
	19/9					B	28 050.9	6.0	0.8165			−1.30		28 049.60
	13/9					B5	27 907.9	2.9	1.2983	2.9	1.2994	−1.32	1.2	27 907.78
3	14/9	FG5-209	METAS	KC	New2	B	27 904.1	2.9	1.2980			−1.32		27 903.98
	15/9					B2	27 891.0	2.9	1.3020			−1.32		27 890.88
	14/9					B5	27 909.8	2.5	1.2772	2.5	1.2777	−1.32	1.2	27 909.68
4	15/9	FG5-213	NMIJ /AIST	KC	New2	B	27 908.5	2.5	1.2781			−1.32		27 908.38
	16/9					B1	27 904.4	2.5	1.2779			−1.32		27 904.28
	14/9					B6	27 910.2	2.4	1.2119	2.4	1.2119	−1.81	1.2	27 909.59
5	15/9	FG5-215	VUGTK /RIGTC	KC	Old	B1	27 923.6	2.4	1.2124			−1.81		27 922.99
	16/9					B5	27 928.5	2.4	1.2115			−1.81		27 927.89
	18/9					B2	28 027.9	7.8	0.8400	7.5	0.8400	−0.79	1.2	28 028.31
6	19/9	JILAg-06	BEV	KC	NA	B5	28 042.8	7.3	0.8400			−0.79		28 043.21
	20/9					B1	28 035.5	7.3	0.8400			−0.79		28 035.91
	17/9					B2	28 020.0	4.5	0.8090	4.5	0.8143	−1.10	1.2	28 020.10
7	18/9	FGL-103	KRISS	KC	NA	B1	28 040.0	4.5	0.8090			−1.10		28 040.10
	20/9					B6	28 020.0	4.5	0.8250			−1.10		28 020.10
	18/9					B6	27 886.0	2.8	1.2822	2.8	1.2835	−1.12	1.2	27 886.08
8	19/9	FG5-224	CMS/ ITRT	KC	New1	B5	27 902.4	2.9	1.2832			−1.12		27 902.48
	20/9					B2	27 886.3	2.8	1.2852			−1.12		27 886.38
	19/9					B1	28 008.7	5.9	0.9000	5.2	0.9000	−0.58	1.2	28 009.32
9	20/9	A10-05	UME	KC	NA	B6	27 999.1	4.8	0.9000			−0.58		27 999.72
	21/9					B	28 012.6	4.9	0.9000			−0.58		28 013.22
	22/9					B	27 898.0	2.7	1.3110	2.7	1.3110	−1.12	1.2	27 898,08
10	23/9	FG5-105	NRC	KC	New1	B1	27 898.7	2.7	1.3110			−1.12		27 898,78
	24/9					B6	27 883.8	2.7	1.3110			−1.12		27 883,88
	30/9					B5	27 935.9	2.7	1.2000	2.7	1.2000	−1.12	0.0	27 934,78
11	1/10	FG5-221	FGI	KC	New1	B2	27 915.8	2.7	1.2000			−1.12		27 914,68
	2/10					B1	27 930.4	2.7	1.2000			−1.12		27 929,28
	8/9					B	28 027.57	6.1	0.9000	6.1	0.9000	−0.58	1.2	28 028.19
12	8/9	A10-14	IPGP	PS	NA	B2	28 000.95	6.1	0.9000			−0.58		28 001.57
	9/9					B6	28 005.28	6.1	0.9000			−0.58		28 005.90
	28/9					B1	28 070.97	10.0	0.7155	10.5	0.7155	−0.58	1.2	28 071.59
13	29/9	A10-20	IGC	PS	NA	B6	28 053.25	10.9	0.7155			−0.58		28 053.87
	30/9					B2	28 058.31	10.6	0.7155			−0.58		28 058.93
	23/9					B	27 906.58	1.92	1.2908	1.9	1.2903	−1.32	1.2	27 906.46
14	24/9	FG5-101	BKG	PS	New2	B1	27 901.65	1.92	1.2902			−1.32		27 901.53
	22/9					B5	27 905.17	1.9	1.2900			−1.32		27 905.05
	5/10					B1	27 896.05	2.4	1.2986	2.4	1.2984	−1.12	1.2	27 896.13
15	6/10	FG5-102	NOAA	PS	New1	B2	27 877.79	2.4	1.2976			−1.12		27 877.87
	7/10					B	27 895.78	2.4	1.2991			−1.12		27 895.86
	7/9					B2	27 999.79	2.23	0.9000	2.2	0.9000	−1.12	1.2	27 999.87
16	8/9	FG5-228	UM	PS	New1	B6	28 000.83	2.23	0.9000			−1.12		28 000.91
	9/9					B	28 019.44	2.23	0.9000			−1.12		28 019.52
	26/9					B2	27 995.37	2.3	0.9000	2.3	0.9000	−1.12	1.2	27 995.45
17	27/9	FG5-230	SGGA /WUT	PS	New1	B	28 013.97	2.4	0.9000			−1.12		28 014.05
	28/9					B6	27 994.85	2.3	0.9000			−1.12		27 994.93
	29/9					B2	27 893.1	2.4	1.2800	2.4	1.2803	−1.12	1.2	27 893.18
18	39/9	FG5-233	Lantma-teriet	PS	New1	B1	27 905.6	2.4	1.2800			−1.12		27 905.68
	1/10					B	27 907.4	2.4	1.2810			−1.12		27 907.48
	29/9					B	27 907.8	2.7	1.2797	2.8	1.2799	−1.12	1.2	27 907.88
19	30/9	FG5-238	INGV	PS	New1	B6	27 894.7	2.8	1.2792			−1.12		27 894.78
	1/10					B5	27 912.0	2.8	1.2807			−1.12		27 912.08
	23/9					B5	27 964.2	8.2	1.1420	8.2	1.1423	−1.35	0.0	27 962.85
20	24/9	MPG-2	MPL	PS	NA	B	27 960.7	8.2	1.1440			−1.35		27 959.35
	27/9					B1	27 946.8	8.1	1.1410			−1.35		27 945.45
	24/9					B2	27 915.8	2.4	1.2000	2.4	1.2000	−1.12	1.2	27 915.88
21	25/9	FG5-220	IfE	PS	New1	B	27 933.2	2.4	1.2000			−1.12		27 933.28
	26/9					B1	27 927.9	2.4	1.2000			−1.12		27 927.98

Table 8. Linear (b) and second-order (c) coefficients of the gravity model.

Stn	b/µGal m^{-1}	c/µGal m^{-2}
B	−301.37	2.667
B1	−295.57	4.917
B2	−290.77	4.667
B5	−302.57	3.667
B6	−296.73	4.083

the weights are introduced in equation (3.1.2). It is expected to constrain the contribution of AGs with poor uncertainties to the better estimated CRVs and offsets. This condition is particularly helpful when the number of the AGs is small and the distribution of the occupations is not homogeneous. This is the case of the KC. As given in table 11, some offsets are as high as 10 µGal.

The observation equations for the *Combined adjustment model of AG and RG* [15] are

$$v_{ij} = s_q(R_i - R_j)_q - (G_i - G_j) \tag{3.1.3}$$

$$v_{jk} = g_{jk} - G_j + \delta_k \tag{3.1.4}$$

with the same offset condition as AG-only given by (3.1.2). Here, v_{ij} is the residual of the tie $(R_i - R_j)$ measured by the RG q and s_q is the scale of this gravimeter with respect to the Scintrex CG5 348 and 593. The scales of these two gravimeters were selected as the reference, i.e. fixed in the adjustment, because the owner-supplied linear scales agreed the best with the calibration baseline at the BIPM as determined using the BIPM FG5-108. The gravity difference of the baseline is 8.8 mGal, which covers the maximum gravity variation in the BIPM network [15].

3.2. The results

The results of the ICAG2009 are (a) the KCRV for the key comparison CCM.G-K1 and (b) the CRV for other solutions. The derived results are the DoE (degree of equivalence) with respect to the KCRV and CRV [24].

Based on the methods of adjustment and the conventions used, we obtained numerous solutions. Seven typical solutions are presented here[33]:

(1) A$KP: AG-only adjustment using only the 11 KC AGs. The result of the 10 PS AGs is given versus the KCRV from the 11 KC AGs;
(2) A$PS: AG-only adjustment using all the 21 AGs during the ICAG2009;
(3) A$PR: combined absolute and relative measurements (AG+RG) adjustment. AG data are as for A$PS;
(4) A^KP: as A$KP with the SAC and DC applied;
(5) A^PS: as A$PS with SAC and DC applied;
(6) A^PR: as A$PR with SAC and DC applied;
(7) R0: RG-only adjustment with g fixed at ICAG2005 result g(B.090) = 28 018.8 µGal [13].

The solution A$KP gives exactly the same gravity values as that of the CCM.G-K1 [16]. To be comparable with other solutions, however, the uncertainties were not enlarged due to the SAC and DC as was done for KCRVs in [16]. In the first three solutions, the SAC and DC are not taken into account. They conform to the TP2009 but not to the present state-of-knowledge in absolute gravimetry. The solution A$PR is the combined adjustment which includes, in addition the data from the 21 AGs as well as data from the RGs.

The SAC and the DC are considered in the solutions 4 to 6. Comparisons between the solutions 1 to 3 and the solutions 4 to 6 allow us to better understand the impact of the SAC and DC. Solution 7 is based on RGs only (fixed to the final result of ICAG2005), the results of which can be found in [15]. It is independent of the AG-only solutions, and hence provides a means to assess the results of the latter. This will be discussed below.

3.2.1. The KCRV and the CRVs of the different solutions. Table 9 lists the CRVs of the seven different solutions. A^PS is the best AG-only solution because all the 21 AGs were used and the SAC and DC were applied. Solution 6 is an AG and RG combination. From a scientific point of view, it is the best one because of better redundancy and the applications of the SAC and the DC. Depending on the cases, the A^PS or A^PR is used as reference in the following analysis.

Table 10 shows the differences between the CRVs of the different solutions and that of the A^PS. The impact of SAC and DC can be directly seen on column A$PS. It is only 0.1 µGal. In fact, because the FG5 dominates the evaluation with about 90% of the total weight and the values of SAC and DC have the opposite sign and similar magnitude, as given in table 7, the effects of SAC and DC are almost cancelled. The differences to the KCRV are 0.66 µGal on average, i.e. the KCRV differs by less than 1 µGal from the best AG-only solution of the ICAG2009 and is robust. The column A^KP shows that the difference of the results of the 11 KC AGs and the total 21 AGs is 0.38 µGal (σ = 0.16 µGal). The differences in the R0 column show a good agreement on the level of few tenths of a µGal (σ = 0.26 µGal) between completely different types of estimations (AG-only versus relative). Relative measurements lead to a significant improvement of about 40% for standard deviations of the CRVs (A^PS versus A^PR in table 9).

3.2.2. The degrees of equivalence. The degree of equivalence (DoE or D_k) for a KC participant represents the difference between the participant's result and the KCRVs along with the expanded uncertainty of this datum [24]. Therefore, the DoE describes a bias and has the opposite sign to the 'offset', traditionally used in ICAGs. According to the TP, the result of ICAG2009 is the CRVs with their uncertainties evaluated using all the measurements performed by all the AGs participating in ICAG2009. The DoE of AG(k) is derived from the CRV after the adjustment and is the weighted average difference between

[33] The solutions described above use the same naming convention as used in the ICAG electronic documentation held at the BIPM for data processing. Because hundreds of solutions have been made and each solution has a set of inputs and parameters slightly different with the others, the only indicator of the full information of a solution is its name. We use the same rule in this paper to keep the solutions traceable to their documentation.

Table 9. The CRVs of the seven different solutions. Standard deviations are shown.

Stn	A\$KP /μGal	A\$PS /μGal	A\$PR /μGal	A^KP /μGal	A^PS /μGal	A^PR /μGal	R0 /μGal
1. B	8019.8 ± 1.3	8019.6 ± 0.6	8019.4 ± 0.4	8019.6 ± 1.3	8019.5 ± 0.6	8019.3 ± 0.4	8018.8 ± 1.1
2. B1	8013.3 ± 1.0	8012.8 ± 0.6	8013.2 ± 0.4	8013.0 ± 1.0	8012.7 ± 0.6	8013.1 ± 0.4	8012.6 ± 1.1
3. B2	7999.2 ± 1.3	7998.5 ± 0.7	7998.4 ± 0.4	7998.9 ± 1.3	7998.4 ± 0.7	7998.3 ± 0.4	7997.8 ± 1.1
4. B5	8021.3 ± 1.0	8020.6 ± 0.8	8020.8 ± 0.5	8021.0 ± 1.0	8020.5 ± 0.8	8020.7 ± 0.4	8020.2 ± 1.1
5. B6	8001.0 ± 1.2	8000.3 ± 0.8	8000.0 ± 0.5	8000.7 ± 1.2	8000.2 ± 0.8	7999.9 ± 0.4	7999.4 ± 1.1

Table 10. The differences of the CRVs of different solutions versus that of the A^PS.

Stn	A\$KP/μGal	A\$PS/μGal	A\$PR/μGal	A^KP/μGal	A^PR/μGal	R0/μGal
1. B	0.3	0.1	−0.1	0.1	−0.2	−0.7
2. B1	0.6	0.1	0.5	0.3	0.4	−0.1
3. B2	0.8	0.1	0.0	0.5	−0.1	−0.6
4. B5	0.8	0.1	0.3	0.5	0.2	−0.3
5. B6	0.8	0.1	−0.2	0.5	−0.3	−0.8
σ	0.20	0.00	0.26	0.16	0.26	0.26
Mean	0.66	0.10	0.10	0.38	0.00	−0.50

Table 11. The degree of equivalence (D_k) and the standard uncertainty (S_k) given by the seven solutions.

K	AG	A\$KP/μGal	A\$PS/μGal	A\$PR/μGal	A^KP/μGal	A^PS/μGal	A^PR/μGal	R0/μGal
1.	NIM-2	8.3 ± 3.8	8.8 ± 3.8	9.0 ± 3.9	8.1 ± 3.8	8.5 ± 3.8	8.7 ± 3.9	8.5 ± 3.9
2.	CAG-1	-0.9 ± 3.5	-0.5 ± 3.6	-0.4 ± 3.6	-1.9 ± 3.5	-1.6 ± 3.6	-1.6 ± 3.6	0.3 ± 3.7
3.	FG5-209	3.5 ± 1.6	4.0 ± 1.6	4.0 ± 1.7	3.6 ± 1.6	4.0 ± 1.6	4.0 ± 1.7	4.6 ± 1.8
4.	FG5-213	-0.4 ± 1.3	0.1 ± 1.4	-0.1 ± 1.4	-0.3 ± 1.3	0.1 ± 1.4	-0.1 ± 1.4	0.5 ± 1.6
5.	FG5-215	-0.8 ± 1.3	-0.2 ± 1.4	-0.3 ± 1.4	-1.1 ± 1.3	-0.7 ± 1.4	-0.8 ± 1.4	0.3 ± 1.5
6.	JILAg-6	6.5 ± 4.2	7.2 ± 4.3	7.0 ± 4.3	7.2 ± 4.2	7.7 ± 4.3	7.5 ± 4.3	7.9 ± 4.3
7.	FGL-103	-2.4 ± 2.5	-1.7 ± 2.6	-1.7 ± 2.6	-2.0 ± 2.5	-1.5 ± 2.6	-1.5 ± 2.6	-2.7 ± 2.7
8.	FG5-224	-5.3 ± 1.5	-4.6 ± 1.6	-4.5 ± 1.6	-4.9 ± 1.5	-4.4 ± 1.6	-4.3 ± 1.6	-4.2 ± 1.5
9.	A10-05	-4.5 ± 2.9	-4.1 ± 2.9	-4.0 ± 3.0	-3.6 ± 2.9	-3.3 ± 2.9	-3.3 ± 3.0	-3.5 ± 3.1
10.	FG5-105	1.0 ± 1.4	1.5 ± 1.5	1.5 ± 1.6	1.4 ± 1.4	1.7 ± 1.5	1.7 ± 1.6	1.7 ± 1.5
11.	FG5-221	2.2 ± 1.4	2.8 ± 1.5	2.7 ± 1.6	1.4 ± 1.4	1.8 ± 1.5	1.6 ± 1.6	3.0 ± 1.5
12.	A10-14	4.6 ± 3.6	5.1 ± 3.5	5.3 ± 3.5	5.5 ± 3.6	5.8 ± 3.5	6.0 ± 3.5	5.9 ± 3.6
13.	A10-20	3.4 ± 3.1	4.3 ± 6.0	4.3 ± 6.1	4.3 ± 3.1	5.0 ± 6.0	5.0 ± 6.1	4.6 ± 3.1
14.	FG5-101	0.2 ± 1.3	0.6 ± 1.1	0.5 ± 1.1	0.3 ± 1.3	0.6 ± 1.1	0.5 ± 1.1	1.1 ± 1.3
15.	FG5-102	-6.6 ± 1.6	-6.1 ± 1.4	-6.1 ± 1.4	-6.2 ± 1.6	-5.9 ± 1.4	-6.0 ± 1.4	-5.5 ± 1.6
16.	FG5-228	0.0 ± 1.5	0.6 ± 1.3	0.8 ± 1.3	0.4 ± 1.5	0.7 ± 1.3	0.9 ± 1.3	1.7 ± 1.8
17.	FG5-230	-5.3 ± 1.4	-4.7 ± 1.3	-4.5 ± 1.4	-4.9 ± 1.4	-4.5 ± 1.3	-4.3 ± 1.4	-3.9 ± 1.3
18.	FG5-233	0.4 ± 1.6	0.9 ± 1.4	0.9 ± 1.4	0.8 ± 1.6	1.1 ± 1.4	1.0 ± 1.4	1.4 ± 1.6
19.	FG5-238	1.9 ± 1.7	2.5 ± 1.6	2.5 ± 1.6	2.3 ± 1.7	2.6 ± 1.6	2.7 ± 1.6	3.2 ± 1.7
20.	MPG-2	9.9 ± 4.8	10.4 ± 4.8	10.2 ± 4.8	8.8 ± 4.8	9.1 ± 4.8	9.0 ± 4.8	10.8 ± 4.8
21.	FG5-220	1.1 ± 1.4	1.5 ± 1.4	1.5 ± 1.4	1.4 ± 1.4	1.7 ± 1.4	1.7 ± 1.4	2.0 ± 1.6
$\sum(W_k \times \delta_k^2)$/ μGal^2		30.7	108.3	105.9	27.7	102.1	100.3	0.0

the measurements of AG(k) transferred to 0.9 m (g_{jk}) and the KCRV or the CRV (G_j):

$$D_k = \left[\sum w_{jk}(g_{jk} - G_j)\right] \Big/ \sum w_{jk}, \quad j = 1, 2, 3. \quad (3.2.1)$$

For the KC solution, equation (3.2.1) is a consequence of equations (3.1.1) and (3.1.2), thus the DoE $D_k = -\delta_k$. The advantage of the simple definition of the D_k is that once the CRV is determined, a participant k can easily calculate for himself the D_k of his AG(k). This is particularly the case for the solution A^KP. Although the 10 PS AGs were not involved in the KCRV determination during the adjustment, their degrees of equivalence can also be obtained by equation (3.2.1). These are the only results which conform to the rules of the CIPM MRA, the TP, and are therefore SI traceable. We interpret the offset δ_k on the other hand simply as a mathematical parameter in the least squares adjustment.

Table 11 lists the D_k and the 1-σ statistics of the seven solutions. The last line of table 11 is the sum of the weighted square of the DoEs $\sum(w_k D_k^2)$. Not all the solutions are comparable because the weighting conditions are not the same, e.g. the weight of PS AGs in KC solutions (A\$KP, A^KP) has to be zero. The $\sum(w_k D_k^2)$, in units of μGal^2, of the solutions A\$PS, A\$PR, A^PS and A^PR are comparable. With the same AG measurements and the same weights, the results are different due to the inclusion of the SAC, DC and relative measurements in the adjustments. They have the relationships 108.3 > 105.9 > 102.1 > 100.3, respectively. Obviously, the smallest is the best in the sense of the least-squares adjustment

Table 12. Differences of the D_k from different solutions versus that of the A^PR.

AG	A$KP	A$PS	A$PR	A^KP	A^PS	R0
NIM-2	−0.3	0.4	0.2	−0.5	−0.2	−0.2
CAG-1	0.7	1.2	1.2	−0.3	0.0	1.9
FG5-209	−0.5	0.0	0.0	−0.4	0.0	0.6
FG5-213	−0.3	0.0	0.2	−0.2	0.1	0.6
FG5-215	0.0	0.5	0.6	−0.3	0.1	1.1
JILAg-6	−1.0	−0.5	−0.3	−0.2	0.2	0.4
FGL-103	−0.8	−0.2	−0.2	−0.4	0.0	−1.1
FG5-224	−1.0	−0.2	−0.3	−0.6	−0.1	0.1
A10-05	−1.3	−0.7	−0.8	−0.4	−0.1	−0.2
FG5-105	−0.7	−0.2	−0.2	−0.3	0.0	0.0
FG5-221	0.6	1.0	1.2	−0.3	0.2	1.4
A10-14	−1.4	−0.7	−0.9	−0.5	−0.2	−0.1
A10-20	−1.6	−0.7	−0.7	−0.7	0.0	−0.4
FG5-101	−0.3	0.0	0.2	−0.2	0.1	0.6
FG5-102	−0.6	−0.2	−0.1	−0.3	0.0	0.4
FG5-228	−0.9	−0.2	−0.4	−0.6	−0.2	0.8
FG5-230	−0.9	−0.2	−0.4	−0.6	−0.2	0.4
FG5-233	−0.6	−0.2	−0.2	−0.3	0.0	0.4
FG5-238	−0.8	−0.2	−0.3	−0.4	−0.1	0.4
MPG-2	0.9	1.3	1.4	−0.2	0.1	1.8
FG5-220	−0.6	−0.2	−0.1	−0.3	0.0	0.3
σ	0.6	0.6	0.6	0.2	0.1	0.7
Mean	−0.5	0.0	0.0	−0.4	0.0	0.4

when normal distribution of the DoE is assumed. The unequal relationship proves that (1) the SAC and DC reduced the scatter of the DoEs of different models of AGs, i.e. the A^PS is better than the A$PS; (2) with the relative-gravimeter-only RG data, the DoEs have been better resolved, i.e. the A^PR is better than the A^PS.

Table 12 shows the differences of the DoEs from different solutions with respect to that of the A^PR. Note that only the 11 KC AGs are used in the solutions A$KP and A^KP. The SAC and DC are not considered in AKP, APS and A$PR. Referring to A^PR, the weighted mean of the differences of 21 AG solutions (APS, APR and A^PS) has to be zero. The RG-only solution agrees well (±0.7 µGal) with the 21 AG solutions. The weighted mean of the difference between the 11 AG A^KP and the 21 AG A^PR is −0.4 µGal with the standard deviation of 0.2 µGal. This is safely within the standard uncertainties from the adjustment and the uncertainty estimations given in table 11. The 21 AG-only solutions give practically same results as the combined AG and RG solutions (differences below 0.2 µGal). KC estimations of DoE (A$KP) differ from the statistically and scientifically best estimation (A^PR) for less than 1.6 µGal (1.0 µGal in case of FG5s).

3.2.3. Short-term reproducibility of an individual AG. The short-term reproducibility of an individual gravimeter AG(k) can be observed in the values of the difference $g_{jk} - G_j$, at the different stations, as plotted in table 13.

The scatter of the adjustment residuals related to a particular AG(k), represented by the standard deviation of the residuals (σ_k), is an indicator of the short-term reproducibility of the AG(k). The lowest values of σ_k (below 2.2 µGal) are associated with FG5s only. However, a good operational status (high precision) does not suggest a good metrological calibration status, e.g. FG5-224 and FG5-230 have a significant DoE of about 4.4 µGal but low short-term reproducibility. The DoE of the FG5-102 reaches value of 6.0 µGal that even exceeds the expanded uncertainty (U_k). As can be seen from table 13, there are 41 positive differences but only 22 negative due to predominant positive differences of AGs with lower weights. The zero axis is not geometrically in the centre but goes through the weighted centre as forced by the constraint equation (3.1.2).

4. Summary and discussion

4.1. KCRV and CRV

Five stations were occupied during the ICAG2009. Altogether 21 AGs, considered each as an independent system, provided 63 measurements. To determine the CRVs at the five stations and the k offset parameters for each gravimeter, the number of the necessary occupations is $5 + k$. Therefore, there are 17 redundant occupations in the KC (11 AGs) and 37 in ICAG2009 (21 AGs). Greater redundancy suggests smaller uncertainty due to the increased number of statistical degrees of freedom. As pointed out above, the KCRV is not statistically the best solution. A^PR is the most redundant solution using data from 21 AGs and 9 RGs. Moreover, it includes also SAC and DC. Differences between the KCRVs and the CRVs of A^PR thus show up in the robustness of the KC solution, see table 14. The mean difference is 0.66 µGal with a standard uncertainty of 0.15 µGal.

4.2. Summary of the main results

Table 15 lists the degree of equivalence given by the solution A^PR and the uncertainties of all the 21 AGs participating in the ICAG2009 (see table 7). The uncertainty reported by the participants should cover both the random and systematic errors of measurements. Therefore the degrees of equivalence (DoEs) D_k should be less than the expanded uncertainties U_k ($U_k = 2u_k$). Twenty of the total 21 AGs fulfil this requirement. However, the FG5-102 ($D_k = 5.99$ µGal, $U_k = 4.80$ µGal) can be classified as discrepant at the 5% level of significance. Interestingly, there are 13 negative but only 8 positive DoEs. Some non-FG5 AGs have large negative DoEs but they also have large uncertainties, i.e. small weights or small contributions to the adjustment. The relative weight of each AG is given in table 15 in the column w_k%. NIM-2, JILAg-6 and MPG-2 have noticeable negative biases within their declared uncertainties but their weights are low. This implies the importance of using weights in the constraining condition of equation (3.1.2).

Short-term reproducibility of AGs (σ) as a parameter for variability of three measurements of particular AGs is in table 15. Comparing σ with DoE we can see that for the FG5-213 (lowest DoE) $D_k = -0.08$ µGal but $\sigma = 0.8$ µGal, while for the FG5-215 (lowest reproducibility) $D_k = 0.81$ µGal but $\sigma = 0.3$ µGal, and for the CAG-1 $D_k = -1.63$ µGal while $\sigma = 7.8$ µGal. From table 7, the uncertainties of the three AGs are, respectively, 2.5 µGal, 2.4 µGal and 6.3 µGal, which

Table 13. Distribution of the 63 measured g values for the 21 AGs versus the CRV of AˆPR and their short-term reproducibility (σ_{wk}).

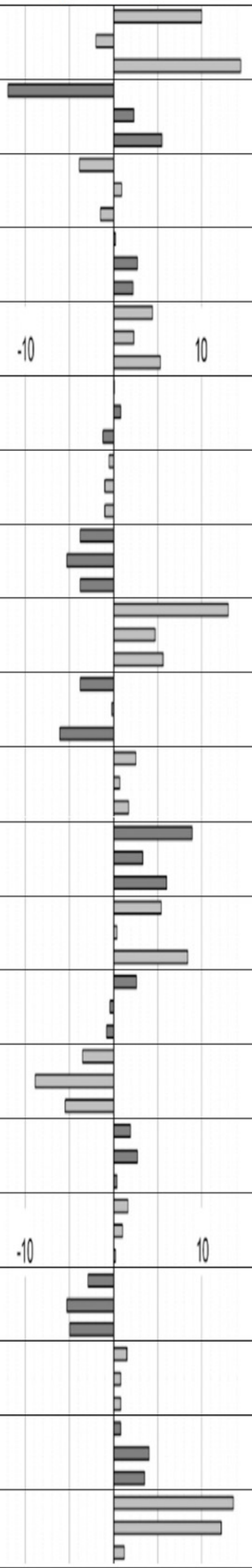
Station	g	CRV	$g - CRV$	u_{jk}	AG	$g - CRV$ plot	σ_{wk}
B2	28 008.3	27 998.3	10.0	6.6			
B6	27 998.0	27 999.9	-2.0	7.4	NIM-2		6.6
B	28 033.7	28 019.3	14.4	6.0			
B1	28 001.1	28 013.1	-12.0	6.1			
B6	28 002.2	27 999.9	2.3	6.7	CAG-01		7.8
B	28 024.8	28 019.3	5.5	6.0			
B2	27 994.4	27 998.3	-3.9	4.5			
B1	28 014.0	28 013.1	0.9	4.5	FGL-103		2.0
B6	27 998.4	27 999.9	-1.5	4.5			
B	28 019.5	28 019.3	0.2	2.7			
B1	28 015.8	28 013.1	2.7	2.7	FG5-105		1.1
B6	28 002.1	27 999.9	2.2	2.7			
B5	28 025.1	28 020.7	4.4	2.9			
B	28 021.6	28 019.3	2.3	2.9	FG5-209		1.3
B2	28 003.6	27 998.3	5.3	2.9			
B5	28 020.8	28 020.7	0.1	2.5			
B	28 020.1	28 019.3	0.8	2.5	FG5-213		0.8
B1	28 011.9	28 013.1	-1.2	2.5			
B6	27 999.5	27 999.9	-0.5	2.4			
B1	28 012.1	28 013.1	-1.0	2.4	FG5-215		0.3
B5	28 019.7	28 020.7	-1.0	2.4			
B6	27 996.1	27 999.9	-3.8	2.8			
B5	28 015.4	28 020.7	-5.3	2.9	FG5-224		0.7
B2	27 994.5	27 998.3	-3.8	2.8			
B2	28 011.3	27 998.3	13.0	7.8			
B5	28 025.4	28 020.7	4.7	7.3	JILAg-6		3.6
B1	28 018.7	28 013.1	5.6	7.3			
B1	28 009.3	28 013.1	-3.8	5.9			
B6	27 999.7	27 999.9	-0.2	4.8	A10-005		2.6
B	28 013.2	28 019.3	-6.1	4.9			
B5	28 023.2	28 020.7	2.5	2.7			
B2	27 999.0	27 998.3	0.7	2.7	FG5-221		0.8
B1	28 014.8	28 013.1	1.7	2.7			
B	28 028.2	28 019.3	8.9	6.1			
B2	28 001.6	27 998.3	3.3	6.1	A10-014		2.3
B6	28 005.9	27 999.9	6.0	6.1			
B1	28 018.5	28 013.1	5.4	10.0			
B6	28 000.3	27 999.9	0.4	10.9	A10-020		3.2
B2	28 006.7	27 998.3	8.4	10.6			
B	28 022.0	28 019.3	2.6	1.9			
B1	28 012.7	28 013.1	-0.4	1.9	FG5-101		1.5
B5	28 019.9	28 020.7	-0.8	1.9			
B1	28 009.6	28 013.1	-3.5	2.4			
B2	27 989.4	27 998.3	-8.9	2.4	FG5-102		2.2
B	28 013.8	28 019.3	-5.5	2.4			
B2	28 000.2	27 998.3	1.9	2.4			
B	28 022.0	28 019.3	2.7	2.4	FG5-220		0.9
B1	28 013.5	28 013.1	0.4	2.4			
B2	27 999.9	27 998.3	1.6	2.2			
B6	28 000.9	27 999.9	1.0	2.2	FG5-228		0.6
B	28 019.5	28 019.3	0.2	2.2			
B2	27 995.4	27 998.3	-2.9	2.3			
B	28 014.0	28 019.3	-5.3	2.4	FG5-230		1.1
B6	27 994.9	27 999.9	-5.0	2.3			
B2	27 999.8	27 998.3	1.5	2.4			
B1	28 013.9	28 013.1	0.8	2.4	FG5-233		0.3
B	28 020.1	28 019.3	0.8	2.4			
B	28 020.1	28 019.3	0.8	2.7			
B6	28 003.9	27 999.9	4.0	2.8	FG5-238		1.4
B5	28 024.2	28 020.7	3.5	2.8			
B5	28 034.3	28 020.7	13.6	8.2			
B	28 031.5	28 019.3	12.2	8.2	MPG-02		5.6
B1	28 014.3	28 013.1	1.2	8.1			
	$\sum \ (w_{jk} \times (g_{jk} - CRV))$		-0.1				

Table 14. Comparison of the KCRV and the CRV of the solution AˆPR.

No. Stn	KCRV/μGal	$\pm\sigma$	AˆPR/μGal	$\pm\sigma$	dif./μGal
1.B	8019.8	±1.3	8019.3	±0.4	0.5
2.B1	8013.3	±1.0	8013.1	±0.4	0.2
3.B2	7999.2	±1.3	7998.3	±0.4	0.9
4.B5	8021.3	±1.0	8020.7	±0.4	0.6
5.B6	8001.0	±1.2	7999.9	±0.4	1.1
				Mean	0.66
				σ_{Mean}	0.15

cover the irreproducibility and the scatters. FG5-101 is also interesting for its low DoE (−0.47 μGal), high σ (1.6 μGal) and lowest uncertainty u_k (1.9 μGal).

To test a possibility of biased CRVs due to the dominant role of FG5s, we can separate all the AGs into three groups according to their reported uncertainties: first group consists of the AGs with $u_k < 4$ μGal (all 13 FG5s only); second group has u_k values between 4 μGal and 6.5 μGal (CAG-1, FGL-103, A10-5, A10-14); third group has $u_k > 6.5$ μGal (A10-20, MPG-2, JILAg-6, NIM-2). The corresponding relative weights for these three groups in the total statistical weight are 90.9%, 6.2% and 2.9%. From table 15, the mean value of the DoEs of the first group is (-0.12 ± 0.85) μGal, the second (-0.12 ± 2.09) μGal and the third (8.23 ± 1.19) μGal. The first two groups agree with each other but the third group seems to be biased. We conclude that no significant bias can be found in the FG5s with respect to the independent group of CAG, A10 and FGL gravimeters. On the other hand, the large statistical weight given to the FG5s has the effect that the weighted offset constraint (equation (3.1.2)) reasonably reduces the impact of possible biases observed in the DoEs of the third group.

4.3. Problems raised during the ICAG2009 and outlook for future ICAGs

A discussion on the problems encountered in the various steps of ICAG2009 is now presented as an aid to the organization of the future ICAGs.

The majority of ICAG2009 participants did not correctly consider the SAC and the DC and their uncertainties [2]. However, the problem was identified during the evaluation. Long discussions between the participants and the pilot laboratory on how to deal with these corrections came to the conclusion that they should not be applied in the gravity values but only in the uncertainty budget in the final KC evaluation. The future Technical Protocol (TP) should be clearer considering the application of all well known effects as indicated by the state-of-the-art in absolute gravimetry.

For the PS participants a complete uncertainty budget was not mandatory. Complete uncertainty budgets should be requested in future ICAGs for instruments participating in the PS, as they are mandatory for participants in the KC part.

It is well known that the gravity value varies significantly along the vertical. Thus, the g value has to be defined at a particular height above the benchmark with an accuracy of 1 mm. To minimize transfer errors from the reference height where gravity is measured to a common height (0.9 m) where gravity measurements are compared, it was requested in the TP to associate gravity with instrumental reference height [21]. However, as seen in table 7, with the group of FG5 gravimeters as an example, the heights of the submitted AG results vary from 0.9 m to 1.2 m to 1.3 m, corresponding, respectively, to the reference height of the comparison, reference height according to [21], and to the so-called top of the drop, respectively. These discrepancies in the height definition may introduce errors of up to 1 μGal in the case of non-constant vertical gravity gradients at site B of the BIPM. A unique height, such as the reference height approximately associated with the effective position [4] (within few centimetres), should be fixed in the TP for future ICAGs. To minimize transfer errors in the CRV estimation, the reference height of the comparison should be adopted according to the accuracies of the participating AGs.

The absolute gravity observations of ICAG2009 were carried out between 1 September and 6 October 2009. The comparison setup presumed a constant gravity signal at the comparison site (after correcting for the influences of tides, polar motion and air pressure), but gravity variations due to hydrological influences may still persist in the gravity signal. From earlier AG time series recorded at the BIPM it is known that only smaller gravity variations became visible. Therefore, it was assumed that error contributions from these gravity variations did not exceed the uncertainty level of the comparison. For future comparisons on other comparison sites it is recommended to monitor these variations with a recording gravimeter and possibly apply corrections. Furthermore, reliable additional measurements make the organization of the ICAG comparisons more independent of the time schedule and may improve their results. A stable recording gravimeter compensates the missing simultaneity of the AG measurements. By the combination of repeated AG observations and recorded gravity variations it improves the comparison site to a gravity reference station.

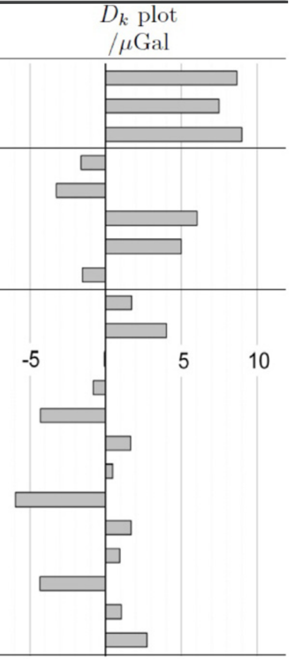
The future ICAGs will be held at different locations. The AG instruments connect the comparison sites and therefore a high continuity of the participating instruments is desirable. The quality of future comparisons could be improved in several ways: (a) optimization of measurements, (b) monitoring and correction for gravity variations during a comparison, (c) enhancement in studying of systematic effects and independence of AGs, (d) improvements in uncertainty estimates of AGs, (e) involving more instruments in the group of the KC instruments. The KC results will be maintained in the KCDB of the BIPM. For the PS part of the ICAG, it is planned to store the results in the AGrav database [35] of the Bundesamt für Kartographie und Geodäsie (BKG) and the Bureau Gravimétrique International (BGI).

5. Conclusions

The ICAG2009 was designed and carried out as the first metrological comparison of absolute gravimeters.

Table 15. The distribution of degree of equivalence (D_k), standard uncertainty (S_k) of the D_k, the mean uncertainty (u_k), the expanded uncertainty (U_k), contribution to the total weight (w_k) and the short-term reproducibility (σ) from the solution AˆPR.

AG k	D_k /µGal	S_k /µGal	u_k /µGal	U_k /µGal	w_k %	σ /µGal
NIM-02	8.7	3.9	6.7	12.4	1	6.6
JILAg-6	7.5	4.3	7.5	15.0	1	3.6
MPG-02	9.0	4.8	8.2	16.3	1	5.6
CAG-01	-1.6	3.6	6.3	12.5	1	7.8
A10-005	-3.3	3.0	5.2	10.4	2	2.6
A10-014	6.0	3.5	6.1	12.2	1	2.3
A10-020	5.0	6.1	10.5	21.0	1	3.2
FGL-103	-1.5	2.6	4.5	9.0	2	2.0
FG5-105	1.7	1.6	2.7	5.4	6	1.1
FG5-209	4.0	1.7	2.9	5.8	5	1.3
FG5-213	-0.1	1.4	2.5	5.0	7	0.8
FG5-215	-0.8	1.4	2.4	4.8	7	0.3
FG5-224	-4.3	1.6	2.8	5.7	5	0.7
FG5-221	1.6	1.6	2.7	5.4	6	0.8
FG5-101	0.5	1.1	1.9	3.8	11	1.5
FG5-102	-6.0	1.4	2.4	4.8	7	2.2
FG5-220	1.7	1.4	2.4	4.8	7	0.9
FG5-228	0.9	1.3	2.2	4.5	8	0.6
FG5-230	-4.3	1.4	2.3	4.7	8	1.1
FG5-233	1.0	1.4	2.4	4.8	7	0.3
FG5-238	2.7	1.6	2.8	5.5	6	1.4
$\sum(w_k \times D_k)=$	0.0				100	



Twelve national metrology institutes (NMIs) and designated laboratories participated in the Key Comparison (KC), named the CCM.G-K1; in addition ten absolute gravimeters from non-designated participants took part in the Pilot Study (PS) comparison.

The pilot laboratory BIPM performed the data processing for the KC (11 AGs) and the ICAG2009 (all 21 AGs) in different ways. Three solutions are recommended:

(1) A$KP is the AG-only adjustment, the result of the KC CCM.G-K1. It gives traceability to SI for the participating instruments,
(2) AˆPS is the best AG-only solution using all the 21 AGs with all corrections applied, including SAC and DC, i.e. self-attraction and diffraction corrections,
(3) AˆPR is the combined AG and RG solution in which all AG and RG measurements were used and therefore it is the statistically best solution for the scientific analysis.

The differences between the mean values of these three solutions remain clearly below 1 µGal. And so, no quality difference could be detected between KC and PS instruments.

The degrees of equivalence (DoEs) were first introduced in the context of this ICAG as a deviation from the Key Comparison Reference Values (KCRVs). Figure 8 shows the DoEs for the participating AGs in the ICAG2009 with respect to the KCRVs (solution A$KP) together with the expanded uncertainties U_k submitted by the participants. The DoEs for all KC gravimeters lie within their expanded uncertainties. However, this is not quite the case for PS gravimeter FG5-102, classified as discrepant at the 5% level of significance for all solutions of ICAG2009. The gravimeter based on atom interferometry, a first for any ICAG, participated successfully in the comparison. No statistically significant offset could be detected with respect to any of the mechanical ballistic absolute gravimeters.

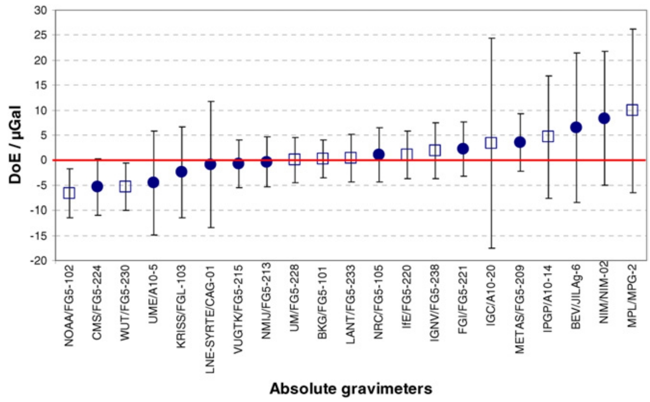


Figure 8. Degrees of equivalence for the AGs participating in the ICAG2009 with respect to the KCRV calculated for CCM.G-K1 following procedures specified by the CIPM MRA (positive DoE means positively biased AG). The dots are the KC AGs and squares the PS AGs. The error bars represent the expanded uncertainties (U_k) at 95% confidence.

Different methods and data sets were used to evaluate the final results. The results agree with each other within less than 1 µGal. The standard deviation of the KCRV for the KC part of the ICAG2009 is below 1.3 µGal and 0.5 µGal for the CRV of the KC+PS, respectively. The standard deviations of the determined degree of equivalences of the AGs strongly depend on the reported uncertainties of the participants and vary from 1.1 µGal to 4.8 µGal.

Absolute gravimetry aligned with modern metrology allows traceability to SI, leading to the establishment and maintenance of a globally accurate and consistent gravity system.

ICAG2009 is an example of the successful cooperation of experts in metrology, geodesy and geophysics under the umbrella of the IAG and the CIPM. We hope that the experience acquired through eight campaigns in their organization, data processing methods and software will be helpful to future ICAGs.

The responsibility for future key comparisons of absolute gravimeters has now been transferred by the CIPM from the BIPM to national metrology institutes. They will organize key comparisons in the context of the CIPM MRA (Mutual Recognition Arrangement of national measurement standards and of calibration and measurement certificates issued by national metrology institutes [1]) as a part of future ICAGs.

Acknowledgments

The authors would like to thank all the pioneers in modern absolute gravimetry and the ICAGs as partially listed in table 1. They also appreciate the full support from BIPM for the last 28 years, in particular from the directors, from the administration and the workshop. They thank R Davis (BIPM, retired) for participating in the planning of ICAG2009 and helping to edit this report.

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