The Seventh International Comparison of Absolute Gravimeters ICAG-2005 at the BIPM. Organization and preliminary results

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[*]**Abstract.** ICAG-2005, an international comparison of absolute gravimeters, was held in September 2005 at the Bureau International des Poids et Mesures (BIPM), Sèvres, France. Nineteen absolute gravimeters performed measurements of free-fall acceleration g at eleven sites of the BIPM gravity network. Fifteen relative gravimeters were used to measure the vertical gravity gradients and to provide gravity ties between the sites. The maximum g-difference was about 9 mGal. The status of a pilot study was agreed for this comparison by the Consultative Committee for Mass and Related Quantities. For the first time in the ICAG series, a technical protocol specifying the organization, measurement strategy, data processing, calculation of the uncertainties and presentation of the results, was developed for the ICAG 2005. The unweighted mean value of the results of absolute measurements referred to the site A is presented and compared with the similar values obtained in ICAG-1997 and ICAG-2001.

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1 Introduction

The seventh in the series of International Comparisons of Absolute Gravimeters begun in 1980, ICAG 2005 was carried out at the BIPM (Sèvres, France). This comparison was organized by the Working Group on Gravimetry of the Consultative Committee for Mass and Related Quantities (CCM) of the International Committee of Weights and Measures (CIPM), Study Group 2.1.1 of the International Association of Geodesy (IAG) and the BIPM.

Comparing the measurement results of absolute gravimeters of the highest metrological quality is the best, and perhaps the only, way to test the uncertainty in absolute measurements of free-fall acceleration.

In a worldwide metrology system all the measuring instruments in any measurement field should be traceable to a primary measurement standard in the corresponding field (often, but not necessarily, the national standard). A primary standard is designated or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity [1].

According to the CIPM Mutual Recognition Arrangement (CIPM MRA) between more than sixty national metrology institutes (NMIs) worldwide (see the information on the CIPM MRA on the website of the BIPM [2]), the equivalence of national measurement standards should be established in key comparisons (KCs). The participants of the KC are the NMIs or other laboratories designated by a NMI as holding the national measurement standards. In the field of gravimetry very often absolute gravimeters are not recognized as the national metrology standards. Such absolute gravimeters can also participate in the KC and their designation can be obtained during the course of the KC. According to the CIPM MRA rules, the results of laboratories which are not NMIs or designated by NMIs cannot appear on the Key Comparison Data Base (KCDB), neither can their results be used in calculation of the Key Comparison Reference Value (KCRV). The KCDB also contains lists of calibration and measurement capabilities (CMCs) offered by NMIs and designated laboratories to the general public. Whenever possible, CMC claims must be supported by KC results.

Ideally, the determination of the KCRV in the ICAGs is a natural way to obtain the shifts of the results of the individual gravimeters from the KCRV and to use them as a correction in the measurement of free-fall acceleration. The realization of such a programme is possible if the reproducibility in the measurement of individual gravimeters is confirmed.

Considering that choosing KC status would limit the participation in ICAG-2005, the BIPM and the steering committee (L. Vitushkin, M. Becker, O. Francis, A. Germak, Z. Jiang) suggested that this comparison be organized as a pilot study. The status of a pilot study made it possible to be more flexible in the invitation of the participants which could be not only the NMIs but also other organizations, for instance the geophysical institutes.

Except for a more inclusive participation, the ICAG-2005 was organized according the rules for KCs. In particular, a technical protocol specifying the organization, measurement strategy, data processing, calculation of the uncertainties and presentation of the results, was developed.

2 Organization of absolute measurements.

To prepare for the ICAG-2005, the BIPM constructed two new outdoor sites having a difference of free-fall acceleration *g* of about 9 mGal to make it possible to calibrate relative gravimeters. Prior to the absolute measurements, the vertical gravity gradients at all the sites and the ties (differences of *g* between the sites) of the BIPM gravity network were measured using fifteen relative gravimeters [3].

The gravity network of the BIPM consists of four sites: A, A0, A1 and A2 in the Observatory building, seven sites: B, B1 – B6 in the Pavillon du Mail and two outdoor sites: C1 and C2.

The FG5-108 absolute gravimeter belonging to the BIPM occupied the B3 site from 3 to 24 September 2005, during the absolute measurements. This gravimeter has performed regular (almost daily) measurements to monitor the stability of the gravity field of the BIPM. With the same goal, the FG5-202 absolute gravimeter (Royal Observatory of Belgium) was used to check the stability of the gravity field at the A2 site from 6 to 21 September.

Nineteen absolute gravimeters from seventeen countries and the BIPM have participated in the comparison (Table 1).

As seen in Table 1, some of gravimeters have already participated in two or even three ICAGs at

the BIPM. It is interesting to analyze, in particular, the reproducibility of their results.
The gravimeters IMGC-2 [4] and TBG are that with the symmetric (up-down) trajectory of free moving test body. All other gravimeters are of a free-fall type. The FGC-1 gravimeter [5] has an original cam-driven dropper mechanics different from that of FG5 gravimeters.
In the GABL-G gravimeter an iodine-stabilized diode-pumped solid-state Nd:YAG laser at 532 nm is used as a coherent light source in the laser displacement interferometer. All other gravimeters used the iodine-stabilized He-Ne lasers at 633 nm.

Table 1. Participation of institutes and gravimeters participated in ICAG-1997, ICAG-2001 and ICAG-2005

	Country, institute	Gravimeter		
		1997	2001	2005
1	Germany, BKG	FG5-101	FG5-101	FG5-101
2	BIPM	FG5-108	FG5-108	FG5-108
3	Belgium, ORB	FG5-202	FG5-202	FG5-202
4	France, EOST	FG5-206	FG5-206	FG5-206
5	Switzerland, METAS		FG5-209	FG5-209
6	Spain, IGN		FG5-211	FG5-211
7	Japan, AIST/NMIJ		FG5-213	FG5-213
8	Czech Republic, GOP			FG5-215
9	Luxemburg, UL/ECGS			FG5-216
10	Finland, FGI	JILAg-5	JILAg-5	FG5-221
11	Chinese Taipei, CMS/ITRI			FG5-224
12	France, DLL CNRS/MU			FG5-228
13	USA/USGS			A10-008
14	USA/JILA CU/NIST			FGC-1
15	Russia/ IAE RAS	GABL-E		GABL-G
16	Italy/INRiM	IMGC	IMGC	IMGC-2
17	Austria/BEV	JILAg-6	JILAg-6	JILAg-6
18	Canada/NRCan	JILA-2	JILA-2	JILA-2
19	Ukraine/NSC IM			TBG

The BIPM calibrated the frequencies of all the lasers and verified the frequency of Rb-clocks and GPS receivers of the absolute gravimeters. The atmospheric pressure was measured continuously during the comparison using a calibrated digital barometer and these data were provided to the participants.
In addition, for the first time the laser beam shapes were determined using the CMOS camera for those gravimeters, whose construction allows this measurement.
During the comparison up to nine absolute gravimeters occupied simultaneously the sites of the BIPM gravity network. The absolute gravimeters usually were installed on the sites and adjusted in the day-time and the measurements were performed in the night (during at least 12 hours).

3 Results of absolute measurements.

97 absolute measurements at eleven sites of the BIPM were performed in the period from 3 to 25 September 2005.
The results of the measurements of FG5-108 at B3 and FG-202 at A2 were stable with the standard deviation of the mean results within 1 µGal. This confirms the appropriate stability of gravity field at the BIPM during the comparison.
According to the Technical Protocol two forms of the presentation of the results of the absolute measurements were used.
For the gravimeters JILA, FG5 and A10 the raw data (pairs of time and length intervals in the format used in the software developed by “Micro-g Solutions, Inc.”, now “Micro-g La Coste, Inc.”) were presented. Then, as in ICAG-1997 and ICAG-2001, the raw data were re-processed using, when possible, the same software. This, in principle, should allow better understanding of the sources of the uncertainties.
For the gravimeters IMGC-2, TBG and GABL-G the presentation of raw data is not possible because data formats different from that used in the gravimeters JILA, FG5 and A10.
Taking in consideration that 1) in the future, wider participation of the gravimeters of different types is possible, including instruments based on atom interferometry, and 2) the participating laboratory is responsible for the presentation of the final results of the measurements obtained during the comparison, the Technical Protocol of ICAG-2005 requires that the final results of the absolute measurements be calculated and presented by the participants.
Finally, the pilot laboratory (BIPM) obtained the raw data from the operators of JILA, FG5 and A10 gravimeters and the final results from all the gravimeters, as calculated and presented by the participants.
It is worth noting, that for the most part, the differences between the results re-processed in the unified manner and those presented by the operators were within 1 µGal.
The CIPM MRA “Guidelines for CIPM key comparisons” (see on BIPM website [2]) define the rules that we followed for the preparation of the report. The first draft, draft A, includes the results transmitted by the participants. It is confidential to the participants. The second draft, draft B, is no

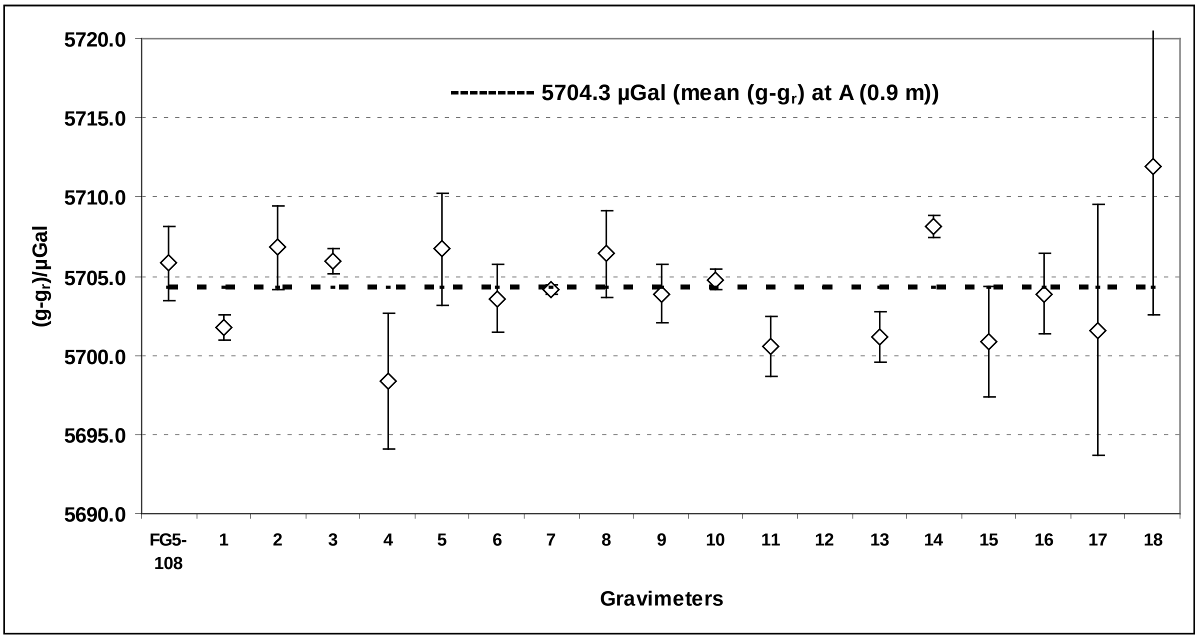

Fig.1. Results of the measurements of the absolute gravimeters during ICAG-2005 transferred to the site A (height of 0.9 m).

longer confidential and may be the subject of a publication. It must include uncertainty estimates for all results. For Key Comparisons, draft B is published as a final report on the KCDB, upon approval of the Consultative Committee.

At the time of preparation of this paper not all the uncertainty budgets were presented and it was decided to present the results of the comparison without the names of the absolute gravimeters.

The results of the absolute measurements of individual gravimeters in ICAG-2005 are presented in Fig. 1 with their standard deviations. The unweighted means of the results of each gravimeter at each site are transferred to site A at a height of 0.9 m above the pillar. The ties between the sites are calculated as the *g*-differences of the means of all the results of gravimeters measured at that site. Such *g*-differences (ties) were used to transfer the *g*-value from each site to site A.

The unweighted mean of all the results transferred to A (at 0.9 m) is $(g - g_r)_A$ = 5704.3 µGal with the standard deviation of 3.2 µGal. The reference value is g_r = 980920000 µGal.

In Fig. 2 the unweighted mean values $(g - g_r)$, obtained at the site A (height of 0.9 m) in three consecutive comparisons at the BIPM in 1997 ([6], Table 7), 2001 ([7], Table 5a) and 2005, are compared.

These values are (5707.8 ± 2.8) µGal, (5698.5 ± 2.2)µGal and (5704.3±3.2)µGal in 1997, 2001 and 2005, respectively.

The results of the absolute gravimeter FG5-108 belonging to the BIPM (transferred to A at the height of 0.90 m), obtained in the comparisons in 1997, 2001 and 2005 are also shown in Fig. 2. All these results are within 1 µGal.

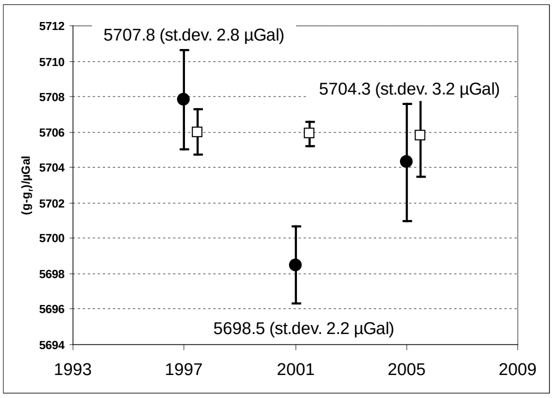

Fig. 2. The unweighted means (•) of the results of all the absolute gravimeters transferred to A (at 0.9 m) obtained in the ICAGs in 1997, 2001 and 2005, and that of FG5-108 (□).

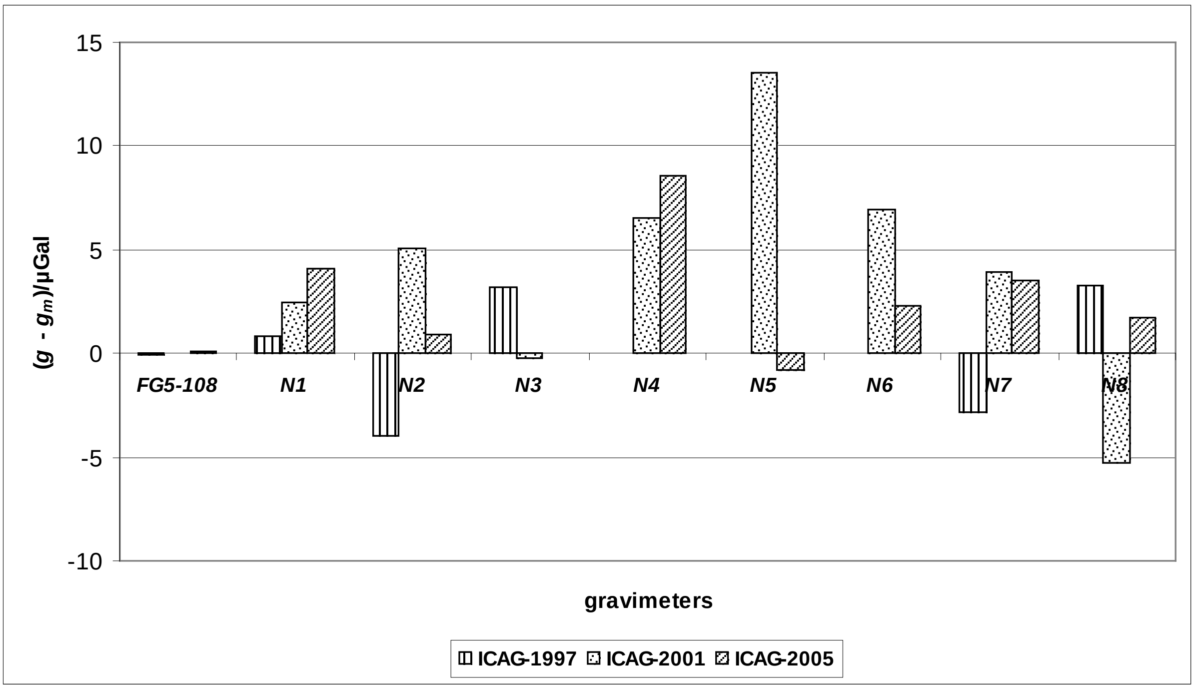

Fig. 3. The results of the measurements of the individual absolute gravimeters, obtained in the ICAGs at the BIPM in 1997, 2001 and 2005 and transferred to site A at the height of 0.9 m. g_m = 980925705.9 µGal is the mean of g-values of the FG5-108, obtained in 1997, 2001 and 2005.

The availability of the results from two or even three consecutive comparisons for some absolute gravimeters allows the analysis of the reproducibility of the results of their measurements on condition that the gravity field at the BIPM is stable. One can come to some conclusions on such reproducibility from the Fig. 3. This figure plots the deviations of the results of individual absolute gravimeters, obtained in the comparisons from 1997 to 2005, with respect to the mean value 980925705.9 µGal of the results of FG5-108 at A (0.90 m) over these three comparisons..

As seen in Fig. 3, the deviations of the results of the measurements of individual gravimeters from the reference value vary in sign and magnitude. The changes in the results of the measurements by the same gravimeters in three ICAGs can reach about 10 µGal. However, the changes in measured values do not imply changes of gravity field of the BIPM for, in this case, all the changes would be of the same sign and of almost the same magnitude. This demonstrates the level of the reproducibility of the measurements of absolute gravimeters.

One of the reasons for such low reproducibility could be the change of the shape of the laser beam in the interferometer [8-10]. It was possible to measure the beam shape of majority of absolute gravimeters that participated in ICAG-2005. Results showed that the diameters of the output beams from the beam splitter of the interferometer, measured by CMOS camera were between 3.2 mm and 6.2 mm (at an intensity level $1/e^2$ relative to the maximum) for the different gravimeters at the same position of the cross section where the beam was measured. If the laser beam diameter if smaller than a certain cut-off value, which depends on the wavelength, the diffraction correction should be calculated. This correction depends on the optical layout of the interferometer (for example, on the difference of the lengths of the measuring and reference arms of the interferometer). In ICAG-2005 the diffraction correction was applied only for the gravimeter GABL-G, which uses a 532 nm laser.

When all the uncertainty budgets for all the absolute gravimeters are completed, a global adjustment of absolute and relative data obtained at all the sites of the BIPM gravity network will be performed to obtain the final weighted results at the sites A and B.

4 Conclusions

The number of the absolute gravimeters participating in the ICAGs at the BIPM continues to increase.

The development of the Technical Protocol brings the ICAG closer to a CIPM key comparison. One aim of CIPM key comparisons is to determine the degree of equivalence among national standards. ICAG-2005 paves the way for including national standards of gravimetry in this programme.

The work on the evaluation of uncertainty budgets for measurement using the absolute gravimeters should be continued.

The analysis of the results of three consecutive ICAGs at the BIPM in 1997, 2001 and 2005 shows that the level of irreproducibility of the results of absolute gravimeters cannot be attributed to long-term instability in the gravity field at the BIPM.

Further investigations of the sources of the uncertainties in absolute measurements should be continued and the methods of adjusting the gravimeters should be improved to make them less operator dependent and better controlled, as, for example, control of the laser beam-shape and evaluation of the diffraction correction, if necessary.

The organization of regional multilateral comparisons of the absolute gravimeters with the appropriate technical protocol is of importance for the further study of their metrological characteristics and of the establishment of the link between the ICAG at the BIPM and regional comparisons and for better understanding of the role of the Key Comparison Reference Values in absolute measurement of free-fall acceleration.

As was concluded after all the previous comparisons, we continue to emphasize the importance of participation in future comparisons of various types of absolute gravimeters based on different basic principles and different designs.

It is important to develop a unified format for the presentation of the final results of the measurements of absolute gravimeters, which will contain the information necessary for the comparison of their results and for the application of the data of the measurements of gravity field.

Regular monitoring of the gravity field at the BIPM between the comparisons as well as continuous monitoring during the comparison should be continued to control the possible changes of gravity field at the BIPM.

The experience in the organization of the pilot study ICAG-2005 according to the rules of CIPM key comparisons is invaluable for the improvement of the technical protocol for the next ICAG at the BIPM in 2009 and for the organization of regional comparisons of absolute gravimeters.

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