Chapter 7

Results of the Seventh International Comparison of Absolute Gravimeters ICAG-2005 at the Bureau International des Poids et Mesures, Sèvres

L. Vitushkin, Z. Jiang, L. Robertsson, M. Becker, O. Francis, A. Germak, G. D'Agostino, V. Palinkas, M. Amalvict, R. Bayer, M. Bilker-Koivula, S. Desogus, J. Faller, R. Falk, J. Hinderer, C. Gagnon, T. Jakob, E. Kalish, J. Kostelecky, Chiungwu Lee, J. Liard, Y. Lokshyn, B. Luck, J. Mäkinen, S. Mizushima, N. Le Moigne, V. Nalivaev, C. Origlia, E.R. Pujol, P. Richard, D. Ruess, D. Schmerge, Y. Stus, S. Svitlov, S. Thies, C. Ullrich, M. Van Camp, A. Vitushkin, and H. Wilmes

Abstract The International Comparison of Absolute Gravimeters ICAG-2005 was held at the Bureau International des Poids et Mesures (BIPM), Sèvres, France in September 2005. The organization of ICAG-2005, measurement strategy, calculation and presentation of the results were described in a technical protocol pre-developed to the comparison. Nineteen absolute gravimeters carried out 96 series of measurements of free-fall acceleration g at the sites of the BIPM gravity network. The vertical gravity gradients were measured by relative gravimeters. For the first time the budgets of uncertainties were presented.

The g-values for the sites A and B of the BIPM gravity network at a height of 0.90 m are (980,925,702.2 $\pm$ 0.7) μGal and (980,928,018.5 $\pm$ 0.7) μGal, respectively. This result is in a good agreement with that obtained in ICAG-2001.

7.1 Introduction

The 7th from 1980 comparison ICAG-2005 at the BIPM was organized by the Working Group on Gravimetry of the Consultative Committee on Mass and Related Quantities, Study Group 2.1.1 on Comparison of Absolute Gravimetry of the International Association of Geodesy (IAG) and the BIPM.

Comparing the measurement results of absolute gravimeters of the highest metrological quality in the ICAGs at the BIPM as well as in the Regional Comparisons of Absolute Gravimeters (RCAG) (see, for example, Vitushkin et al., 2002; Boulanger et al., 1981; Francis et al., 2007) is currently the only way to test the uncertainty in absolute g-measurements and to determine the offsets of individual gravimeters with respect to Comparison Reference Values (CRV) (Vitushkin, 2008; Vitushkin et al. 2007). The CRVs in the ICAGs and RCAGs are the g-values obtained at one or more gravity stations at BIPM or at the sites of RCAGs.

The ICAGs and RCAGs may be organized as a key comparison (KC) or as a pilot study (Vitushkin et al., 2007; CIPM, 1999). The KCs are organized to establish the equivalence of national measurement standards. The pilot study is more flexible in the invitation of the participants which could be not only the National Metrology Institutes or designated laboratories responsible for the metrology in gravimetry but also other organizations, for example, geodetic, geophysical and geological institutes or services.

The ICAG-2005 was organized as a pilot study but according to the rules for KCs concerning the technical protocol which specified the organization, measurement strategy, data processing, calculation of the uncertainties and presentation of the results and reports.

L. Vitushkin (✉)
Bureau International des Poids et Mesures (BIPM), Sèvres, France
e-mail: lvitushkin@bipm.org

S.P. Mertikas (ed.), *Gravity, Geoid and Earth Observation*, International Association of Geodesy Symposia 135,
DOI 10.1007/978-3-642-10634-7_7, © Springer-Verlag Berlin Heidelberg 2010

7.2 Absolute Measurements

The gravity network of the BIPM consists of four sites with 13 gravity stations. The site in the Observatory building consists of two pillars located in one laboratory room with three gravity stations A, A0 and A1 at one pillar and the gravity station A2 at the other. There is also the site in Pavillon du Mail where seven gravity stations B and B1–B6 are located on the 80-tons basement installed on the special elastic pads. Two outdoor gravity stations C1 and C2 are in the garden of the BIPM. The *g*-difference between the sites C1 and C2, located on the hill, is about 9 mGal.

Ninety Six absolute measurements were carried out by 19 absolute gravimeters at 11 gravity stations of the BIPM gravity network mainly in the period from 3 to 24 September. The gravimeter FG5-108 belonging to the BIPM started the measurements on 5 August and subsequently measured on A2, A, A2, A, C2, B, C1, B, B3. The measurements were performed in the night during about 12 h and such measurement was considered as an individual result. Up to nine AGs occupied simultaneously the sites of the BIPM during the comparison.

From 3 to 24 September the FG5-108 occupied the B3 for the regular "in-the-night" measurements to monitor the stability of the gravity field. With the same goal, the FG5-202 was used at the gravity station A2 from 6 to 21 September.

In Table 7.1 all the AGs participated in the ICAG-2005 are presented. In addition this table lists those gravimeters which participated in ICAG-1997 and ICAG-2001. The gravimeter IMGC-2 (Germak et al., 2002) and TBG are that with rise-and-fall trajectory of free-moving test body. All other are of a free-fall type.

The BIPM verified the frequencies of all the lasers used in the laser displacement interferometers of AGs and the frequencies of Rb clocks or GPS receivers used as the reference for the time interval measurement systems of AGs. The atmospheric pressure was also measured continuously during the comparison. Prior to the absolute measurements, the vertical gravity gradients were measured using fifteen relative gravimeters.

Table 7.1 Participation of institutes and gravimeters in ICAG-2005

		Gravimeter		
	Country, institute	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

7.3 Results of ICAG-2005

The result of the ICAG is the CRV with its uncertainty. For the evaluation of the results of the ICAG the operators provided the results of *g*-measurements performed at all the sites occupied by their gravimeters and the uncertainties of these measurements.

The important work on the evaluation of uncertainties was done by the operators, pilot laboratory and Task Group on Technical Protocol and Budget of Uncertainties of the CCM WGG and IAG SG 2.1.1. Currently the participants in ICAG-2005 are agreed on the unified assignment of the instrumental uncertainty of 2.3 μGal for the FG5-type gravimeters, FGC-1 and JILA-2 and on the unified site-dependent uncertainty of 1.1 μGal for the FG5-108, -202, -209, -211, -213, -216, -221, -224, FGC-1, A10-008 and GABL-G.

Table 7.2 shows the estimated uncertainties of the AGs participated in ICAG-2005. The instrumental uncertainty of A10-008 was presented by the operator without the detailed budget of uncertainties.

The expanded uncertainty of each gravimeter in the absolute measurement of FFA was evaluated according to the ISO (International Standartization Organization) guide (ISO, 1993), sometimes referred to as the GUM. The evaluation of instrumental and site-dependent uncertainties was based on the current knowledge of the variability of input quantities, the results of verification of the laser and Rb clock frequencies, theoretical

Table 7.2 Estimations of the uncertainties of absolute gravimeters participated in ICAG-2005

Gravimeters	Instrumental uncertainty/μGal	Site-dependent uncertainty/μGal	Experimental standard deviation/μGal	Expanded uncertainty/μGal
FG5	2.3	1.1–1.3	0.2–0.7	4.8–5.6
FGC-1	2.3	1.1	1.2–2.2	5.6–6.6
A10-008	5.9	1.1	2.1–3.8	12.4–14.2
JILA	1.8–2.6	1.0–2.1	0.2–0.9	5.0–7.0
IMGC-2	3.8	1.5	1.1–1.3	8.6
GABL-G	5.1	1.1	1.1–1.5	11.6–11.8
TBG	10.0	8.7	7.0–15.0	29–40.0

models for the evaluation of geophysical effects (tides, ocean loading, etc.), manufacturer's specifications, etc.

An expanded uncertainty U is defined by the formula:

$$U = k_{\mathrm{p}}\, u_{\mathrm{c}}, \tag{1}$$

where u_{c} is the combined uncertainty and k_{p} is the coverage factor. An expanded uncertainty defines an interval of the values of the measurand FFA that has a specified coverage probability or level of confidence p. The usual value of 95% was chosen for such a probability in the case of ICAG-2005. The coverage factor k_{p} is used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty. The values of k_{p} were obtained under the assumption that the resultant probability distribution is a Student's one and with the evaluation of effective degrees of freedom from the Welch-Satterthwaite formula (ISO, 1993).

Combined uncertainty u_{c} is the square root of the sum of the squared instrumental uncertainty, site-depended uncertainty and experimental standard deviation. The expanded uncertainties are then used for the evaluation of the weight of each measurement result in the CRV calculation.

The comparison of absolute gravimeters is not somewhat similar to the comparison, for example, of the measurement of line scales in dimensional metrology when the measurement results of such a traveling standard by means of each of the laser interference comparator are compared. In the ICAGs the g-measurements at several gravity stations by means of several AGs are carried out and not all the stations are measured by all the AGs.

For this reason the adjustment of the results of gravity measurement in the gravity network was used to evaluate the CRV and its uncertainty (Vitushkin et al., 2002).

The CRVs of ICAG-2005 at the gravity stations A and B were calculated using the combined adjustment of all the absolute and relative data obtained in the comparison. The final results of ICAG-2005 are presented in Tables 7.3 and 7.4, and in Fig. 7.1. All the g-values are expressed in microgals after the subtraction of the integer value g_{r} = 980,920,000 μGal. The standard uncertainties u_{av} of the adjusted CRVs are also expressed in microgals.

Table 7.3 presents the g-values at a height of 0.9 m above the mark of corresponding gravity station and Table 7.4 presents the offsets of all the AGs with respect to CRV at the station A for various selections of the results of the absolute and relative measurements to be adjusted. The results of the adjustments of the results of only absolute and only relative measurement as well as the results of the combined adjustment of all the absolute and relative data are presented in these tables. The adjustment results with only the absolute measurements are presented for both unweighted and weighted data.

The ICAG-2005 CRVs with the standard uncertainties of adjusted values at the gravity stations A and B are (980,925,702.2 ± 0.7) μGal and (980,980,018.5 ± 0.7) μGal, respectively. This result is in a good agreement (within 1 μGal) with the g-values obtained at A and B in the ICAG-2001 (Vitushkin et al., 2002). The results of ICAG-2001 at A and B are (980,925,701.2 ± 0.9) μGal and (980,928,018.8 ± 0.9) μGal, respectively (see Table 7.4 in (Vitushkin et al., 2002)). It should be remarked that the results of ICAG-2001 are obtained with the some omitted gravimeters.

The differences between the g-values at A and B obtained using the adjustments of various combinations of the measurement results (absolute, relative, absolute and relative, etc.) are not greater than 1.4 μGal and 0.8 μGal, respectively.

Table 7.3 Results of the adjustment of the results of the absolute and relative measurements carried out during ICAG-2005 for each gravity station (at 0.90 m above the mark) expressed in microgals after subtraction of the integer value $g_r = 980{,}920{,}000$ μGal. The standard uncertainty of adjusted values u_{av} is expressed in microgals

Gravity station	Results of adjustment of only unweighted absolute data		Results of adjustment of only weighted absolute data		Results of adjustment of only relative data		Results of combined adjustment of all the absolute and relative data	
	$g-g_r$	u_{av}	$g-g_r$	u_{av}	$g-g_r$	u_{av}	$g-g_r$	u_{av}
1	2	3	4	5	6	7	8	9
A	5,703.3	0.5	5,702.7	0.5	5,701.9	1.1	5,702.2	0.7
A1	5,690.0	0.9	5,689.7	0.8	5,690.7	1.1	5,690.9	0.8
A2	5,710.0	0.8	5,709.4	0.6	5,707.1	1.1	5,707.4	0.8
B	8,018.0	0.5	8,018.8	0.5	8,018.8	1.0	8,018.5	0.7
B1	8,012.3	0.8	8,012.3	0.6	8,013.3	1.0	8,012.9	0.7
B2	7,996.4	0.7	7,997.9	0.7	7,997.6	1.0	7,997.2	0.7
B3	8,002.3	0.9	8,002.4	0.6	8,001.7	1.0	8,001.4	0.7
B5	8,022.0	0.9	8,022.3	0.8	8,020.5	1.0	8,020.1	0.7
B6	8,000.0	0.8	7,998.4	0.9	7,997.8	1.0	7,997.4	0.7
C1	3,279.9	1.2	3,281.6	1.0	3,281.6	1.1	3,282.3	1.1
C2	12,040.4	1.5	12,040.4	1.0	12,040.3	1.1	12,039.1	1.3

Table 7.4 The offsets of each absolute gravimeter with respect to CRV at the gravity station A for various adjustments of the data of the absolute and relative measurements carried out during ICAG-2005 (expressed in microgals after subtraction of $g_r = 980{,}920{,}000$ μGal). The standard uncertainty of adjusted values u_{av} is in microgals (i = FG5-101, FG5-108, FG5-202...)

Gravimeter	Results of adjustment of only unweighted absolute data		Results of adjustment of only weighted absolute data		Results of adjustment of only relative data		Results of combined adjustment of all the absolute and relative data	
	$g_A-g_r=5{,}703.3$		$g_A-g_r=5{,}702.7$		$g_A-g_r=5{,}701.9$		$g_A-g_r=5{,}702.2$	
	g_i-g_r	u_{av}	g_i-g_r	u_{av}	g_i-g_r	u_{av}	g_i-g_r	u_{av}
1	2	3	4	5	6	7	8	9
FG5-101	2.4	0.9	2.4	1.2	2.7	1.8	2.5	1.5
FG5-108	−3.5	1.5	−3.5	1.2	−4.1	1.1	−4.3	1.1
FG5-202	−2.4	1.5	−2.7	1.2	−4.4	0.9	−4.2	1.1
FG5-206	−1.6	0.4	−0.8	0.9	−0.5	0.4	−0.7	0.1
FG5-209	7.5	1.0	7.7	0.4	6.8	0.5	6.7	0.8
FG5-211	−2.9	0.9	−2.7	0.9	−3.3	0.3	−3.4	0.3
FG5-213	1.4	0.4	1.2	1.0	0.7	1.1	0.5	1.1
FG5-215	−0.1	0.8	0.2	0.8	0.2	0.6	0.0	0.6
FG5-216	−2.2	1.9	−2.4	2.1	−1.9	2.6	−1.9	2.7
FG5-221	0.5	1.4	1.0	1.7	0.7	2.0	0.5	1.8
FG5-224	−0.8	0.3	0.0	1.3	−0.9	2.2	−1.1	1.9
FG5-228	3.3	0.2	3.0	0.1	3.1	1.0	3.0	0.7
JILA-2	1.3	1.6	2.1	1.2	2.3	1.5	1.9	1.5
JILAg-6	4.2	5.9	4.0	5.3	3.6	5.4	3.2	5.5
A10-008	−5.7	1.7	−6.1	2.7	−7.1	3.0	−7.2	3.3
IMGC-2	−0.1	0.1	0.1	0.8	−0.3	1.2	−0.3	0.9
FGC-1	7.0	3.3	6.4	2.3	5.0	2.8	4.6	2.8
GABL-G	−4.7	1.0	−4.8	1.6	−5.3	2.0	−5.2	1.7
TBG	−4.1	8.7	−3.9	>10.0	−4.4	>10.0	−4.6	>10.0

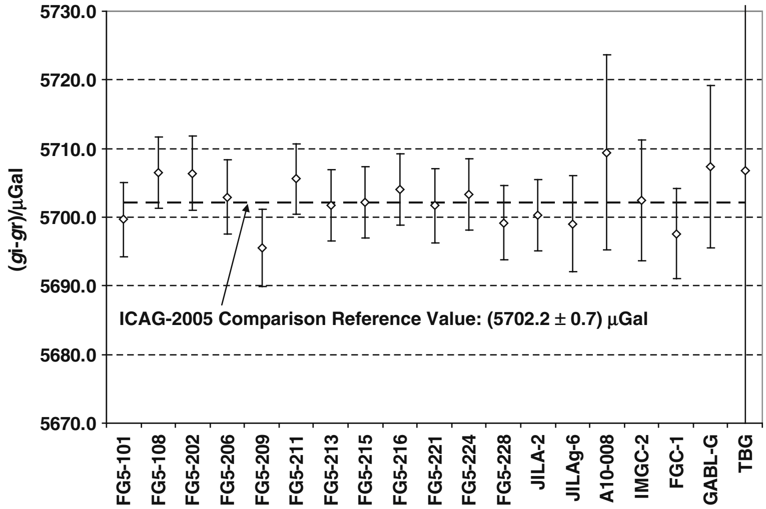

Fig. 7.1 Measurement results of the absolute gravimeters during ICAG-2005 with their expanded uncertainties. All the results transferred to site A (height of 0.90 m above the mark on the pillar). The results are expressed in microgals after subtraction of integer value g_r = 980,920,000 μGal

The offsets of the results of each gravimeter at all the gravity stations of the BIPM gravity network with respect to corresponding CRV are the same as that at A (at 0.90 m) in Table 7.4.

The results of the absolute measurements of each gravimeter in ICAG-2005 are presented in Fig. 7.1 with their expanded uncertainties U_i. For each gravimeter the maximum of all the expanded uncertainties obtained in measurements, is presented in Fig. 7.1. The variations of the expanded uncertainties of each gravimeter are related to the various experimental standard deviations obtained in each measurement at each site, i.e. these variations are statistical. It is seen from Fig. 7.1 that almost all the offsets of absolute gravimeters are within of their expanded uncertainties.

In Fig. 7.2 the CRVs at the station A obtained in the ICAG-2001 and ICAG-2005 and the result of ICAG-1997 are presented. The CRVs of ICAG-2001 and ICAG-2005 obtained using the combined adjustment of the absolute and relative data. The result of ICAG-1997 is the unweighted mean of all the absolute results transferred to A (Robertsson et al., 2001). The measurement results of FG5-108 obtained in three comparisons (Vitushkin et al., 2002, Robertsson et al., 2001) are also presented in Fig. 7.2 in confirmation of the gravity field stability at BIPM.

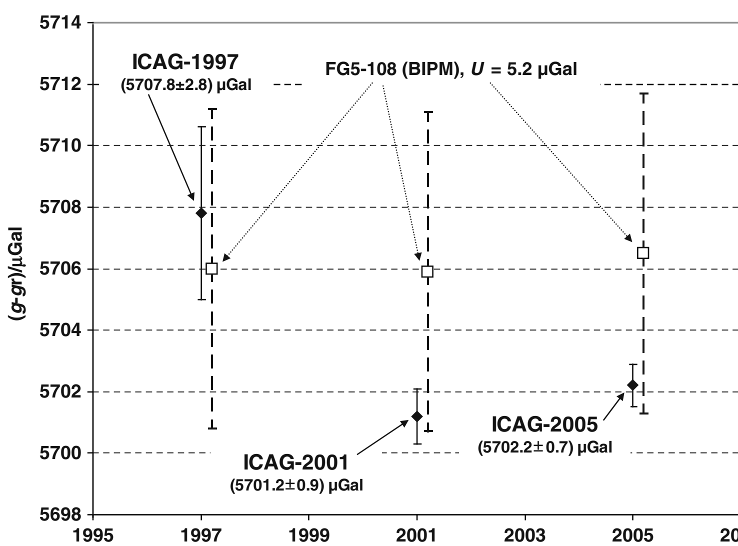

Fig. 7.2 The results of ICAG-1997, ICAG-2001, ICAG-2005 and the results of the gravimeter FG5-108 (BIPM) obtained in these comparisons

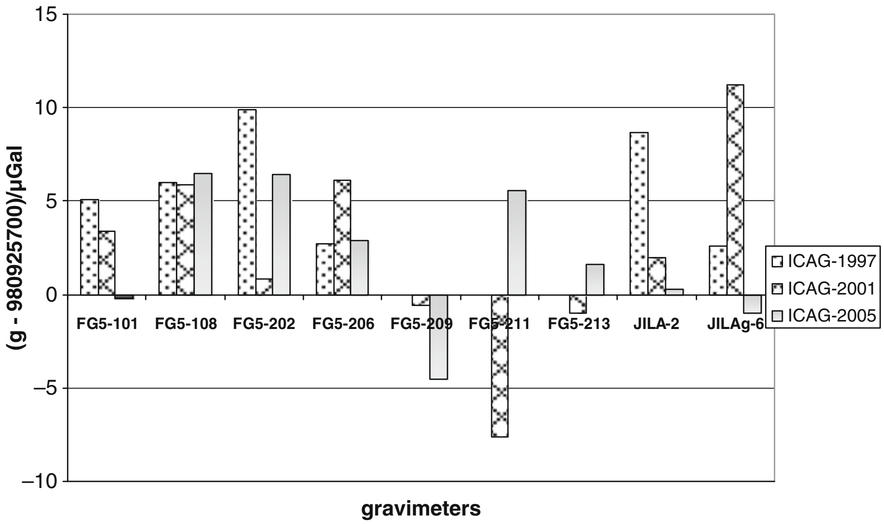

Fig. 7.3 Measurement results of the absolute gravimeters participated in the ICAG-1997, and in the ICAG-2001 and ICAG-2005 (CRVs at station A at 0.90 m)

The reproducibility (defined as a closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement, as, for example, the location of measurement (VIM, 1993)) of the measurement results of AGs, participated in the ICAGs from 1997 to 2005, is illustrated by Fig. 7.3.

It is seen that for some gravimeters the discrepancy between their results in different comparisons is bigger than their expanded uncertainty.

The actual discrepancies between the results of the comparisons, illustrated by Fig. 7.2, and the discrepancies of individual AGs (Fig. 7.3) require further studies of the reproducibility of AGs which can be expressed quantitatively in terms of the dispersion characteristics of the results of measurement and included in the combined uncertainty of the AG. In the budgets of uncertainties applied in ICAG-2005 such uncertainty component was not included because of the lack of information on the reproducibility of the measurement results for each gravimeter. Such information may be obtained from the results of the next ICAGs at the BIPM and in the RICAGs with the participation of the same gravimeters.

Table 7.5 presents the polynomial coefficients of the second-order polynomials which describe the gravity field distribution $g(h)$ above the gravity stations measured during the ICAG-2005 by relative gravimeters.

Table 7.5 Polynomial coefficients for gravity field distributions above the gravity stations of the BIPM

Station	*a*	*b*	*c*
A	25,980.8	−315.37	6.417
A1	25,971.1	−321.73	11.583
A2	25,987.9	−319.80	9.000
B	28,287.2	−300.10	1.750
B1	28,276.0	−296.93	5.083
B2	28,254.4	−289.60	4.250
B3	28,274.3	−310.77	8.417
B5	28,287.0	−297.33	0.833
B6	28,263.0	−300.33	5.833
C1	23,282.3	−314.00	0.0
C2	32,039.1	−285.50	0.0

Such distributions are described by the formula:

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

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

7.4 Conclusions

The CRVs (g-values obtained as a result of a combined adjustment of the weighted results of the absolute and relative measurements during ICAG-2005) at the gravity stations A and B are (Table 7.3) at a height of 0.90 m above the mark are:

$$\text{at A:} 980\,925\,702.2\ \mu\text{Gal};$$

$$\text{at B:} 980\,928\,018.5\ \mu\text{Gal}.$$

The standard uncertainty of adjusted values is 0.7 μGal. These results are in a good agreement with the results of the ICAG-2001.

The budgets of uncertainties were prepared by the operators except that of A10-008, for which only the instrumental uncertainty was declared.

For the first time unified instrumental uncertainties were agreed for gravimeters of similar type and the expanded uncertainties were evaluated for all the gravimeters. A big delay in achieving the evaluation of the results of ICAG-2005 was due to difficulties in the estimation of the uncertainties and in the harmonization of approaches.

Finally, almost all the offsets of the results of individual absolute gravimeters with respect to the CRV were within the expanded uncertainty of the corresponding gravimeters. For the first time it was demonstrated that the rise-and-fall gravimeter and free-fall gravimeters give the same result.

Nevertheless, some questions remain to be answered. One of them concerns the reproducibility of the absolute gravimeters. This question arises from the fact that for some gravimeters the differences between their results in subsequent ICAGs are bigger than their expanded uncertainties. Further investigations of the reproducibility of the AGs are required as well as their regular participation in the comparisons at the BIPM or in the regional comparisons of AGs.

The stability of the gravity field at the BIPM during the comparisons was confirmed in the continuous absolute gravity measurements with FG5-108 (in 2001 and 2005) and FG5-202 (in 2005). Their results were stable within 1 μGal.

The work on the technical protocol should be continued taking into account a possible and quite advisable participation in the future ICAGs of absolute gravimeters based on the use of different basic principles of operation (free motion of the massive test bodies or atom interferometry of free moving atoms) and different technical realizations. The important part of the work on the evaluation of the budgets of uncertainties made in the frame of the ICAG-2005 makes it possible to decrease significantly the period of preparation of the report on the future comparisons.

Nevertheless, the study of the sources of the uncertainties and of the evaluation procedure of the comparison results should be continued.

The study on linking of the ICAG results to the results of the RCAGs and the use of the CRVs in practical gravity measurements should be initiated.

Acknowledgements The authors wish to thank Dr R. Davis for many useful discussions and all staff members of BIPM for their invaluable support.

References

Boulanger, Yu., et al. (1981). Results of comparison of absolute gravimeters, Sèvres, 1981. *Bull. Inf. BGI*, 52, 99–124.

Francis, O., et al. (2007). Results of European comparison of absolute gravimeters in Walferdange (Luxembourg) in November 2007, ibidem.

Germak, A., S.Desogus, and C. Origlia (2002). Interferometer for the IMGC rise-and-fall absolute gravimeter. *Metrologia*, 39, 471–475.

Guide to expression of uncertainty in measurement, ISO, 1993.

International Vocabulary of Basic and General Terms in Metrology (VIM), ISO, 1993.

Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes, CIPM, 1999, available from http://www.bipm.org

AugustRobertsson, L., et al. (2001). Results from the fifth international comparison of absolute gravimeters, ICAG-97. *Metrologia*, 38, 71–78.

Vitushkin, L. (2008). Measurement standards in gravimetry, Proceedings of the International Symposium "Terrestrial Gravimetry. Static and Mobile Measurements. TGSMM-2007", 20–23 August 2007, St Petersburg, Russia, SRC of Russia Electropribor, pp. 98–105.

Vitushkin, L., et al. (2002). Results of the sixth international comparison of absolute gravimeters, ICAG-2001. *Metrologia*, 39, 407–424.

Vitushkin, L., et al. (2007). The seventh international comparison of absolute gravimeters ICAG-2005 at the BIPM. Organization and preliminary results, Proceedings of the 1st International Symposium of the International Gravity Field Service "Gravity Field of the Earth", 28 August-1 September, 2006, Istanbul, Turkey, Ed. General Command of Mapping, June 2007. Special Issue:18, pp. 382–387.