Sixth International Comparison of Absolute Gravimeters, ICAG-2001.

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Abstract. Like all the previous International Comparisons of Absolute Gravimeters (ICAGs) the sixth, ICAG-2001, was held at the Bureau International des Poids et Mesures (BIPM). Major improvements in the 2001 campaign were a new measurement strategy using the absolute gravimeters to measure the ties of the gravity network, new sites constructed at the BIPM, improved relative measurements of the ties and gravity gradients, and combined adjustment of the absolute and relative data, realized using new software with a novel data weighting and rejection scheme. The *g*-values at four sites of the BIPM were measured with an uncertainty of 6 µGal[1]. Good agreement was obtained between the results of the absolute and relative measurements of the ties of the gravity network. The final mean *g*-value obtained at the reference site A was 7 µGal less than that obtained in the previous comparison, ICAG-97.

Keywords. Gravimetry, absolute gravimetry, relative gravimetry, gravimeter, ICAG, BIPM

1 Introduction

Comparing results of measurements made using absolute gravimeters is the only way to determine the level of accuracy in such absolute measurements of free-fall acceleration *g*. For this purpose six International Comparisons of Absolute Gravimeters (ICAGs) have been carried out at the BIPM between 1981 and 2001. The sixth, ICAG-2001, was organized jointly by the BIPM and Working Group 6 of the International Gravity and Geoid Commission. Like all the previous ICAGs, ICAG-2001 was held at the BIPM.

This paper presents the goals, organization and results of the ICAG-2001. Details of the relative measurements supporting the ICAG-2001 are described in (Becker, et al.,2003) and the pre-processing of the results of the absolute measurements is described in (Francis and van Dam, 2003).

Relative measurements were used to obtain the vertical gravity gradients at the sites of the BIPM gravity micronetwork and the ties between the sites. Seventeen absolute gravimeters (AGs) participated in the ICAG-2001. The AGs measured not only the *g*-values at various sites but also the ties between the sites, i.e. each absolute gravimeter measured at at least two sites of the gravity network over at least 24 hours (when possible). This made it possible (a) to compare the ties measured by only the absolute and only the relative gravimeters, and (b) to make a combined adjustment of the absolute and relative data.

The final results of the ICAG-2001 are the *g*-values at four sites of the BIPM network given with an uncertainty of 5.5 µGal. The second-order polynomials describing the *g*-distributions with height over each site were also evaluated using the results of the relative measurements. Knowledge of the *g*-values at the BIPM sites is of importance because it makes possible a study of the long-term stability of the local gravity field.

Besides determining the current level of uncertainty in absolute *g*-measurements and in the *g*-values at the sites of the BIPM, the ICAG-2001 made an important step in the development of traceable metrology in gravimetry.

2. Organization of the comparison

The first call to participants of the ICAG-2001 was distributed in September 2000. The steering committee (L. Vitushkin, M. Becker, Z. Jiang, O. Francis and T. van Dam) had its first meeting at the ECGS in Luxembourg on 29-30 January 2001. The steering committee proposed the programme for the absolute and relative measurements, and methods of data processing.

[1] 1 Gal = 1 cm s^{-2}

To allow all the measurements using sixteen AGs to be performed, four sites (A, A2, B and B1) of the BIPM gravity micronetwork were used (Vitushkin et al, 2002). Two of these sites, B and B1, are on the foundation (mass of about 70 tonnes) specially constructed by the BIPM in a new building, Pavillon du Mail. The BIPM is situated in the Parc de Saint-Cloud in Sèvres. The *g*-value at site A, in the Observatory building of the BIPM, has been measured in the period from November 1997 to November 2000 with the BIPM's absolute gravimeter FG5-108. These measurements covered more than 140 days and usually (with a few exceptions, when the gravimeter was subject to maintenance or repair) were performed during two days per week (24 sets per day, 100 or 150 drops per hour). The peak-to-peak variances of the measured *g*-values at site A were within 5 µGal, with a standard deviation of 1.5 µGal calculated over all diurnal results. The noisiest periods, with relatively high microseismic level, were observed annually between November and January. In general, the gravity network of the BIPM is typical in terms of stability of the gravity field and the level of microseismics. An admissible level of microseismic disturbances allows the efficiency of the vibroisolation systems of the reference reflector in the interferometer of the AGs to be checked.

The maximum difference between *g*-values at different sites of the BIPM gravity network used in the ICAG-2001 was 2.3 mGal (tie B - A) at the height 0.9 m. The difference of the altitudes of the sites A and B is 9.61 m.

Site B3, one of five sites (B, B1, B2, B3 and B4) on the new foundation, was devoted to almost continuous measurements over 30 days using the BIPM's absolute gravimeter FG5-108, to monitor the stability of the gravity field during the comparison of absolute gravimeters. These measurements also confirmed the stability of the gravity field at the BIPM. The peak-to-peak variations of the diurnal values were within 2 µGal, with a standard deviation of 1 µGal.

Seven sites (A, A2, B, B1, B3, L3 and L4) were used for the relative measurements. The BIPM also made absolute measurements at the sites A, A2, B and B1 before and after the main comparison campaign.

Seventeen AGs from twelve countries and the BIPM, and seventeen relative gravimeters (RGs) from seven countries participated in the comparison. The absolute measurements began on 2 July and finished on 1 August 2001. A team from Italy with their absolute gravimeter IMGC performed measurements from 27 September to 2 October 2001.

The participants in the ICAG-2001 are listed in Table 1.

Table 1. Participants in the ICAG-2001 and their gravimeters.

Country	*Institution*	*Absolute gravimeter(s)*	*Relative gravimeter(s)*
Austria	*Bundesamt für Eich- und Vermessungswesen (BEV), Vienna*	*JILAg-6*	*LCR-D51*
Austria	*Institute für Meteorologie and Geophysik (IMG), Universität Wien, Vienna*	–	*LCR-G625*
Belgium	*Observatoire Royal de Belgique (ORB), Brussels*	*FG5-202*	*LCR-G906, Scintrex-265*
Canada	*Natural Resources Canada (NRCan), Ottawa*	*JILA-2, A10-003*	–
Finland	*Finnish Geodetic Institute, (FGI), Masala*	*JILAg-5*	
France	*Bureau de Recherches Géologiques et Minières (BRGM), Orléans*	–	*Scintrex-245*
France	*Institut de Recherche pour le Dévelopement (IRD), Bondy, Institut de Physique du Globe de Paris (IPGP), Paris, Ecole Nationale des Sciences Géographiques (ENSG), Marne-la-Vallée*	–	*Scintrex-136, Scintrex-193, Scintrex-323*
France	*Institut Géographique National (IGN), Saint-Mandé*	–	*Scintrex-408, Scintrex-379*
France	*Ecole et Observatoire des Sciences de la Terre (EOST), Strasbourg*	*FG5-206*	–
Germany	*Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt*	*FG5-101, FG5-301, A10-b002*	–

Germany	*Institut für Erdmessung (IfE), Universität Hannover, Hannover*	–	*LCR-G079, LCR-G368, LCR-G709*
Italy	*Istituto di Metrologia "G. Colonnetti" (IMGC), Turin*	*IMGC*	–
Japan	*National Metrology Institute of Japan, National Institute of Advanced Industrial Science and Technology (NMIJ/AIST), Tsukuba*	*FG5-213*	–
Czech Republic	*Geophysical Institute AS CR (GI ASCR), Prague*	–	*LCR-D188*
Russia	*Sternberg Astronomical Institute of Moscow State University (SAI MSU), Moscow*	–	*Sodin-212*
Spain	*Instituto Geográfico Nacional (IGN), Madrid*	*FG5-211*	–
Switzerland	*Swiss Federal Office of Metrology and Accreditation (METAS), Bern-Wabern*	*FG5-209*	*Scintrex-494*
UK	*National Physical Laboratory (NPL), Teddington*	*FG5-105*	–
UK	*Proudman Oceanographic Laboratory (POL), Bidston*	*FG5-103*	–
USA	*National Institute of Standards and Technology (NIST), Gaithersburg*	*FG5-204*	–
	Bureau International des Poids et Mesures (BIPM), Sèvres	*FG5-108*	*LCR-G336, Belonging to ORB*

Some of the gravimeters had participated in previous ICAGs. Only the gravimeter IMGC uses a rise-fall path of the test body. All the others are free-fall gravimeters of JILA-type, FG5 type and A10 type. The FG5 group can be subdivided into three subgroups which differ in dropping mechanics, length of free-fall path of the test body, laser interferometer units, electronic units, software, etc. The gravimeters FG5-213 and FG5-204 used an electronic timing unit belonging to the BIPM, due to some problems with their own electronics). All the gravimeters used He-Ne lasers with radiation at 633 nm (red light). The interferometer unit and laser of the gravimeter JILAg-5 were replaced during the comparison and the measurement data of this gravimeter were processed as the data from two different gravimeters, JILAg-5/1 (at A and A2) and JILAg-5 (at B and B1).

The laser frequencies were measured at the BIPM by beat frequency techniques against one of the BIPM's reference He-Ne/I_2 lasers. The frequencies of rubidium clocks or GPS receivers (nominal value of 10 MHz) used in the AGs were measured against a local caesium clock using an SRS620/1 frequency counter in frequency mode (averaging over 100 samples with a gate of 10 s). The results of these measurements are presented in Table 2.

The barometers were also compared against the calibrated barometer of the BIPM but no individual corrections were applied because no standard calibration protocol existed.

Table 2. Results of the measurement of the frequencies of Rb clocks and GPS receivers

Gravimeter	Frequency/MHz	St.dev./mHz	Date/dd.mm.yy
FG5-101	10.000 000 008 8	0.2	25.07.01
FG5-103	10.000 000 007 5		
FG5-105	10.000 000 434 3	0.5	09.07.01
FG5-202	10.000 000 002 9	0.2	19.07.01
FG5-204	10.000 000 022 1	0.2	12.07.01
FG5-209	10.000 000 007 2	0.1	15.07.01
FG5-211	9.999 999 994 6	0.2	09.07.01
FG5-211	9.999 999 995 5	0.1	18.07.01
FG5-213	10.000 000 000 6	0.2	02.08.01
FG5-301	9.999 999 952 7	0.1	25.07.01
FG5-301	9.999 999 962 8	0.2	27.07.01
JILA-2 (*)	9.999 999 999 5	0.4	11.07.01
JILAg-5	10.000 000 041 8	0.1	25.07.01
JILAg-6	10.000 000 025	0.2	06.07.01
A10-b002	10.000 000 001 8	0.2	26.07.01
A10-003	9.999 999 999 4	0.4	06.07.03
FG5-108	10.000 000 017 3	0.2	28.06.01
FG5-108	10.000 000 017 2	0.3	09.07.01
FG5-108	10.000 000 017 2	0.2	22.07.01
FG5-108	10.000 000 016 8	0.2	01.08.01
FG5-206	9.999 999 999 1	0.4	03.07.01
IMGC	9.999 999 999 8	0.3	01.10.01

(*) GPSTRACK S/N 436

3. Absolute measurements and their results.

Each AG (with a few exceptions) measured the *g*-value at two or three sites of the BIPM gravity network, thus measuring the gravity ties (differences in *g*-values) between these sites. In Table 3 the results are presented for the gravimeters measuring the ties between the four sites A, A2, B and B1.

Table 3. Ties of the BIPM gravity network measured by absolute gravimeters

Ties	Gravimeters, measured corresponding ties
A-A2	A10-003, FG5-101, FG5-108, FG5-202, FG5-204, FG5-211
A-B	FG5-101, FG5-204, FG5-213, FG5-301
A-B1	A10-003, FG5-103, FG5-105, FG5-108, FG5-211, JILAg-5/1, JILAg-6
A2-B	FG5-103, FG5-202, FG5-209, FG5-209, JILA-2, JILAg-6
A2-B1	FG5-105, FG5-108, FG5-209
B-B1	A10-003, FG5-108, FG5-204, JILA-2, JILAg-5, IMGC

The raw data of the absolute measurements (pairs of time and path intervals of the free-falling test body) were pre-processed using, where possible, the same software to provide the *g*-values measured by each gravimeter at its reference height (Francis and van Dam, 2003).
The vertical gravity gradients used in the motion equation for free-falling test body in the gravity field were calculated from the results of relative measurements performed at four heights above each site (Becker, Jiang, Vitushkin). It was assumed that the gravity field over the sites may be represented by a second-order polynomial function of the height *h* above the benchmark:

$$g(h) = c_0 + c_1 h + c_2 h^2 .$$

The polynomial coefficients c_0, c_1 and c_2 and the vertical gravity gradients γ at the sites are presented in Table 4. The gradient at a height of 1.20 m was used in the equation of motion for the FG5-type gravimeters and the gradient at 0.90 m for the others.

Table 4. Polynomial coefficients and corresponding vertical gravity gradients γ at heights 0.9 m and 1.2 m (Vitushkin et al., 2002).

	Coefficients			Gradients	
Site	c_0/ µGal	c_1/ (µGal/m)	c_2/ (µGal/m^2)	γ(0.9 m)/ (µGal/m)	γ(1.2 m)/ (µGal/m)
A	5.9847	–322.69	9.8	–305.1	–299.2
A2	5.9887	–324.14	12.7	–301.3	–293.7
B	8.2880	–300.81	2.1	–297.0	–281.5
B1	8.2801	–302.39	8.1	–287.8	–281.0
B3	8.2747	–310.70	9.0	–294.5	–289.1
L3	6.8670	–279.25	4.4	–273.3	–268.7
L4	6.8822	–276.51	0.1	–276.3	–276.3

All the *g*-values at the reference heights of the individual AGs were then transferred to a height of 0.9 m over the sites using the polynomials for the gravity field distributions.
For the first time in the ICAGs, in the ICAG-2001 some data were rejected and data weighting was applied. A weighting model assuming non-correlated measurements (observations) was applied with upper and lower limits to avoid the domination of any gravimeter and ensure that the results of all the gravimeters contributed. Two independent models of data adjustment were tested and after the demonstration of good agreement between their results one of them, labelled BIPM, based on the adjustment of gravity differences (Jiang, Xu, Qiu, Zou, 1985), was used for the final data adjustment (Becker, Jiang, Vitushkin; Vitushkin et al, 2002).
A few data were rejected because of excessive discrepancies (more than three standard deviations) from the mean result. The data from

some gravimeters were omitted because the raw data were not presented or the results included an unexplained shift (17 µGal for FG5-301) determined by the manufacturer.

Using the BIPM adjustment model and software, various combinations of the data were processed. These were combined adjustments of: (a) all weighted absolute and relative data; and (b) weighted absolute and relative data with some omitted AGs; and adjustments of (c) only unweighted absolute data of all the AGs; (d) only weighted absolute data of all the AGs; (e) only weighted absolute data with some omitted AGs; and (f) relative data only.

Different adjustments of the data of the ICAG-2001 are essential because the technical protocol for the comparison was not existing and the data rejection and weighting had never before been applied in an ICAG.

The results of the ICAG-2001 are

- the individual results of the measurements of each AG at the sites. These results depend on the values of the vertical gravity gradients, measured by relative gravimeters.
- *g*-values at the sites A, A2, B, B1 of the gravity micronetwork obtained using the combined adjustment of accepted weighted absolute and relative data. These values B2B3B4 sont-ils abandonnés? depend on all the measurements by the AGs and RGs.

The combined adjustment of weighted absolute and relative data, omitting the data from the gravimeters IMGC, FG5-301 and JILAg-5 gives the following *g*-values (at the height 0.90 m) at the sites of the BIPM gravity network:

A.090: 980 925 701.2 µGal;
A2.090: 980 925 706.6 µGal;
B.090: 980 928 018.8 µGal;
B1.090: 980 928 014.5 µGal.

The standard uncertainty of these values is 5.5 µGal (6 parts in 10^9), which is calculated as the weighted mean of the residuals (differences between the *g*-value obtained by each AG at point A.090 and that obtained by the combined adjustment).

The degree of precision of *g*-measurement by an individual gravimeter may be estimated by the difference between the adjusted and individual *g*-values measured at the sites. To compare the individual results of each AG the *g*-values measured at each site may be transferred to one site (for example, A at a height of 0.90 m) using the gravity differences (ties) between the sites obtained from the combined adjustment.

Figure 1 summarizes the results of the absolute measurements at point A.090 during ICAG-2001 (Vitushkin et al, 2002) and ICAG-97 (Robertsson, 2001).

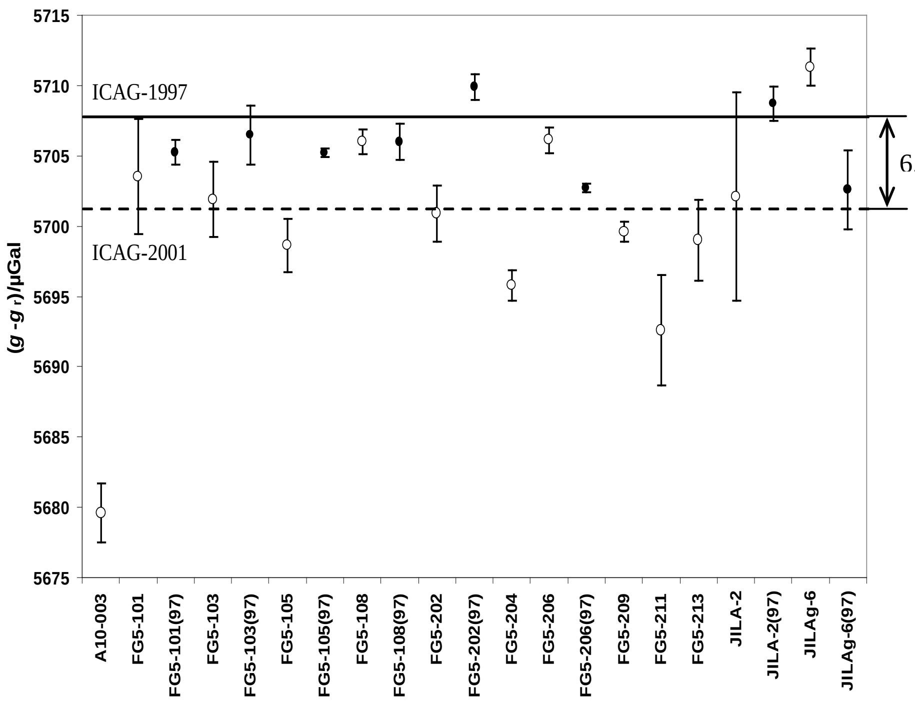

Fig. 1. Results of the absolute measurements at the point A.090 during the ICAG-2001 and ICAG-97 for each gravimeter. ○ results of the ICAG-2001; ● results of the ICAG-97; solid line: unweighted mean value of the ICAG-97 (980 925 707.8 ± 2.8) µGal; dashed line - weighted mean value with some omitted data of absolute measurements of ICAG-2001 (980 925 701.2 ± 5.5) µGal. g_r = 980 920 000 µGal.

The error bars represent the standard deviations for each absolute gravimeter. The unweighted mean value g_{1997} = (980 925 707.8 ± 2.8) μGal of all the absolute measurements during ICAG-97 transferred to point A.090 is 6.6 μGal lower than the weighted mean g_{2001} = (980 925 701.2 ± 5.5) μGal obtained in ICAG-2001. The standard uncertainty 5.5 μGal of g_{2001} is larger than that of 2.8 μGal of g_{1997}.

The results of the measurements using the BIPM's gravimeter FG5-108 in 1997 and 2001 coincide within 1 μGal. On the assumption that this gravimeter has a good reproductibility this agreement indicates again the stability of the gravity field at the BIPM.

g-value measured during ICAG-2001 by the gravimeter IMGC and transferred to point A.090 is 980 925 688.4±0.7 μGal and that measured in 1997 is 980 925 717.5±9.7 μGal.

For JILAg-5 *g* at A.090 are 980 925 714.9±0.2 μGal and 980 925 708.3±3.6 μGal, respectively, in 2001 and 1997.

For FG5-301 *g*-value at A.090 measured in 2001 is 980 925 696.1±2.8 μGal.

4. Conclusions

The highlights in the ICAG-2001 were the improvement of the gravity micronetwork of the BIPM, introduction of a new absolute measurement strategy (sufficient measurement by AGs of the links between the sites), almost continuous monitoring of the stability of the gravity field during the comparisons, better measurement of gravity gradients, the use of a combined adjustment of the absolute and relative data, and the rejection and weighting of absolute data using reasoned criteria.

Despite all these improvements the *g*-values at four sites of the BIPM gravity micronetwork were obtained in the ICAG-2001 with an uncertainty (of 5.5 μGal, or 6 parts in 10^9) larger than that obtained in ICAG-97 (2.8 μGal). This shows that the accuracy of absolute *g*-measurements has not improved during the four years since ICAG-97, which is an unexpected result. It should be also noted that this uncertainty was reached using just thirteen of the absolute gravimeters. The maximum difference between the *g*-values obtained at A.090 by different AGs is 19 μGal (between JILAg-6 and FG5-211) if we omit the result of A10-003, which is quite far from the mean value but has a low weight.

We conclude that the reason for such a decline in the absolute measurements during the ICAG-2001 is related to non-optimal adjustment and operation of the absolute gravimeters. There remains a large discrepancy between the estimated potential uncertainty of (1 to 2) μGal in absolute measurements and the real uncertainty obtained in the last ICAG.

It is important to continue further investigations of the sources of systematic uncertainties of AGs, possible time variations in the preliminary adjusted offsets, improved methods of instrumental adjustment, and so on, which do not depend on operators.

International comparisons of gravimeters should be continued and enlarged on a regional basis. The technical protocol of the comparisons should be developed and adopted for future comparisons, to regulate the organization of both the ICAGs at the BIPM and regional comparisons at other sites, selected by the geophysical and metrology communities, as well as the measurement strategy, methods of data processing, calculation of uncertainties and presentation of the results.

The participation of many different AGs, developed using a range of basic principles and designs, and produced by different manufacturers, is very important in the regional comparisons and the ICAGs.

The ICAG-2001 was an example of practical use of absolute gravimeters in the measurement of a gravity network. Good agreement between the absolute and relative data was obtained in the measurements of the gravity differences (see Table 5).

The relative measurements of the ties of the gravity network and gravity gradients during the international comparisons should be continued to confirm the stability of the ties and gradients, and to explore the reason for the discrepancies between the ties and gradients obtained in 1997 (Robertsson et al, 2001) and 2001 (Vitushkin et al, 2002).

Adjustment	A.090		A2.090		B.090		B1.090	
	$g - g_r$	M	$g - g_r$	M	$g - g_r$	M	$g - g_r$	M
a) Combined, with weighted data, some absolute data omitted.	5701.2	0.9	5706.6	0.9	8018.8	0.9	8014.5	0.9
b) Combined, with weighted data, all absolute data.	5700.5	0.8	5706.2	0.9	8018.3	0.8	8013.8	0.9
c) Only all unweighted absolute data.	5698.5	2.2	5701.8	2.4	8018.2	2.2	8012.0	2.4
d) Only all weighted absolute data.	5700.9	1.2	5705.8	1.2	8019.1	1.2	8012.7	1.2
e) Only absolute data, weighted, some data omitted as in a).	5701.4	1.2	5706.3	1.3	8019.6	1.3	8013.4	1.3
f) Only relative data.	5701.2	0.0	5706.3	0.4	8019.3	0.7	8015.6	0.7

Table 5. Comparison of the results of the different versions of the adjustment of the relative and absolute data of the ICAG-2001. Weighted mean of all the g values transferred to the points A, A2, B or B1 at the height 0.9 m are expressed in microgals after the subtraction of the reference value 980 920 000 µGal. M is the mean square error of adjustment expressed in microgals.

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