Relative Gravity Measurement Campaign during the 7th International Comparison of Absolute Gravimeters (2005)

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Relative Gravity Measurement Campaign during the 7th International Comparison of Absolute Gravimeters (2005)

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Abstract
Since the 1st International Comparison of Absolute Gravimeters (ICAG) and accompanying Relative Gravity Campaign (RGC) held at the BIPM in 1981, repeated ICAG-RGCs have been organized every four years. A total of 19 absolute gravimeters (AG) and 15 relative gravimeters (RG) participated in the 7th ICAG-RGC, which took place in 2005. Co-located absolute and relative gravity measurements as well as precision levelling measurements were carried out.

The final version of the absolute g values of the 7th ICAG has been officially released recently. This paper is the final report of the 7th RGC and replaces the preliminary results published earlier. It covers the organization of the RGC and the data processing, analyses RG behaviour, computes g, δg and O_{AG} (offset of AG) and discusses their uncertainties. In preparation for the BIPM key comparison ICAG-2009, a standard data-processing procedure has been developed and installed in the BIPM ICAG-RGC software package, GraviSoft. This was used for the final data processing.

(Some figures in this article are in colour only in the electronic version)

Notation

1 Gal = 1 cm s^{-2}	
AG	absolute gravimeter
RG	relative gravimeter
g	absolute gravity acceleration value in µGal (minus a constant value of 980 900 000 µGal)
δg	difference of g
$\delta g/\delta H$	vertical gradient
ICAG	International Comparison of Absolute Gravimeters
RGC	Relative Gravity Campaign organized in association with ICAG
MSE	mean square error given by a least-squares adjustment
BIPM	Bureau International des Poids et Mesures
Offset or O_{AG}	systematic bias of an AG versus a common reference defined by all AG values during the ICAG

1. Introduction

The 1st International Comparison of Absolute Gravimeters (ICAG) and accompanying Relative Gravity Campaign (RGC) was held in 1981 at the Bureau International des Poids et Mesures (BIPM), Sèvres, France [1, 2]. Since then, repeated ICAG-RGCs have been organized every four years [3–12]. A total of 19 absolute gravimeters (AG) and 15 relative gravimeters (RG) participated in the 7th ICAG-RGC, which took place in 2005 (table 1). Co-located absolute and relative gravity measurements as well as precision levelling measurements were carried out (table 2). The purpose of the RGC is to supply the precise vertical and horizontal gravity differences (δg) to bring the individual AG determinations to a common reference to make the comparisons, i.e. to determine the offset (O_{AG}) of each AG. The combination of relative and absolute measurements should improve the accuracy of the gravity value (g) at each point. Additionally the δg measured by the RG provides a 'truth check' on the δg measured by the AG. A highly accurate local gravity network was established.

The 7th ICAG and RGC were co-organized by the BIPM, the Study Group 2.1.1 on Comparisons of Absolute Gravimeters of the International Association of Geodesy (SGCAG-IAG) and the Working Group on Gravimetry of the Consultative Committee for Mass (WGG-CCM). Participants included 19 AGs of seven different models made by different manufacturers or institutions and 15 RGs of three different models. In total, 26 institutes from 14 countries took part in the comparison (table 1). The 15 RGs comprised eight Scintrex (models CG-3 and CG-5) and six LaCoste-Romberg (models G, D and EG) as well as one ZLS (model B). However, not all of them fulfilled the complete horizontal/vertical measurement schedule.

The main goal of the ICAG-RGC is to determine the O_{AG} of each AG with respect to a common reference which is defined by the adjusted g values of all participant AGs [13]. To do this, all g values determined at different reference heights depending on a particular apparatus over different points must be brought to a common reference point, B.090, which is 90 cm above the benchmark of station B at site B (figures 1 and 2). Instead of the ground surface, the principal points of the network are defined at 90 cm above ground level to reduce the strong influence of the non-linearity of the vertical and horizontal gradients produced by the local gravity field. The main result of the RGC is the accurate determination of the vertical and horizontal δg. The measurements were carried out during 4–8 July, 24–28 July and 11–12 September 2005. The AG campaign was performed in September 2005.

Precision levelling was carried out on 6 and 7 July 2005 by the Bureau de Recherches Géologiques et Minières (BRGM) in France. The height reference was the French national levelling network point located at the BIPM, i.e. 66.12 m in the French

Table 1. Participants and relative gravimeters at the 7th RGC.

Main observer	Institute	Gravimeter
J Mrlina	GI	LCR D188
M van Ruymbeke, S Naslin	ORB	LCR G336
O Francis, M Ferry	UL/UE	CG-5 S008
C W Lee, C L Tsai	ITRI	LCR EG184
P Jousset	BRGM	CG-3 S245
F Dupont		CG-5 S028
M Becker	IPGD	LCR D038
B Meurers	IMG	LCR D009
F Pereira Dos Santos	LNE-SYRTE	CG-5 S105
S Deroussi	IPGP	CG-3 S193
L Métivier		CG-3 S323
G Pajot		CG-3 S424
V Palinkas, J Kostelecky	GOP	ZLS B020
H Wilmes, R Falk	BKG	CG-3 S202
D Ruess, M C Ullrich	BEV	LCR D051

Table 2. Height of the ground benchmark of the BIPM network stations in French IGN 69 levelling reference system/m (δH is the measured height difference between the starting point (66.12 m) and a network station; σ is the standard deviation of the δH measurements).

Stn	δH/m	σ/m	H/m
C2	−28.483	0.003	37.637
C1	10.337	0.001	76.457
A	−0.181	0.001	65.939
A1	−0.179	0.001	65.941
A2	−0.163	0.001	65.957
B	−9.792	0.002	56.328
B1	−9.778	0.002	56.342
B2	−9.78	0.002	56.340
B3	−9.785	0.002	56.335
B4	−9.79	0.002	56.330
B5	−9.791	0.002	56.329
B6	−9.785	0.002	56.335

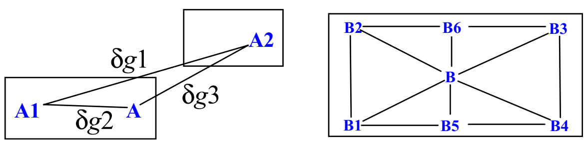

Figure 1. Indoor stations over sites A and B plus the relative δg measurement scheme.

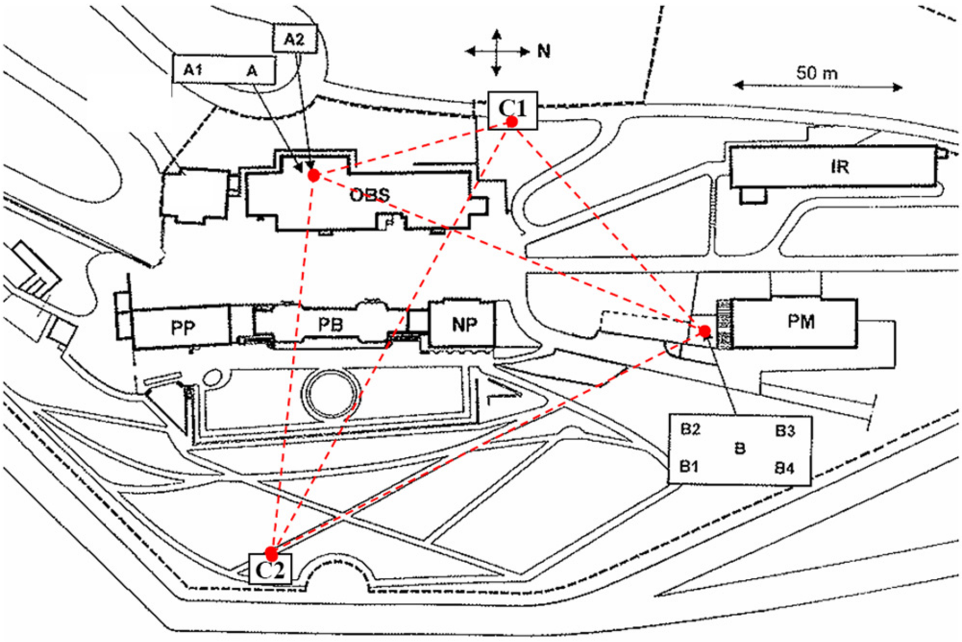

Figure 2. The BIPM local gravity network comprises four sites (A, B, C1, C2), 12 stations (see figure 1) and 34 points. At each station, three points are defined at 30 cm, 90 cm and 130 cm above the ground benchmark (C1 and C2 have only two points at 90 cm and 130 cm); they are named by station plus height, e.g. A.030, A.090 and A.130.

reference network IGN 69. No observable changes were found compared with earlier levelling results. Table 2 gives the results.

In the following sections, the design of the BIPM local gravity network and the measurement schedule are described, the data-processing principles and the results presented and the uncertainty estimated. The final computation is based on the official release of the AG results [13] and the RGC final results presented here replace the preliminary reports published earlier [14–16].

2. The 7th Relative Gravity Campaign (RGC)

The goals of the earlier RGCs were to serve the ICAG by supplying highly accurate δg and gradients, and to perform an international comparison to calibrate the relative gravimeters. The calibration was important for the very long-distance and large-scale relative gravimetric field campaigns. Over the last three decades, great progress has been made in the instrumentation, construction and manufacturing of absolute gravimeters. An increasing number of high-precision portable AGs are used in field surveying. This facilitates very long-distance δg surveys, reducing the influence of error on large-scale calibration and thus increasing accuracy. Therefore, the long-distance RG field measurements become less important while AG calibration becomes more important for metrological purposes. During the 1st Joint Meeting of the SGCAG-IAG and WGG-CCM on 25–26 May 2004, it was decided that the role of the RGC is to provide a metrological service to the ICAG, a decision that represents a fundamental change in its history. The 7th RGC was therefore redesigned to adapt to its new role: to supply as accurately as possible the δg values and $\delta g/\delta H$ (gradient) under BIPM laboratory conditions.

The dominating error sources in gravimeter comparisons arise from scale, zero drift, temperature variation, transport vibration and the non-linearity effects of the vertical and horizontal gradients, as well as site-dependent error. This paper focuses on the network structure, measurement schedule and data-processing strategy, based on error source analysis and gives the final results and their uncertainties for the 2005 RGC.

2.1. Design of network and measurement schedule

The network structure was designed to achieve the lowest possible uncertainty in δg under BIPM laboratory conditions. The basic criteria were as follows:

1. To perform AG comparisons and RG measurements as far as possible between points of quasi-zero δg and quasi-zero distance, in order to reduce the influence of error sources in RG measurements.
2. To follow a schedule that is traceable and has a triangle-closing sequence with short and equal time intervals, in order to further reduce the residual influence of the error sources and avoid the operator errors that occurred in the earlier RGCs.
3. To use fixed-level tripods for the vertical δg measurements to eliminate error in height measurements. An operator is thus responsible only for a gravimeter, the height measurements having been established in advance to avoid operator error and save time. All the indoor stations were air-conditioned with a maximum temperature variation of 0.5 °C during RGC 2005.
4. To define the main point of a station 90 cm vertically above the ground level benchmark at a distance from the walls or other heavy objects to reduce the non-linearity effects of

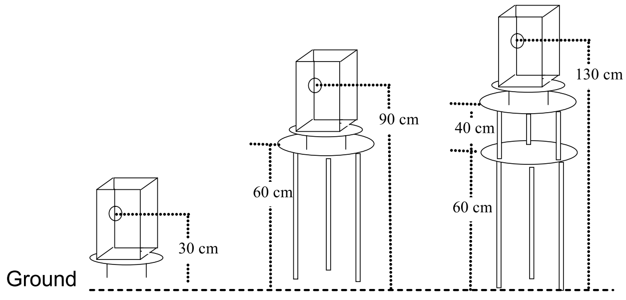

Figure 3. BIPM fixed-level tripod and the set-up for vertical δg measurements at the heights of 30 cm, 90 cm and 130 cm above ground for the Scintrex CG gravimeter over its manufacturer's tripod with sensor coincided at the required levels.

the gravity field produced by the anomaly masses. In fact, the reference heights of AGs vary from 30 cm to 130 cm and the average reference height is about 90 cm. Two models have reference heights very close to 90 cm.

In the earlier ICAGs, site L (points L1 and L2) and the points 5 cm above ground level at sites A and B were measured. As a consequence of the above criteria, these points were dropped. The present BIPM local gravity network comprises four sites, A, B, 1C and C2, with a total of 12 stations (figures 1 and 2). A and B are indoor sites with 10 indoor stations. C1 and C2 are outdoor sites. The maximum δg is between C1 and C2, which is designed for RG scale calibration. The δg within sites A and B are the most favourable ties in ICAG-2005. Most are less than 10 µGal. The maximum δg is 23 µGal and the maximum inter-point distances are 4 m at A and B. The average occupation takes 3 min to 4 min. According to the Technical Protocol of the 7th ICAG, all horizontal relative observations (except for S202 occupying the points of 130 cm between only AA1, B1A, B1B3 and B1B) were performed between the points of 90 cm in height and followed the same scheme. Over site A: A, A1, A2, A, A1, A2, A, A1, A2 and A. This takes about 1 hour. Over site B: B, B1, B2, B, B2, B6, B, B6, B3, B, B3, B4, B, B4, B5, B, B5, B1, B, B2, B1, B, B3, B6, B, B5, B4 and B. This takes about 2 h. Each point has at least three occupations. The vertical δg measurement schedule is composed of 11 occupations: 30 cm, 130 cm, 30 cm, 90 cm, 130 cm, 90 cm, 130 cm, 90 cm, 130 cm, 90 cm and 30 cm (figures 3 and 4), realized with the help of the BIPM fixed-level tripod. The 90 cm to 130 cm segment is strengthened because the majority of AGs (FG5) have a reference height of about 130 cm. The outdoor ties are mainly designed for the relative meter calibration following the schedule: C1, C2, C1, B, A, B, C2, A, C1, C2 and C1. The RGs are always oriented to the north.

All the schemes are designed based on triangle or self-closures. One of the advantages of the closing scheme is to better monitor the zero-drift behaviour of an RG. Because the zero drift is independent of both the measured g value and the other RGs or AGs, the best way to approximate it is to model it within a limited operating period with its self-closure measurements. A raw-data pre-processing procedure has been developed. For each horizontal or vertical individual indoor or outdoor schedule, we set a zero-drift model which has a maximum life of $p \leqslant 2.5$ h and contains minimum $n \geqslant 3$ closures. A normal zero-drift model is a 2-order polynomial determined by a least-squares adjustment. Suppose $R_{q,p}(t_k)$ is the reading of the RG q at time epoch t_k during period p, t_o is its starting reading epoch, n is the total number of the closing readings and $D_{q,p}(t_k)$ is the zero-drift model expressed by a polynomial:

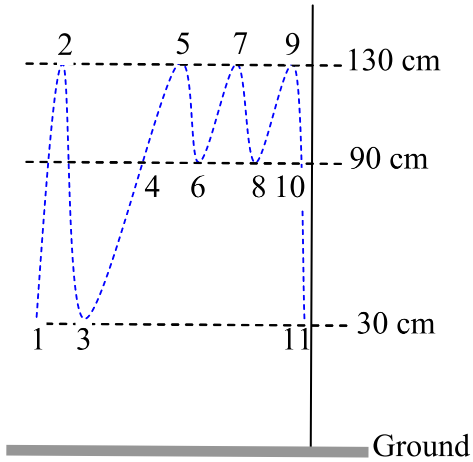

Figure 4. Vertical δg measuring schedule with 11 occupations.

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

Here, $D_{q,p}(t_k) = A_{q,p}(t_o) + B_{q,p} \times (t_k - t_o) + C_{q,p} \times (t_k - t_o)^2$. $A_{q,p}(t_o)$ is the zero drift at t_o and can be set to zero in our case. Therefore, two unknowns are to be determined, $B_{q,p}$ and $C_{q,p}$. For $n \geqslant 2$, the solution is optimal and unique using the least-squares method. In abnormal cases, such as zero-drift jumps and schedule interruption, the initial 2-order zero-drift model is degraded into several linear regressions ($C_{q,p}$ set to zero) and cut off into several sub-drift-periods. As given above, the number of triangle and go-back closures n is mainly greater than 2, e.g. the site B schedule contains 10 closures for the B.090 point alone. With the redundant closures, the measurement error is greatly reduced in zero-drift modelling. After the zero-drift corrections, the closures are usually not zero. The residuals can be used for the measuring error analysis in order to estimate the uncertainty in terms of MSE for an individual RG q over a particular operating period p. This is used for the relative δg observation weighting in the network adjustment.

In this paper, the terms 'site', 'station' and 'point' are not synonymous. A site may have several stations and a station may have 2 or 3 points (see caption to figure 2).

Each indoor station consists of three points at 30 cm, 90 cm and 130 cm above the benchmark, which is installed on top of a specially built concrete pillar, of which the surface is the same height as the surrounding ground. The outdoor points consist of two levels at 90 cm and 130 cm. The heights of the levels are selected to be close to the reference heights of the currently available AG apparatus: 30 cm (FGC1), 90 cm (GABL 90 cm and JILA 91 cm) and 130 cm (FG5). This three-level structure minimizes gradient reduction error. In fact, 16 of the 19 AGs have their gradient reduction distance within 2 cm of one of the three levels, the exceptions being IMGC (53 cm), A10 (70 cm) and TBG (82 cm). The maximum gradient reduction distance is 23 cm.

The BIPM tripod is also designed to accommodate the instrument sensors of LCR or Scintrex gravimeters to be located within 1 cm to 2 cm with respect to the 30 cm, 90 cm and 130 cm height levels by different combinations of the three sub-tripods. Slight eccentricities of the instrument sensor to the defined point are corrected using the vertical and horizontal gradients obtained in an iterative procedure. In all cases, the gradient reduction error is within 1 µGal (see section 2.7.2).

Except for station B4, all stations were occupied by AGs. All points of the 12 stations were occupied by RGs. 15 indoor, six outdoor horizontal δg and 24 vertical δg were measured. A complete schedule contains 157 occupations and takes 15 h to 18 h for an experienced operator.

2.2. *Data-processing strategy*

The goals of the 2005 RGC were:

(1) Determination of the horizontal and vertical gravity difference and its uncertainty $\delta g \pm u_g$ so that by fixing the gravity value g of an arbitrary point in the network we obtain the g values for all points;
(2) Estimation of the offsets $O_{\mathrm{AG}}(k)$ for each AG(k) and their uncertainties: $O_{\mathrm{AG}}(k) \pm u_k$.

The relative-only adjustment was performed with the same principles given in [12, 17]. All the vertical and horizontal δg measurements were adjusted as a whole. This is a typical unconstrained network adjustment with the observation equation

$$V_{q,ij} = S_q \times (R_{q,i} - R_{q,j}) - (G_i - G_j), \tag{2}$$

where $V_{q,ij}$ is the adjustment residual for RG q between points i and j; $R_{q,i}$ and $R_{q,j}$ are the measurement readings of RG q at points i and j; G_i and G_j are adjusted g values of points i and j and S_q is the linear factor of the scale function for RG q. For 14 of the 15 RGs, only linear factors are required. Non-periodic terms are applied for LCR RGs. The unknowns to be determined are G and S, i.e. the g values and the scale factors of RG. In equation (2), if we fix the g value of B.090 and the scale of at least one RG or one δg (starting baseline), we can obtain, in the least-squares sense, the most optimal solution as well as the MSE estimate for every unknown determined. Instead of fixing a δg, we fixed a RG scale. The solution is unique. We use the classical least-squares method which may be readily found in textbooks.

The weight of an observation equation is defined as

$$w_{q,p} = \mu_0^2 / m_{q,p}^2, \tag{3}$$

where μ_0 is the unit weight MSE and $m_{q,p}$ is the MSE *a priori* of the $\delta g_{,q,p}$ measured by RG q during the period p.

To evade any biases due to unreasonable modelling of the local gravity field, the gradients are not unknowns in the adjustment but determined using the adjusted gravity values g. We assume that g at a station can be vertically approximated by a polynomial as a function of height H:

$$g(H) = a + bH + cH^2. \tag{4}$$

For a set of g values defined at 30 cm, 90 cm and 130 cm at a station, a, b and c can be determined with an iterating procedure. We first use the approximated a, b and c to perform a preliminary adjustment to determine the g values and then compute the improved a, b and c. As pointed out above, the sensors of the RG almost coincide with the three height levels of 30 cm, 90 cm and 130 cm, and the iteration converges immediately. Following are some useful expressions with coefficients b and c. From equation (4), the δg between H_1 and H_2 can be written as

$$\delta g = g(H_2) - g(H_1) = b(H_2 - H_1) + c(H_2^2 - H_1^2). \tag{5}$$

Here a is cancelled. Dividing the two sides by the term $(H_2 - H_1)$, we obtain the mean gradient between H_1 and H_2:

$$\delta g/(H_2 - H_1) = b + c(H_2 + H_1). \tag{6}$$

When $H_1 \to H$ and $H_{12} \to H$, we obtain the gradient at height H:

$$\mathrm{d}g/\mathrm{d}H = b + 2cH \qquad \text{or} \qquad \delta g/\delta H = b + 2cH. \tag{7}$$

In the following discussion, the term $\delta g/\delta H$ stands for the approximate gradient of a station.

The second goal of the RGC is to estimate the O_{AG} for each AG and its uncertainties: $O_{\mathrm{AG}} \pm u_k$. By comparing the g values obtained by the relative-only adjustment and that of the AG determinations, we compute their differences. The average of the differences is the O_{AG} and the corresponding standard deviation is its uncertainty.

2.3. *Final result of gravity and gradient values*

Observation equation (2) is used for the relative-only adjustment. The gravity value at B.090 obtained by the absolute-only adjustment is $g = 28\,018.8 \pm 1.1$ µGal [13]. This and the scale of the two RGs S008 and S245 are fixed in the relative-only adjustment (cf tables 1 and 6). The two RGs have been chosen as the scale reference because they have fulfilled the complete measurement schedule with satisfactory precision (both have 157 occupations with the root mean square (RMS) of the residuals of 0.9 µGal and 1.7 µGal, respectively, cf figure 5 and table 7). Table 3 lists the adjusted g values (g_{R05}) that vary between 23 281.6 µGal (C1) and 32 040.3 µGal (C2) and the MSEs that vary between 1.0 µGal and 1.2 µGal. Differencing the g values, table 4 gives the δg values between all points at 90 cm in height. In table 3, $\delta g/\delta H$ is the vertical linear gradient between two vertically adjacent points in µGal m^{-1} using equation (6). Strong non-linearity is observed in the gradients of certain stations. The strongest is at point A1: from 30 cm to 90 cm the gradient is 296.5 µGal m^{-1} and from 90 cm to 130 cm it increases to 307.7 µGal m^{-1}. The corresponding polynomial approach

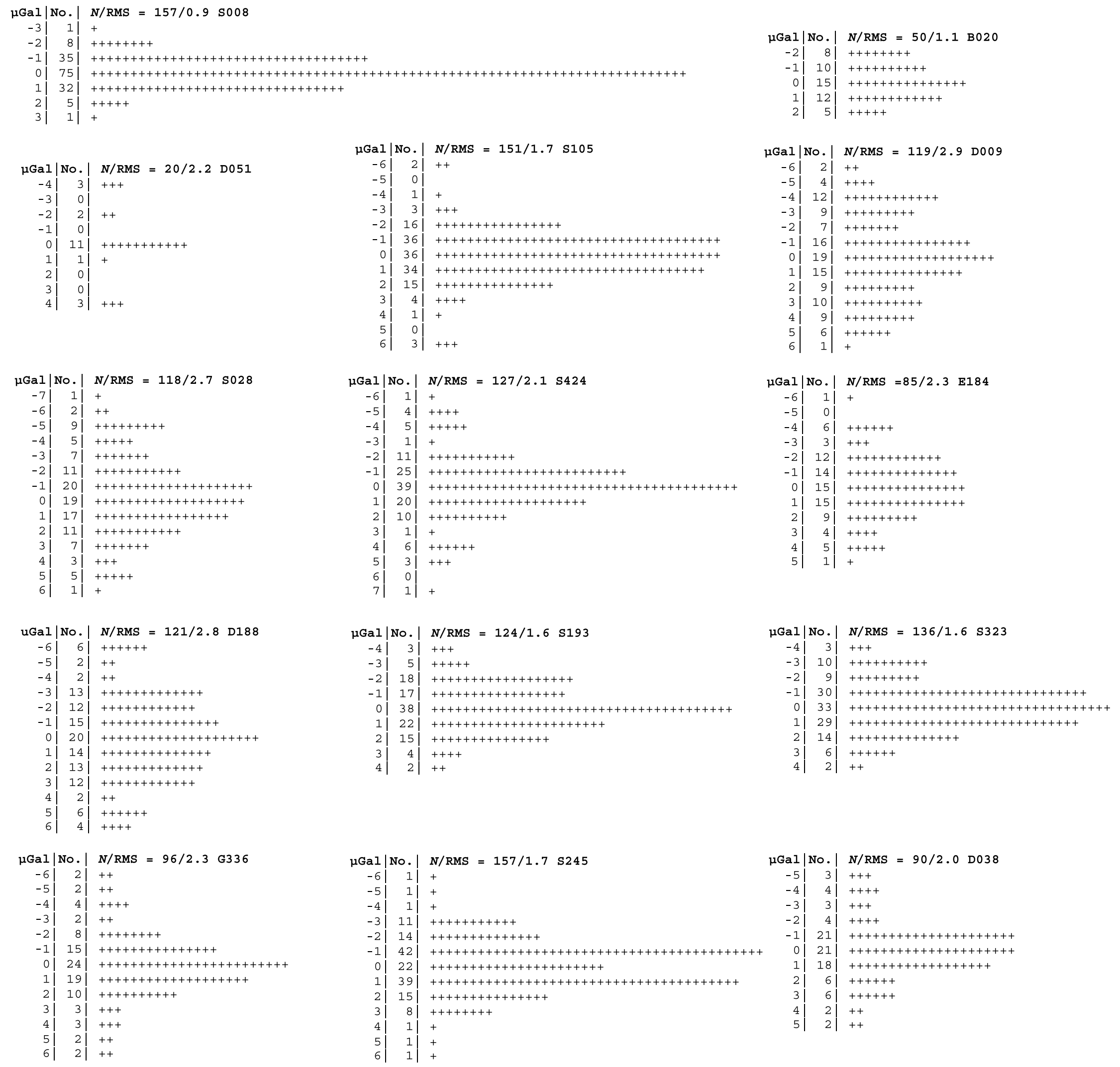

Figure 5. Histograms of the residuals from the relative-only adjustment for each RG. N is the number of the δg measurements; RMS is root mean square; µGal marks the intervals and No. is the number of residuals falling in an interval.

is $b = 321.07\,\mu\mathrm{Gal\,m^{-1}}$ and $c = 11.167\,\mu\mathrm{Gal\,m^{-2}}$. The latter is the largest c value in table 5. The δg in table 4 varies from 0.2 µGal (B2–B6) to 8758.7 µGal (C1–C2). Using the MSE of the g values given in table 3, the MSE of the δg_{ij} can be calculated with the MSE of g_i and g_j: $M_{\delta gij} = \sqrt{M_{gi}^2 + M_{gj}^2}$. It varies between 1.4 µGal and 1.6 µGal. Table 3 also compares the different adjustment results. Here R01 and R05 are the relative-only g of ICAG-2001 and ICAG-2005; A05 is the absolute-only g of ICAG-2001; C01 is the g value of the relative–absolute combined adjustment of ICAG-2001 [12]; $d_{\mathrm{C01}} = g_{\mathrm{C01}} - g_{\mathrm{R05}}$ and $d_{\mathrm{R01}} = g_{\mathrm{R01}} - g_{\mathrm{R05}} - 0.5$. Here, g_{R01} at B.090 is shifted -0.5 µGal to be equal to that of g_{R05}. This simplifies the comparisons: instead of comparing δg we can compare the g values. d_{C01} and d_{R01} are the differences of the results of the two campaigns separated by four years. The biggest changes happen on the near-ground points B1.030 and A2.030. The averages of the discrepancies (d_{C01} and d_{R01}) are close to zero and the RMS of the discrepancies are 1.5 µGal and 1.0 µGal. $d_{\mathrm{A05}} = g_{\mathrm{A05}} - g_{\mathrm{R05}}$ is the difference between the ICAG-2005 absolute-only and relative-only results. It should be emphasized that g_{A05} and g_{R05} are two independent data sets, hence the comparison between them is a 'truth check'. The average of d_{A05} is 0.4 µGal and the RMS is 1.0 µGal. The highest d_{A05} value is 2.3 µGal at station A2. If we omit this value, the RMS reduces to 0.8 µGal. It seems that the measurements at A2 were subject to a bias in relative and/or absolute results. From the right plot in table 9, the absolute g values at A2 were determined by the AG, all with a negative offset, the greatest of which is -9.5 µGal. This might explain the 2.3 µGal discrepancy. The results of the relative and absolute campaigns agree within the measurement uncertainty (see section 2.5 for more details).

Table 5 gives the polynomial approximation of the g values (g_{R05} in table 3). By the equations in section 2.2, the polynomials can be used to interpolate the g values between the measured points.

In table 6, the Scale-Rel column is the list of linear scale factors of the RG and their uncertainties given in terms of MSE obtained by the relative-only adjustment with the scales of S008 and S245 fixed. The Scale-Abs column is the list of scales and their uncertainties calibrated by the relative–absolute

Table 3. Relative-only adjusted g values of the 7th ICAG-RGC with the g of B.090 fixed at 28 018.8 µGal ($\delta g/\delta H$ stands for the vertical linear gradient between two vertically adjacent points in µGal m^{-1}. R01, R05 and A05 in µGal are the g values by relative-only and absolute-only adjustments of ICAG-2001 and ICAG-2005; C01 in µGal is the relative-absolute combined adjustment of 2001 [12]; $d_{R01} = g_{R01} - g_{R05} - 0.5$/µGal, $d_{C01} = g_{C01} - g_{R05}$, $d_{A05} = g_{A05} - g_{R05}$/µGal).

No	point	g_{R05}	MSE	$\delta g/\delta H$	g_{R01}	g_{C01}	d_{R01}	d_{C01}	d_{A05}
1	A_.030	25 886.6	1.1	−307.8	25 887.6	25 887.4	0.5	0.8	
2	A_.090	25 701.9	1.1	−301.3	25 701.2	25 701.2	−1.2	−0.7	0.8
3	A_.130	25 581.4	1.1		25 580.4	25 580.4	−1.5	−1.0	
4	A1.030	25 875.3	1.1	−307.7					
5	A1.090	25 690.7	1.1	−296.5					−1.0
6	A1.130	25 572.1	1.1						
7	A2.030	25 892.6	1.1	−309.2	25 890.5	25 890.7	−2.6	−1.9	
8	A2.090	25 707.1	1.1	−300.0	25 706.3	25 706.6	−1.3	−0.5	2.3
9	A2.130	25 587.1	1.1		25 586.8	25 587.2	−0.8	0.1	
10	B_.030	28 197.7	1.0	−298.2	28 197.6	28 197.1	−0.6	−0.6	
11	**B_.090**	**28 018.8**	**1.0**	−296.2	**28 019.3**	**28 018.8**	**0.0**	**0.0**	**0.0**
12	B_.130	27 900.3	1.0		27 900.2	27 899.8	−0.6	−0.5	
13	B1.030	28 187.8	1.0	−290.8	28 191.0	28 189.9	2.7	2.1	
14	B1.090	28 013.3	1.0	−285.7	28 015.6	28 014.5	1.8	1.2	−1.0
15	B1.130	27 899.0	1.0		27 901.4	27 900.4	1.9	1.4	
16	B2.030	28 168.3	1.0	−284.5					
17	B2.090	27 997.6	1.0	−280.5					0.3
18	B2.130	27 885.4	1.0						
19	B3.030	28 182.2	1.0	−300.8	28 183.3	28 182.5	0.6	0.3	
20	B3.090	28 001.7	1.0	−292.0	28 002.3	28 001.7	0.1	0.0	0.7
21	B3.130	27 884.9	1.0		27 886.4	27 885.8	1.0	0.9	
22	B4.030	28 197.6	1.0	−303.0					
23	B4.090	28 015.8	1.0	−299.2					
24	B4.130	27 896.1	1.0						
25	B5.030	28 198.3	1.0	−296.3					
26	B5.090	28 020.5	1.0	−295.7					1.8
27	B5.130	27 902.2	1.0						
28	B6.030	28 173.8	1.0	−293.3					
29	B6.090	27 997.8	1.0	−287.7					0.6
30	B6.130	27 882.7	1.0						
31	C1.090	23 281.6	1.1	−314.0					0.0
32	C1.130	23 156.0	1.1						
33	C2.090	32 040.3	1.1	−285.5					0.1
34	C2.130	31 926.1	1.2						
						Average	0.0	0.1	0.4
						RMS	±1.5	±1.0	±1.0

Table 4. Relative-only adjusted δg values in µGal between points of 90 cm in height, based on table 3.

Pt	A	A1	A2	B	B1	B2	B3	B4	B5	B6	C1	C2
A	**0.0**	11.2	−5.2	−2316.9	−2311.4	−2295.7	−2299.8	−2313.9	−2318.6	−2295.9	2420.3	−6338.4
A1	−11.2	**0.0**	−16.4	−2328.1	−2322.6	−2306.9	−2311.0	−2325.1	−2329.8	−2307.1	2409.1	−6349.6
A2	5.2	16.4	**0.0**	−2311.7	−2306.2	−2290.5	−2294.6	−2308.7	−2313.4	−2290.7	2425.5	−6333.2
B	2316.9	2328.1	2311.7	**0.0**	5.5	21.2	17.1	3.0	−1.7	21.0	4737.2	−4021.5
B1	2311.4	2322.6	2306.2	−5.5	**0.0**	15.7	11.6	−2.5	−7.2	15.5	4731.7	−4027.0
B2	2295.7	2306.9	2290.5	−21.2	−15.7	**0.0**	−4.1	−18.2	−22.9	−0.2	4716.0	−4042.7
B3	2299.8	2311.0	2294.6	−17.1	−11.6	4.1	**0.0**	−14.1	−18.8	3.9	4720.1	−4038.6
B4	2313.9	2325.1	2308.7	−3.0	2.5	18.2	14.1	**0.0**	−4.7	18.0	4734.2	−4024.5
B5	2318.6	2329.8	2313.4	1.7	7.2	22.9	18.8	4.7	**0.0**	22.7	4738.9	−4019.8
B6	2295.9	2307.1	2290.7	−21.0	−15.5	0.2	−3.9	−18.0	−22.7	**0.0**	4716.2	−4042.5
C1	−2420.3	−2409.1	−2425.5	−4737.2	−4731.7	−4716.0	−4720.1	−4734.2	−4738.9	−4716.2	**0.0**	−8758.7
C2	6338.4	6349.6	6333.2	4021.5	4027.0	4042.7	4038.6	4024.5	4019.8	4042.5	8758.7	**0.0**

combined adjustment. They are independently defined, Scale-Rel by the RG-only scale and Scale-Abs by the AG scale. RG D188 has a strong non-linear scale with the linear and second-order coefficients 0.203 44 ± 0.010 24 and 0.002 705 ± 0.000 035 determined with the help of the AG scale. The g value in the network varies by 8758 µGal, which allows a relative calibration uncertainty of about (2–3) × 10^{-4}. However, some uncertainties in table 6 are rather large, up to 1 × 10^{-3}. This is because the δg in question for the related RG is too small or the measurement number is too low. For example, S202 had only four δg measurements between sites A and B. The scale of S245 is almost equal to the absolute

Table 5. Polynomial approximation of g listed in table 3 (cf equation (2.2.3): a in µGal, b in µGal m^{-1}, c in µGal m^{-2}, d the mean of the two-segment $\delta g/\delta H$ in table 3; Sn the station/point number of the BIPM network).

Stn	Sn	a	b	c	d
A_	1.090	25980.73	−315.73	6.583	
A1	2.090	25 970.61	−321.07	11.167	−302.1
A2	3.090	25 987.82	−320.17	9.167	
B_	4.090	28 287.67	−300.47	1.917	−297.2
B1	5.090	28 276.42	−296.93	5.083	
B2	6.090	28 254.73	−289.30	4.000	
B3	7.090	28 274.83	−311.43	8.833	
B4	8.090	28 289.51	−307.50	3.750	
B5	9.090	28 287.36	−297.03	0.583	
B6	10.090	28 263.31	−300.03	5.583	
C1	11.090	23 281.60	−314.00	0.000	
C2	12.090	32 040.30	−285.50	0.000	

Table 6. Linear scales and MSE of the RG. Scale-Rel is determined by the relative-only adjustment and Scale-Abs by the relative-absolute combined adjustment.

RG	Scale-Rel	Scale-Abs
S008	**1.0 ± 0.0**	0.999 67 ± 0.000 20
S245	**1.0 ± 0.0**	1.000 01 ± 0.000 21
S009	0.982 92 ± 0.000 92	0.982 71 ± 0.000 95
S028	1.000 02 ± 0.000 25	0.999 81 ± 0.000 31
S105	1.000 47 ± 0.000 09	1.000 25 ± 0.000 21
S193	1.000 67 ± 0.000 18	1.000 46 ± 0.000 26
S202	1.001 77 ± 0.001 29	1.001 49 ± 0.001 30
S323	1.000 98 ± 0.000 12	1.000 77 ± 0.000 22
S424	1.000 96 ± 0.000 24	1.000 68 ± 0.000 32
B020	0.999 31 ± 0.000 95	0.999 10 ± 0.000 97
D038	0.999 17 ± 0.000 32	0.998 96 ± 0.000 36
D051	0.999 94 ± 0.000 16	0.999 73 ± 0.000 25
E184	1.003 03 ± 0.001 01	1.002 84 ± 0.001 04
G336	1.000 17 ± 0.000 19	0.999 96 ± 0.000 27

scale: Scale-Abs = 1.000 01. The average scale of S008 and S245 is 0.999 84, which may be considered as the reference scale used in the relative-only adjustment and is 1.6×10^{-4} smaller than the absolute scale. From table 4, the δg from B to C1 and C2 are 4737.2 µGal and −4021.5 µGal. Considering that B.090 is the starting point, the g values in the relative-only solution may have a maximum deviation of 0.8 µGal due to scale error.

2.4. Analysis of the relative gravimeters

In this section, we analyse the relative-only adjustment residuals for each RG. Table 7 and figure 5 present the statistical results and histograms of the residuals of each RG from the relative-only adjustment. Here N is the number of the measured δg; R denotes the RMS of the residuals and Σ is the simple sum of the residuals. The mean value of the residuals of most RGs is quasi-zero, as illustrated. S202 has only four δg measurements and its histogram is not given here. The plots show that measurement accuracies vary widely: the smallest RMS is 0.9 µGal and the largest is 2.9 µGal. The Scintrex CG5 S008 fulfilled the complete schedule with 157 occupations and none of them has been rejected. Its residuals scatter within ±3 µGal, peak to peak 6 µGal. It was operated by experienced personnel and closely followed the designed schedule. Although S008 was one of the RGs with the strongest zero drifts, up to several hundred µGal per day, its zero drift has been perfectly approximated by the polynomial model designed to match the network structure and measuring schedule. Other RGs are less accurate than S008 but generally worked very well. The residuals are of normal distribution with the mean values approximately zero. Two RGs have a RMS within 1.5 µGal, 10 RGs between 1.5 µGal and 2.3 µGal and three RGs between 2.3 µGal and 2.9 µGal. The average is 1.9 µGal. Σ in table 7 is the simple sum of the residuals which is expected to tend to zero under least-square conditions. S008 has $\Sigma = 0.1$ µGal and the Σ of all the RGs equals −13.2 µGal. Here the simple sum is not zero because the adjustment is an unequal weight one. Only the sum of the weighted residuals should be zero. The CG5 S028 has RMS = 2.7 (largest of all Scintrex RGs) and $\Sigma = -38.3$ µGal (largest of all RGs). This RG seemed to be affected by some disturbances during the measurement campaign that were reported by the operator. Due to its anomaly, S028 was weakly weighted. Its simple Σ of the residuals (−38.3 µGal) biased the simple Σ of the residuals of all RGs (−13.2 µGal).

Table 7. Statistics of residuals obtained by the relative-only adjustment.

RG	N	RMS/µGal	Σ/µGal
S008	157	0.9	0.1
S028	118	2.7	−38.3
S193	124	1.6	−1.3
S245	157	1.7	0.1
S202	4	2.0	−5.4
S323	136	1.6	1.4
S424	127	2.1	0.8
B020	50	1.1	0.0
D009	119	2.9	3.9
D038	90	2.0	−0.8
D051	20	2.2	−2.7
D105	151	1.7	9.5
D188	121	2.8	10.2
E184	85	2.3	1.6
G336	96	2.3	7.7
All	1555	2.0	−13.2

2.5. Comparisons of g from different adjustment results

With different considerations of weighting, outlier setting and handling of zero drift, etc, many adjustment solutions have been computed. We further separate the RG into two groups: Scintrex CG (quartz spring) and LCR (metal spring) to study their behaviour and the influence of each group on the final adjustment result. For brevity we compare below only four solutions:

(1) absolute-only;
(2) relative-only (all RGs);
(3) Scintrex-only (models CG3 and CG5);
(4) LCR-only (models D, G and EG).

Table 8. Comparisons between the Scintrex-only (g_S), LCR-only (g_{LCR}), relative-only (g_R) and relative–absolute combined (g_C) solutions (µGal).

Stn	$g_{LCR} - g_S$	$g_C - g_R$	$g_{LCR} - g_R$	$g_S - g_R$	$g_{LCR} - g_C$	$g_S - g_C$
A	−1.1	0.3	−1.1	0.0	−1.4	−0.3
A1	−0.2	0.2	−0.4	−0.2	−0.6	−0.4
A2	−1.2	0.3	−1.2	0.0	−1.5	−0.3
B	−0.1	−0.3	−0.1	0.0	0.2	0.3
B1	0.5	−0.4	0.3	−0.2	0.7	0.2
B2	1.6	−0.4	1.2	−0.4	1.6	0.0
B3	0.1	−0.3	0.0	−0.1	0.3	0.2
B5	−0.7	−0.4	−0.6	0.1	−0.2	0.5
B6	2.8	−0.4	2.3	−0.5	2.7	−0.1
C1	1.7	0.7	1.5	−0.2	0.8	−0.9
C2	0.9	−1.2	0.6	−0.3	1.8	0.9
RMS	±1.2	±0.5	±1.1	±0.2	±1.3	±0.5
Mean	3.6	−0.2	0.2	−0.2	0.4	0.0

The ZLS is grouped into LCRs. Thus there are eight RGs in the first group and seven in the second.

Table 3 compares the g values of the relative-only adjustments between the 2001 and 2005 comparisons. The mean of d_{R01} is 0.0 µGal and the RMS is 1.5 µGal. The mean of d_{R01} at stations B and B3 is −0.4 µGal and 0.6 µGal and the largest occur at A2.030 and B1.030: −2.6 µGal and 2.7 µGal. In the RGC 2001, the points 5 cm above ground level were measured only by LCR RG. As shown in figure 3, the sensor of the Scintrex is much higher than 5 cm. The LCR RGs dominated the near ground (5 cm to 30 cm above ground and the field nearby) vertical gradient determinations in 2001, while the 2005 comparison, with lowest points of 30 cm, was dominated by Scintrex RGs. This may increase the discrepancies between the two types of RG and explain the bigger d_{R01} on points of 30 cm. But it is difficult to give the exact cause because d_{R01} is still within the measurement uncertainty tolerance (2σ). $d_{A05} = g_{A05} - g_{R05}$ is the difference between the two independent measurements: relative-only and absolute-only during ICAG-2005. They agree within their accuracies: the average and RMS of d_{A05} are 0.4 µGal and 1.0 µGal respectively, which is an encouraging result.

Table 8 presents the results of the comparison between the Scintrex-only (g_S) and LCR-only (g_{LCR}) adjustment solutions. The mean and RMS of $g_S - g_{LCR}$ are 3.6 µGal and ±1.2 µGal, respectively. We compare the solutions from the two groups with the two more accurate solutions: (a) the relative-only solutions (g_R) of all RGs and (b) the combined solutions (g_C) of all RGs and all AGs [13]. The RMS and mean of $g_C - g_R$ are ±0.5 µGal and −0.2 µGal, respectively. They closely agree. Taking g_R as the reference, the RMS of $g_S - g_R$ is ±0.2 µGal while the RMS of $g_{LCR} - g_R$ is ±1.1 µGal; taking g_C as the reference, the RMS of $g_S - g_C$ is ±0.5 µGal while the RMS of $g_{LCR} - g_C$ is ±1.3 µGal. As a result of these comparisons, we conclude that the Scintrex-only solution dominates the relative-only adjustment. In fact there are more Scintrex δg measurements than LCRs (table 7 and figure 5). The Scintrex solution is closer to the two references. An earlier study in the 4th ICAG came to similar conclusions [18].

2.6. *Offset of AG: O_{AG}*

Table 9 gives a comparison between g_{R05} (the relative-only result in table 3) and g_A (the individual AG measurements). Averaging the differences is one of the approaches to determine O_{AG}. The left plot is arranged in order of AG and measuring schedule; the right plot in order of station. The stars on the left of '0'(blue) illustrate the negative O_{AG} and the stars on the right of '0' (red) the positive O_{AG}, where '0' stands for position zero; '|' stands for position ±10 µGal and '#' for O_{AG} greater than ±10 µGal. As shown in the right plot, station B.090 has 15 occupations by four models of 11 AGs. If rounded to integer µGal, as shown in the table, there are six negative, two zero and seven positive O_{AGs} at station B. B is therefore the best measured station in view of accuracy and robustness. In addition, it is located in the middle of the network. For this reason, B.090 was chosen as the starting point for the relative-only adjustment. The absolute-only adjusted g at B.090 is 28 018.8 µGal which was used as the starting value. Two of the most occupied stations are B3 (16 occupations) and A2 (15 occupations) but they are occupied only by two AGs of the same model: FG5 108 and FG5 202. These are not the ideal candidates to be taken as the reference for the relative-only adjustment. From table 9, almost half of the total occupations are realized by FG5 108 and FG5 202 and both have negative O_{AG} of about −4 µGal. A2, B3 and C2 are only measured by these two AGs and their values are all below the relative-only ones, which represent the reference given by all the AGs. The AG FG5 215 measured four stations and the differences from the relative-only g are 0.3 µGal, −0.1 µGal, 1.1 µGal and −0.4 µGal with 0.2 µGal on average. The plots depict that the systematic biases, i.e. O_{AG}, are the dominant error sources in most of the AG determinations. Table 10 lists the offsets and uncertainties estimated in terms of MSE for the 19 AGs. N is the number of total occupations of an AG. The N of FG5 108 is 29, the highest value, but its MSE (±1.1 µGal) is not the lowest. Note that the absolute reference (g of B.090 = 280 18.8 µGal) is not given by a simple or weighted mean value of an AG at B.090 but by the global absolute-only adjustment taking into account the offset constraint. Therefore, although FG5 108 made so many individual determinations, it does not have such a strong influence on the absolute reference adjusted. Of the MSEs, five are smaller than 1 µGal and they are all FG5; while six are between 1 µGal and 2 µGal, for models FG5, JILA and IMGC. The IMGC is the only AG based on the symmetric free-fall principle. It made two determinations and the O_{AG} are −1.5 µGal and 0.9 µGal with 0.3 µGal on average. Reference [13] gives more rigorous O_{AG} determinations using absolute and relative combined adjustment. However, the discrepancies between different solutions are not great and all are within their uncertainties. For example, the RMS of the differences of O_{AG} given by the absolute-only and relative-only adjustments is 0.7 µGal. The MSE of the computed O_{AG} given in table 10 may be considered as the measurement uncertainty of an AG. In metrology, systematic error contributes the major part of the error budget for most of the AGs. An example is FG5 209. In tables 9 and 10, its O_{AG} and MSE are 6.8 µGal and ±0.5 µGal, respectively. The above discussion demonstrates that the Relative Gravity Campaign is very useful in that it

Table 9. Comparison of *g* (in µGal) between the relative-only adjustment and the 96 AG measurements during ICAG-2005. The left plot is arranged in order of AG and measurement schedule; the right plot in order of station.

Plot of $g_R - g_A$

-098765432101234567890+

Point	g_A	g_R	g_R-g_A	AG
A_.090	25701.9	25701.9	0.0	FG5 101
B_.090	28015.3	28018.8	3.5	N=4
B1.090	28010.6	28013.3	2.7	
B1.090	28008.5	28013.3	4.8	
A_.090	25705.6	25701.9	-3.7	FG5 108
A_.090	25705.1	25701.9	-3.2	N=29
A_.090	25705.4	25701.9	-3.5	
A_.090	25706.2	25701.9	-4.3	
A2.090	25712.0	25707.1	-4.9	
A2.090	25713.5	25707.1	-6.4	
B_.090	28025.1	28018.8	-6.3	
B_.090	28024.6	28018.8	-5.8	
B_.090	28026.1	28018.8	-7.3	
B_.090	28023.3	28018.8	-4.5	
B3.090	28006.0	28001.7	-4.3	
B3.090	28005.7	28001.7	-4.0	
B3.090	28004.8	28001.7	-3.1	
B3.090	28005.3	28001.7	-3.6	
B3.090	28005.2	28001.7	-3.5	
B3.090	28006.0	28001.7	-4.3	
B3.090	28006.0	28001.7	-4.3	
B3.090	28005.7	28001.7	-4.0	
B3.090	28005.8	28001.7	-4.1	
B3.090	28004.9	28001.7	-3.2	
B3.090	28005.0	28001.7	-3.3	
B3.090	28004.7	28001.7	-3.0	
B3.090	28004.9	28001.7	-3.2	
B3.090	28005.3	28001.7	-3.6	
B3.090	28006.4	28001.7	-4.7	
C1.090	23285.7	23281.6	-4.1	
C1.090	23284.5	23281.6	-2.9	
C2.090	32043.8	32040.3	-3.5	
C2.090	32043.5	32040.3	-3.1	
A_.090	25705.8	25701.9	-3.9	FG5 202
A_.090	25704.9	25701.9	-3.0	N=11
A2.090	25710.9	25707.1	-3.8	
A2.090	25712.0	25707.1	-4.9	
A2.090	25711.4	25707.1	-4.3	
A2.090	25711.7	25707.1	-4.6	
A2.090	25711.8	25707.1	-4.7	
A2.090	25711.3	25707.1	-4.2	
A2.090	25711.6	25707.1	-4.5	
B_.090	28022.5	28018.8	-3.7	
B3.090	28008.6	28001.7	-6.9	
A1.090	25691.7	25690.7	-1.0	FG5 206
B_.090	28019.2	28018.8	-0.4	N=3
B2.090	27997.7	27997.6	-0.1	
A_.090	25694.6	25701.9	7.3	FG5 209
B_.090	28011.7	28018.8	7.1	N=3
B5.090	28014.4	28020.5	6.1	
A_.090	25705.4	25701.9	-3.5	FG5 211
B1.090	28016.1	28013.3	-2.8	N=3
B5.090	28024.0	28020.5	-3.5	
A_.090	25701.4	25701.9	0.5	FG5 213
B2.090	27995.5	27997.6	2.1	N=3
B6.090	27998.4	27997.8	-0.6	
A1.090	25690.4	25690.7	0.3	FG5 215
B_.090	28018.9	28018.8	-0.1	N=4
B1.090	28012.2	28013.3	1.1	
B5.090	28020.9	28020.5	-0.4	
A_.090	25706.7	25701.9	-4.8	FG5 216
A1.090	25689.1	25690.7	1.6	N=3
B1.090	28015.9	28013.3	-2.6	
A_.090	25703.6	25701.9	-1.7	FG5 221
B_.090	28015.6	28018.8	3.2	N=3
B2.090	27997.1	27997.6	0.5	
A2.090	25711.2	25707.1	-4.1	FG5 224
B2.090	27996.9	27997.6	0.7	N=3
B2.090	27997.1	27997.6	0.5	
A_.090	25699.8	25701.9	2.1	FG5 228
B1.090	28009.2	28013.3	4.1	N=2
B_.090	28015.8	28018.8	3.0	JILA002
B_.090	28016.1	28018.8	2.7	N=4
B1.090	28009.8	28013.3	3.5	
B2.090	27997.8	27997.6	-0.2	
B_.090	28008.0	28018.8	10.8	JILA006
B2.090	28001.9	27997.6	-4.3	N=4
B6.090	27995.2	27997.8	2.6	
B6.090	27992.6	27997.8	5.2	
A2.090	25716.6	25707.1	-9.5	A10 008
B5.090	28026.7	28020.5	-6.2	N=5
B6.090	28004.6	27997.8	-6.8	
B6.090	28008.7	27997.8	-10.9	
C1.090	23283.8	23281.6	-2.2	
A_.090	25703.4	25701.9	-1.5	IMGC002
B_.090	28017.9	28018.8	0.9	N=2
B5.090	28017.1	28020.5	3.4	FGC 001
B5.090	28017.8	28020.5	2.7	N=3
B6.090	27988.8	27997.8	9.0	
A_.090	25709.2	25701.9	-7.3	GAB
A_.090	25708.0	25701.9	-6.1	N=3
B_.090	28021.4	28018.8	-2.6	
A_.090	25716.7	25701.9	-14.8	TBG
B2.090	27996.0	27997.6	1.6	N=4
B2.090	27988.5	27997.6	9.1	
B6.090	28011.5	27997.8	-13.6	

Plot of $g_R - g_A$

-098765432101234567890+

Point	g_A	g_R	g_R-g_A	AG
A_.090	25701.9	25701.9	0.0	FG5_101
	25705.6	N=17	-3.7	FG5_108
	25705.1		-3.2	FG5_108
	25705.4		-3.5	FG5_108
	25706.2		-4.3	FG5_108
	25705.8		-3.9	FG5_202
	25704.9		-3.0	FG5_202
	25694.6		7.3	FG5_209
	25705.4		-3.5	FG5_211
	25701.4		0.5	FG5_213
	25706.7		-4.8	FG5_216
	25703.6		-1.7	FG5_221
	25699.8		2.1	FG5_228
	25703.4		-1.5	IMGC002
	25709.2		-7.3	GAB
	25708.0		-6.1	GAB
	25716.7		-14.8	TBG
A1.090	25691.7	25690.7	-1.0	FG5_206
	25690.4	N=3	0.3	FG5_215
	25689.1		1.6	FG5_216
A2.090	25712.0	25707.1	-4.9	FG5_108
	25713.5	N=11	-6.4	FG5_108
	25710.9		-3.8	FG5_202
	25712.0		-4.9	FG5_202
	25711.4		-4.3	FG5_202
	25711.7		-4.6	FG5_202
	25711.8		-4.7	FG5_202
	25711.3		-4.2	FG5_202
	25711.6		-4.5	FG5_202
	25711.2		-4.1	FG5_224
	25716.6		-9.5	A10_008
B_.090	28015.3	28018.8	3.5	FG5_101
	28025.1	N=15	-6.3	FG5_108
	28024.6		-5.8	FG5_108
	28026.1		-7.3	FG5_108
	28023.3		-4.5	FG5_108
	28022.5		-3.7	FG5_202
	28019.2		-0.4	FG5_206
	28011.7		7.1	FG5_209
	28018.9		-0.1	FG5_215
	28015.6		3.2	FG5_221
	28015.8		3.0	JILA002
	28016.1		2.7	JILA002
	28008.0		10.8	JILA006
	28017.9		0.9	IMGC002
	28021.4		-2.6	GAB
B1.090	28010.6	28013.3	2.7	FG5_101
	28008.5	N=7	4.8	FG5_101
	28016.1		-2.8	FG5_211
	28012.2		1.1	FG5_215
	28015.9		-2.6	FG5_216
	28009.2		4.1	FG5_228
	28009.8		3.5	JIL_502
B2.090	27997.7	27997.6	-0.1	FG5_206
	27995.5	N=9	2.1	FG5_213
	27997.1		0.5	FG5_221
	27996.9		0.7	FG5_224
	27997.1		0.5	FG5_224
	27997.8		-0.2	JILA002
	28001.9		-4.3	JILA006
	27996.0		1.6	TBG
	27988.5		9.1	TBG
B3.090	28006.0	28001.7	-4.3	FG5_108
	28005.7	N=16	-4.0	FG5_108
	28004.8		-3.1	FG5_108
	28005.3		-3.6	FG5_108
	28005.2		-3.5	FG5_108
	28006.0		-4.3	FG5_108
	28006.0		-4.3	FG5_108
	28005.7		-4.0	FG5_108
	28005.8		-4.1	FG5_108
	28004.9		-3.2	FG5_108
	28005.0		-3.3	FG5_108
	28004.7		-3.0	FG5_108
	28004.9		-3.2	FG5_108
	28005.3		-3.6	FG5_108
	28006.4		-4.7	FG5_108
	28008.6		-6.9	FG5_202
B5.090	28014.4	28020.5	6.1	FG5_209
	28024.0	N=6	-3.5	FG5_211
	28020.9		-0.4	FG5_215
	28026.7		-6.2	A10_008
	28017.1		3.4	FGC_001
	28017.8		2.7	FGC_001
B6.090	27998.4	27997.8	-0.6	FG5_213
	27995.2	N=7	2.6	JILA006
	27992.6		5.2	JILA006
	28004.6		-6.8	A10_008
	28008.7		10.9	A10_008
	27988.8		9.0	FGC_001
	28011.5		13.6	TBG
C1.090	23285.7	23281.6	-4.1	FG5_108
	23284.5	N=3	-2.9	FG5_108
	23283.8		-2.2	A10_008
C2.090	32043.8	32040.3	-3.5	FG5_108
	32043.5	N=2	-3.1	FG5_108

Table 10. Offset of the 19 AGs given by the relative-only adjustment (in μGal).

AG	N	O_{AG} + MSE	Plot of O_{AG} −98765432101234567890+
FG5_101	4	2.7 ± 1.8	`|         0  *        |`
FG5_108	29	-4.1 ± 1.1	`|     *   0           |`
FG5_202	11	-4.4 ± 0.9	`|     *   0           |`
FG5_206	3	-0.5 ± 0.4	`|        *0           |`
FG5_209	3	6.8 ± 0.5	`|         0      *    |`
FG5_211	3	-3.3 ± 0.3	`|      *  0           |`
FG5_213	3	0.7 ± 1.1	`|         0*          |`
FG5_215	4	0.2 ± 0.6	`|         *           |`
FG5_216	3	-1.9 ± 2.6	`|       * 0           |`
FG5_221	3	0.7 ± 2.0	`|         0*          |`
FG5_224	3	-0.9 ± 2.2	`|        *0           |`
FG5_228	2	3.1 ± 1.0	`|         0  *        |`
JILA002	4	2.3 ± 1.5	`|         0 *         |`
JILA006	4	3.6 ± 5.4	`|         0   *       |`
A10_008	5	-7.1 ± 3.0	`|  *      0           |`
IMGC002	2	-0.3 ± 1.2	`|         *           |`
FGC_001	3	5.0 ± 2.8	`|         0    *      |`
GAB	3	-5.3 ± 2.0	`|    *    0           |`
TBG	4	-4.4 ± 9.9	`|     *   0           |`
Average		-0.4	

Table 11. Mean values of the 21 δg ties in the network (in μGal).

Tie		δg	N	RMS	RMS/$\sqrt{N}$	Max
A	A1	−11.2	49	±1.4	±0.2	
A	A2	5.2	44	±1.5	±0.2	
A	B	2316.9	11	±3.0	±0.9	
A	C2	6338.4	8	±2.6	±0.9	5.2
A	C1	−2420.3	10	±2.8	±0.9	
A1	A2	16.4	45	±1.8	±0.3	
B	B2	−21.2	28	±0.9	±0.2	
B	B3	−17.1	34	±2.4	±0.4	5.1
B	B4	−3.0	28	±2.1	±0.4	5.2
B	B5	1.7	29	±1.3	±0.2	
B	B6	−21.0	25	±1.0	±0.2	
B	C1	−4731.7	9	±2.3	±0.8	5.9
B	C2	4021.5	6	±0.8	±0.3	
B1	B2	−15.7	19	±2.5	±0.6	6.1
B1	B5	7.2	9	±1.5	±0.5	
B2	B6	0.2	11	±0.9	±0.3	
B3	B4	14.1	9	±1.6	±0.5	
B3	B6	−3.9	19	±2.5	±0.6	
B4	B5	4.7	20	±2.0	±0.4	
C1	C2	8758.7	33	±1.2	±0.2	
	Average		24	±1.8	±0.43	

gives an independent estimate or a 'truth check' for g and O_{AG}, making the ICAG result more robust.

2.7. Uncertainty estimate

This section discusses the uncertainty estimate using raw-data analysis and the results obtained above.

2.7.1. Raw-data analysis. The accuracy of δg values can be estimated using raw-data analysis by comparing the δg measured by different RGs, the triangle closures comprised by the δg measured by different RGs, and the adjusted residuals.

Table 11 gives the statistics of the δg values measured between different ties. N is the number of measurements. The tie of A–A1 has been measured 49 times. The RMS of the differences between a measured δg (a single RG δg) and the mean value varies from 0.8 μGal to 3.0 μGal with 5.1 μGal to 6.1 μGal maximum (Max column). The average is 1.8 μGal. This implies that the MSE of a single RG δg is expected to be 1.8 μGal normally and approximately 3 μGal in the worst case (1σ). The uncertainty of the mean value of N single RG δg equals RMS/$\sqrt{N}$, 0.43 μGal on average.

The relative measurement schedule was designed to enable the triangle closure ($\boldsymbol{\Delta}$) examination (figure 1). We know that the closure is defined by the sum of the three δg measurement vectors: $\boldsymbol{\Delta} = \delta g1 + \delta g2 + \delta g3$. A non-zero closure is true error. If the δg ties are independent, it is easy to estimate the uncertainty of the single RG δg: u_Δ using the closures $\boldsymbol{\Delta}$. In fact, by the MSE propagation law, the MSE of a closure can be obtained by the relation $M_\Delta^2 = M_{\delta g1}^2 + M_{\delta g2}^2 + M_{\delta g3}^2$, where $M_{\delta g}^2$ is the MSE of a δg tie. For the same RG, assuming $M_{\delta g1}^2 = M_{\delta g2}^2 = M_{\delta g3}^2 = u_\Delta^2$, we obtain $3u_\Delta^2 = M_\Delta^2$. Replacing M_Δ^2 by the average of $\boldsymbol{\Delta}_i^2$ with $i = 1, 2, 3, \ldots$, i.e. $M_\Delta \approx \mathrm{RMS}(\boldsymbol{\Delta})$, we have $u_\Delta \approx \mathrm{RMS}(\boldsymbol{\Delta})/\sqrt{3}$. However, the δg may be correlated. But, in any case, it is expected that $u_\Delta \leqslant \mathrm{RMS}(\boldsymbol{\Delta})$. Table 12 gives the triangle closure statistics of all RGs at sites A and B. Most of the $|\boldsymbol{\Delta}|$ are less than 3 μGal. A few of them are greater than 5 μGal, stemming from S193, D009 and D188. According to the survey reports, the reasons for this were that S193 had a battery failure, while D009 and D188 started the measurements immediately after long-distance transport by air and road. The RMS of all $\boldsymbol{\Delta}$ is 2.2 μGal. Therefore the triangle closure analysis implies that the MSE of a single RG δg is normally 2.2 μGal and approximately 3 μGal in the worst case. In view of the triangle closure statistics, S008, D038, S105 and G184 give the best results, with the RMS of their $\boldsymbol{\Delta}$ less than 2 μGal. This estimate is obtained under the hypothesis of a strong correlation between the measured δg and would be the worst case. The most optimistic estimate may be obtained by dividing by a factor of $\sqrt{3}$.

2.7.2. Adjusted data analysis. Analysis of the adjusted residuals and g values is discussed in sections 2.3, 2.4 and 2.5. Here we estimate the uncertainty of the vertical gradient and its influence on the final result.

We use a 2-order polynomial to approximate the g value varying as a function of height. There are three unknowns: a, b and c as given in equation (4) and table 5. They can be uniquely determined using the three g values defined at 30 cm, 60 cm and 90 cm in height. Here g was measured and adjusted in the relative-only network as a whole. Because no redundant g is available, adjustment error will be introduced in the polynomial representation. For a station where the gradient is linear, the influence of the measurement error will be limited. For a station where the non-linear gradient is very strong, we should keep in mind the reduction distance. Figure 6 displays the influences of non-linearity: $g'' - g_o$ and $g - g_o$. Here g_o

Table 12. Triangle closures of each RG (in µGal).

	Δ		Triangle closures/µGal											
			S008	S105	S028	S245	D038	S323	S424	G184	S193	D009	D188	Mean
A	A1	A2	−2.8	−0.8	−4.7	0.5	−1.8	1.9	1.2	−0.6	2.8	2.4	−1.7	−0.3
B	B1	B2	0.3	−0.9	0.1	−1.2	1.0	0.7	0.9	−0.6	0.4	8.7	2.4	1.0
B	B2	B6	−2.8	3.2	2.7	3.6	−0.7	5.7	−4.9	−0.1	−0.4	0.2	−6.7	−0.7
B	B6	B3	1.1	0.0	−4.2	−0.5	−2.3	−0.2	0.1	−1.5	1.2	−9.0	−3.5	−1.7
B	B3	B4	0.8	2.3	−0.6	−2.9	2.5	4.4	−1.7	−5.3	6.7	11.0	−0.5	−0.7
B	B4	B5	−0.6	−2.0	4.8	2.7	−0.1	4.5	2.8	−2.6	5.6	−6.4	−3.5	1.2
B	B5	B1	0.2	0.0	−6.3	4.3	0.8	−0.1	−4.1	−0.3	0.9	5.8	7.3	0.7
	Mean		−0.5	0.3	−1.2	0.9	−0.1	2.4	−0.8	−1.6	2.5	1.8	−0.9	−0.1
	RMS		1.6	1.8	4.1	2.7	1.7	2.4	2.9	1.9	2.7	7.5	4.6	1.1

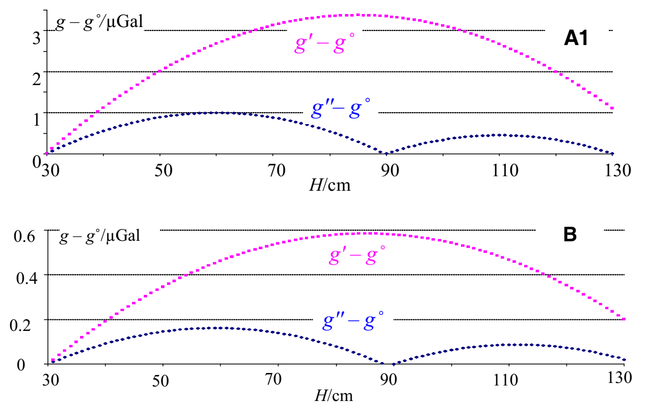

Figure 6. The vertical non-linearity of the g value variations at stations A1 and B. The x-axis is the height above ground in cm; the y-axis is $g - g_o$ in µGal; g_o is given by a, b and c in table 5; the $g = g''$ curve (below, blue) is given by the two-segment (30–90 cm and 90–130 cm) linear gradients in table 3; the $g = g'$ curve (above, pink) uses the mean value of the two-segment gradients for the reduction distance between 30 cm and 130 cm.

is computed using the polynomial coefficients a, b and c in table 5 and g'' is computed using two gradients corresponding to the two segments of 30–90 cm and 90–130 cm (table 3). g' is computed using d in table 5. d is the mean gradient between 30 cm and 130 cm obtained by averaging the two gradients of 30–90 cm and 90–130 cm in table 3. At station B, the difference of g_o and g'' is less than 0.2 µGal (lower curve in blue) and the maximum difference of g_o and g' is about 0.6 µGal (upper curve in pink); while at station A1, due to its strong non-linear variation in the vertical gradient, the corresponding differences reach a maximum of, respectively, 1 µGal and 3.2 µGal at the height of 80 cm. Taking 3.2 µGal, the non-linear disturbance in the worst case, the maximum gradient error may reach 3.2 µGal/80 cm. As pointed out in section 2.1, for most AGs and RGs, the gradient reducing distances are within 2 cm, the gradient reduction error is less than 0.1 µGal and negligible. The greatest reduction distance is 23 cm for the AG of the IMGC. The maximum error would reach 0.9 µGal if it were to occupy A1 and use the mean gradient between 30 cm and 130 cm. From table 9, the O_{AG} of the IMGC are −1.5 µGal and 0.9 µGal, average −0.3 µGal. This implies that the error in gradient should be very limited. In general, the gradient reduction error is negligible. However, from table 5, the non-linearity at site A is stronger than at site B. It is always suggested that AGs where the reference height is not close to 30 cm, 90 cm and 130 cm (for example, A10, IMGC, etc) should occupy site B stations.

2.7.3. Summary of uncertainty estimates for δg obtained in relative-only adjustment. The absolute and relative data are completely independent. The comparison between them gives the objective uncertainty estimate. d_{A05} in the last column of table 3 is the discrepancy of g values between the absolute-only and the relative-only results. The average is 0.4 µGal and the RMS is 1.0 µGal. Taking the latter as the MSE of g and considering the definition of δg, the uncertainty of an adjusted δg is about $\sqrt{1^2 + 1^2} = 1.4$ µGal on average.

As discussed above, the uncertainty of a single RG δg given by the relative-only adjustment is 2.9 µGal; given by table 7 2.0 µGal; given by the raw δg measurement analysis 1.8 µGal and by the triangle closure analysis 2.2 µGal. On average, the uncertainty of a single RG δg is 2.3 µGal. An indoor δg is measured independently at least four times, the uncertainty of the mean value of four δg measurements is then about $2.3/\sqrt{4} = 1.2$ µGal. This is the relative-only estimate, which is similar to the estimate of 1.4 µGal obtained above by comparing the differences between absolute and relative results. The results given here are those of the 1σ estimate. For the outdoor δg, the corresponding uncertainty is estimated to be slightly higher at 1.8 µGal.

3. Conclusion

In association with the 7th ICAG held at the BIPM, an accurate Relative Gravity Campaign and precision levelling were organized. The goal of the 7th RGC was to supply a metrological service to the ICAG as a BIPM key comparison, i.e. to determine the offsets of each absolute gravimeter. The BIPM gravity network and the measurement schedule were designed to best achieve this purpose. Vertical and horizontal gravity differences (δg) were measured over a network composed of 34 points.

A relative-only adjustment was carried out. Using the RGC measurement data, g was computed for each point as well as the offset for each AG and related uncertainties. The average uncertainty of a single RG δg measurement is about 2.3 µGal. The uncertainty of the adjusted δg is estimated to be about 1.5 µGal. The average discrepancy of the two RGCs performed in 2001 and 2005 is 1.5 µGal. In most cases, the vertical gradient reduction error is less than 1 µGal.

The agreement of the relative-only adjusted gravity value g and the absolute-only adjusted g is about 1 µGal. The agreement of the offsets of the absolute gravimeters is 0.7 µGal between the relative-only and absolute-only adjustments. The data of the Scintrex CG gravimeters make up the bulk of the raw-data set and they dominate the LaCoste data in the relative gravimetry adjustment. The Scintrex results are of slightly better uncertainty than the LaCoste results.

The independent validation of the absolute gravimeter results for instrumental offset determination by the strengthening of ties between sites, together with the indispensible determination of vertical gradients, justifies the efforts made in the RGC. This holds good in particular for comparisons where not all points are equally occupied by the absolute gravimeters and where the horizontal and vertical gravity gradients vary between sites.

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Disclaimer

In this paper, mention of various models of gravimeter does not imply any preference on the part of the authors for any particular model, AG or RG.

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