PRELIMINARY RESULTS OF THE BIPM RELATIVE GRAVITY MEASUREMENT CAMPAIGN DURING THE 8TH INTERNATIONAL COMPARISON OF ABSOLUTE GRAVIMETERS (2009)

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Abstract

Keywords: absolute gravimetry, relative gravimetry, ICAG, RGC, BIPM, Key comparison

The 8th International Comparison of Absolute Gravimeters (ICAG) and the accompanying Relative Gravity Campaign (RGC) were carried out at BIPM between July and October 2009. Altogether 24 institutes with 22 absolute gravimeters and 9 relative gravimeters participated in the ICAG/RGC campaigns. Accurate absolute and relative gravity measurements as well as precision levelling measurements were performed on the micro-gravity 3D-network at the Bureau International des Poids et Mesures (BIPM).

The 2009 comparison was the first one that was organized as a CIPM (Comité International des Poids et Mesures) metrological Key Comparison under the MRA (Mutual Recognition Arrangement), i.e. the result will be recognized officially by the responsible governmental organizations. In consequence, the relative gravimeters employed were carefully selected and the measurement schedules were enforced rigorously compared with the earlier comparisons. The quality of the determination of the BIPM local gravity field is improved.

We present in this paper firstly the background of the RGC and then the organization, the data treatment and the first results of the gravity and levelling measurements of the RGC 2009. By the time of preparing this paper, the final results of the ICAG 2009 is not delivered yet, the result of the RGC 2009 presented here is preliminary.

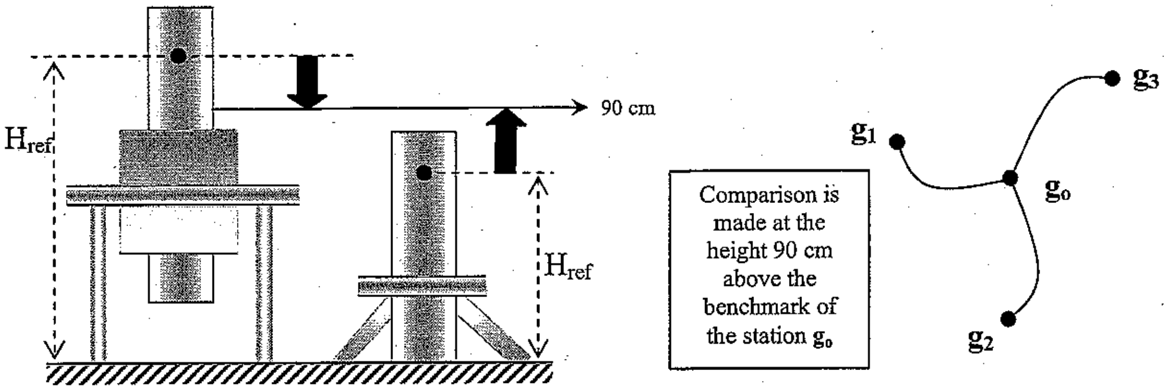
1. Introduction

The 8th International Comparison of Absolute Gravimeters (ICAG) and accompanying Relative Gravity Campaign (RGC) were carried out at BIPM between July and October 2009. The goal of the RGC, as mandated in the Technical Protocol of the ICAG 2009 [1] is: a) to support the ICAG as a CIPM key comparison (Figure 1). The 2009 comparison was the first one that was organized as a CIPM (Comité International des Poids et Mesures) metrological Key Comparison under the MRA (Mutual Recognition Arrangement) [2, 3], i.e. the result will be recognized officially by the responsible governmental organizations; b) to better know and monitor the BIPM local gravity field; c) to support the BIPM watt balance project [4]. In consequence, not as the earlier RGCs when all the voluntary participants were invited to come to BIPM to make the measurements, the relative gravimeters employed in the RGC 2009 were carefully selected and the measurement schedules were rigorously followed. The quality of the determination of the BIPM local gravity field is expected to be improved.

A steering committee (SC) was set up to take care all the technical issues of the ICAG and the RGC 2009 [1, 3]. The members of the SC were: H. Baumann from METAS, M. Becker from IPGD, O. Francis from LU, A. Germak from INRiM, V. Palinkas from RIGTC, H. Wilmes from BKG, L. Vitushkin, L. Robertsson and Z. Jiang from BIPM.

Altogether 24 institutes with 22 absolute gravimeters and 9 relative gravimeters participated in the ICAG/RGC campaigns. Accurate absolute and relative gravity measurements as well as precision levelling measurements were performed on the micro-gravity 3D-network at the BIPM.

In the following discussion in this paper, we firstly present in section 2 the network structure design and the organization of the RGC 2009 based on the uncertainty required [1] and then in section 3 the measurements, performances of the gravimeters and the preliminary results. Finally we analyse of the raw and adjusted measurement data of the RGC 2009.



AG measurements are made at different heights and different points
The RGC results brings them to a common reference to make the comparison

Fig. 1. Support the ICAG 2009, to bring the absolute g-values measured at different stations (g_1, g_2, g_3) on different heights to a same reference (g_0 at 90 cm above the ground benchmark) to make the comparisons

2. The organisation and the network of the RGC 2009

The Steering Committee held two meetings, the first was in Dec. 2008 at the BIPM and the second was in May 2009 at the Geodetic Observatory Pecny (GOP), Research Institute of Geodesy, Topography and Cartography, Czech Republic. The SC was in charge of drafting and approving the Technical Protocol (TP) of the ICAG 2009. The TP layouts all the technical details in the absolute and relative gravity measurement and data processing strategy taking into account the specifications of the CIPM Key comparison.

2.1 Participants

In the earlier RGCs, anyone could come to BIPM with his gravimeter to participate in the measurement campaigns. Limited by their time or other conditions, some of them could not perform the full and rigorous schedules. In principle, all the measured data should be used in the data processing. Due to the quality of the measurement data were not homogeneous and this may have disturbed the result of the final adjustment. It was decided by the Steering Committee that only well performed gravimeters selected and recommended by the experts would be invited. 9 relative gravimeters, among the best performing ones in Europe, from 7 organizations with experienced operators participated in the RGC 2009. Only the gravimeters that enabled an automatic digital recording were considered. Table 2.1 lists the participants, the gravimeters and the belonging institutes.

Table 2.1 Participants in RGC 2009

7 Participating organizations and Operator	9 Relative Gravimeter
Angewandte Gravimetrie, Germany: H. R. Schulz, K. U. Kessler-Schulz	ZLS Burris B025
RIGTC, Geodetic Observatory Pecny (GOP), Czech Rep.: V. Palinkas	ZLS Burris B020
BIPM, France: L. Tisserand, Z. Jiang	Scintrex CG5 S348
University of Luxembourg: O. Francis, C. Rothleitner	Scintrex CG5 S008/S010
LNE-SYRTE, France: S. Merlet	Scintrex CG5 S105
BRGM, France: P. Jousset, D. Lequin	Scintrex CG5 S028/S539
FGI, Finland: J. Mäkinen	Scintrex CG5 S053

2.2 Consideration on the network structure and the measurement schedule

Statistically, the basic requirement of the final result of the RGC 2009 is that the total uncertainty of a gravity tie should be less or equal to 1 µGal. Therefore assuming the total uncertainty of a relative measurement tie, the so called one reading tie of one meter, is δ_g and the number of the measurements is N, we should have $\delta_g/\sqrt{N} \leq 1$ µGal. Table 2.2 lists the standard uncertainty estimated in a measurement tie of a relative gravimeter. The total combined uncertainty is 3.8 µGal, i.e. if $N \geq 16$, the required standard uncertainty will be satisfied. In the design of the measurement schedule, the repeated measurement number for a relative horizontal or a vertical tie is to be no less than 16. Roughly speaking, the final reachable standard uncertainty of RGC 2009 is:

- Standard uncertainty of a gravity tie $\leq 3.8/\sqrt{16} < 1$ µGal
- Standard uncertainty of a vertical gradient ≤ 2 µGal/m

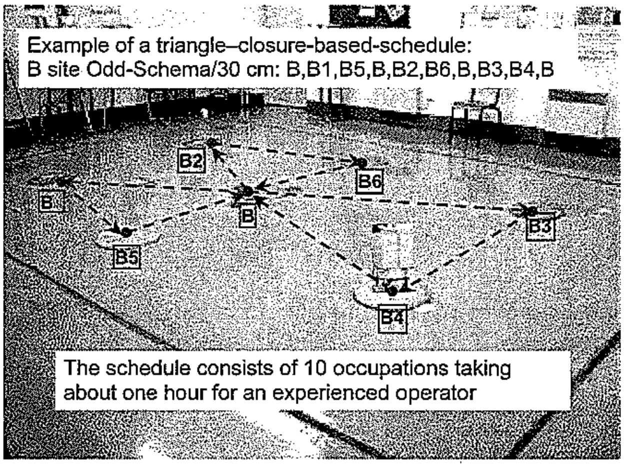
Table 2.2 Composition of the standard uncertainty of a gravity tie

Source of uncertainty	***u*** [µGal]
Resolution of gravimeter readout	1.0
Scale factor	0.5
Feedback and non-linearity	0.5
un-leveling effect	1.0
Environmental effects (e.g. Temperature)	1.5
Transport/Displacement	1.0
Atmosphere Pressure correction	0.1
Eccentricity of gravimeter sensor	1.5
Tidal corrections	0.5
Zero-drift correction	1.5
Others	2.0
Total	**3.8**

Considerations on network structure and measurement schedule:

Based on the above analysis, the following points were considered in the design of the RGC 2009 3D-grid network and the measurement schedules:

- To minimize the influence of the uncertainties due to gravimeter zero-drift, measurement set-up, displacement and environmental influences, the measurement schemes had (Figures 2.2 and 2.3):
    - triangle-closure-based sequence
    - short and symmetrical time-distance intervals
- To avoid errors due to the height measurement and the vibrations: the enforced, fixed-level tripods were used (Figures 2.4.2). 5 levels on heights of 30, 90, 130, 155 and 170 cm were measured to have a better vertical gradient polynomial fitting
- 3D grid: on and between the sites A, B, WB, horizontal ties were measured on 30, 90 and 130 cm as well as on 155 and 170 cm in height
- Measurement schedules were adapted to each gravimeter of each operator to avoid as many as possible man-made errors


Example of a triangle–closure-based-schedule:
B site Odd-Schema/30 cm: B,B1,B5,B,B2,B6,B,B3,B4,B

The schedule consists of 10 occupations taking about one hour for an experienced operator

Fig. 2.2 The 3D-grid network measuring: example of the horizontal ties at the height of 30 cm above the ground bench marks·

2.3 The RGC 2009 Network

As illustrated in Figure 2.3, the BIPM 3D-grid network is comprised of 5 Sites (A, B, C1, C2 and WB), 12 stations (A, B, B1, B2, B3, B4, B5, B6, C1, C2, W1 and W2) and 80 points. A point is a measurement setting up of 30, 90, 130, 155 and 170 cm in height above the ground benchmark.

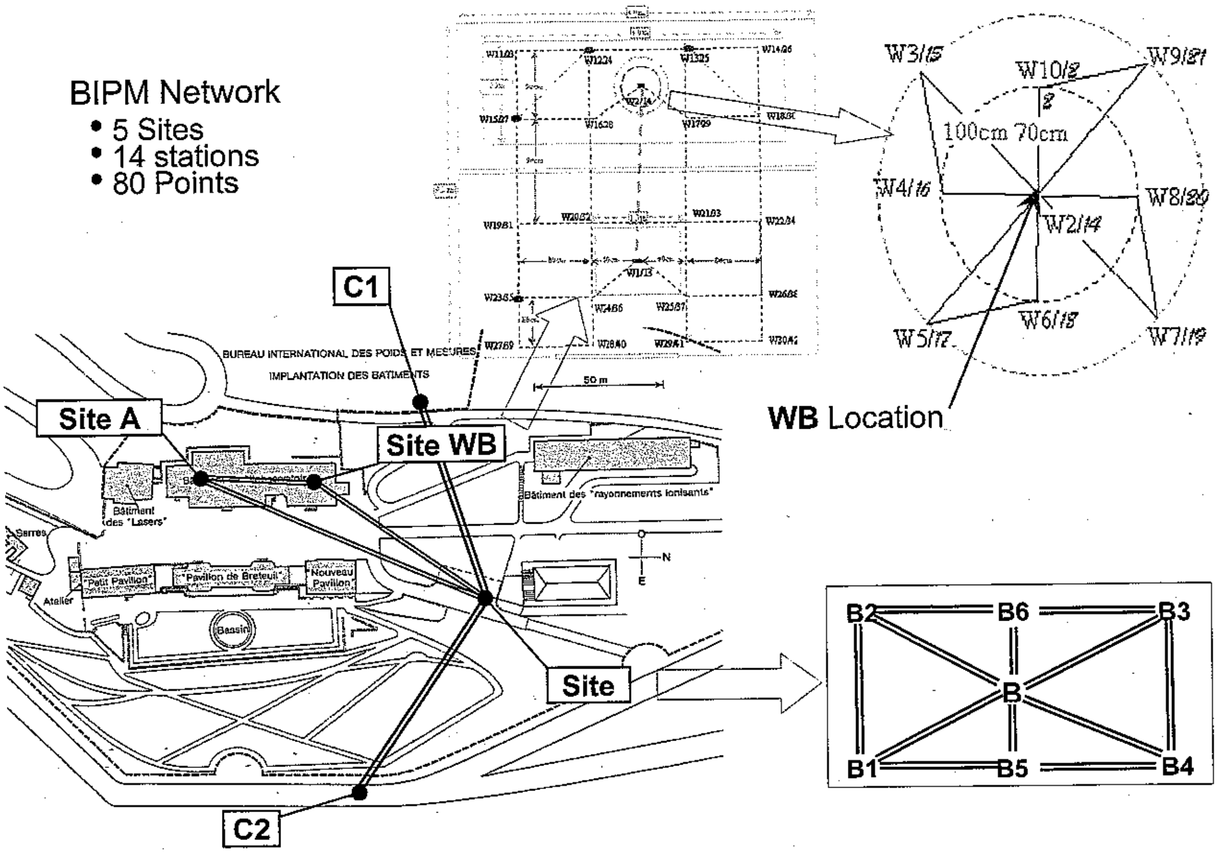
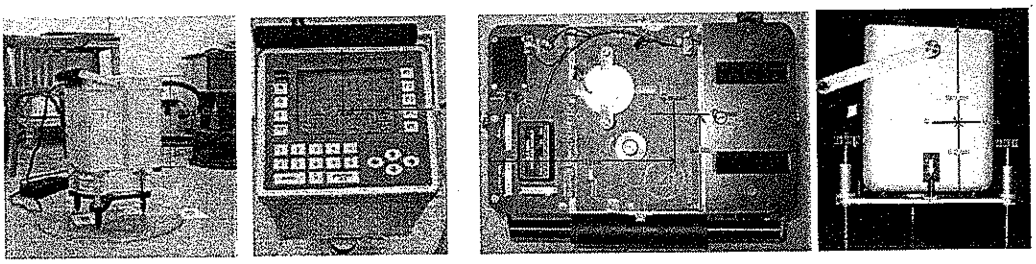


Fig. 2.3 The network of the RGC 2009 with a short baseline between C2 and C1 of 8.8 mGal absolutely determined for RG scale calibration/verification

2.4 Setup of the gravimeters and tripods

The sensor of a gravimeter is not located in its geometric centre. According to the manufactures, Figure 2.4.1 illustrates the sensors of the Scintrex CG5 and ZLS Burris. For Scintrex CG5, it is 21.1 cm below the top cover of the meter box and 11 cm from the up-edge and 11.2 cm from the right-edge on the top cover as shown in the left pictures of the Figure 2.4.1. For ZLS Burris it is 16.9 cm from the top-cover of the meter box and 9.6 cm from the bottom-edge and 15.5 cm from the left-edge on the top cover as shown in the right pictures in the figure. It is important that the gravimeter sensor coincides with the point to be measured.

The enforced BIPM level-fixed tripods with movable legs supplies a platform, by different combinations of the sub-tripods, of exactly 90 cm, 130 cm, 155 cm and 170 cm in height above the ground benchmarks. This allows a precise measurement of the vertical ties so as to calculate the vertical gradient at each station. Figure 2.4.2 illustrates a measurement setting up on the point 155 cm in height for a ZLS Burris gravimeter on the W1 station in the watt balance laboratory.



Scintrex **ZLS Burris**

Fig. 2.4.1 The Scintrex/ZLS relative gravimeters and the locations of the sensors. The gravimeter's sensor must be coincided with the point defined within mm and the orientation kept the same for each occupation

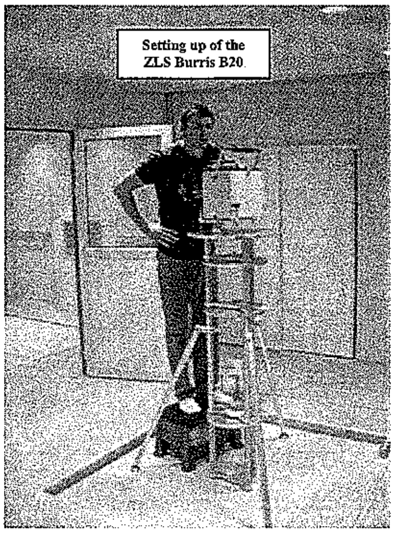


Fig. 2.4.2 Setting up of the ZLS Burris B20 with the level-fixed tripods.
Measurement at the height of 150 cm above the ground benchmark

3. Data processing of the RGC 2009

The principle of the RGC data processing strategy is given in the technical protocol of the ICAG-RGC 2009 [1] and is as same as what were used in the earlier ICAG-RGCs [5, 6]. The following discussion presents only the observation equation used in the adjustment of the RGC 2009. More details can be found in [5, 6].

3.1 Observation equation

A network adjustment using the least squares method was carried out. The adjusted unknowns are the linear scale coefficient of the gravimeters and the point gravity values. The starting g-value is that of the ICAG 2005 result at the point B.090, i.e. 90 cm above the benchmark of the station B on site B. The maximum gravity difference between the gravity points within the BIPM yard is about 10 mGal. The linear term of the scale function is enough for a relative gravimeter. Suppose the linear scale for the gravimeter q is S_q. The zero-drift and the Earth tide free readings at the points i and j are R_i and R_j, of which the corresponding adjusted gravity values are G_i and G_j. The measured relative tie is then $(R_i - R_j)_q$. The observation equation of a tie measured by the relative meter q between points i, j reads:

$$V_{ij} = S_q \times (R_i - R_j)_q - (G_i - G_j)$$

Here V_{ij} is the adjustment residual of the tie $(R_i - R_j)$. The linear scale coefficient S_q is defined with respect to the Scintrex CG5 S348 and S539, which were selected to be scale-fixed during the least squares network adjustment because their scale approximated the best to the absolute baseline C1-C2 and they performed a high quality and full schedule without data missing or outliers.

3.2 Vertical gradient

The vertical gradients were determined by using the adjusted gravity value between two points divided by their precisely known distance. A polynomial fitting was applied to approximate the gravity value variation along the vertical distance (h) above the ground benchmark. A 2nd order polynomial approach formula reads as below:

$$g(h)=a+b\times h+c\times h^2$$

As mentioned above, over each station, 3 to 5 points were measured on the heights of 30 cm, 90 cm, 130 cm, 155 cm and 170 cm. Hence the coefficients a, b and c in the above equation can be uniquely determined. Table 3.2 lists the coefficients of the 2nd order polynomial approach. Compared with the vertical gradients determined in the earlier RGCs, no significant discrepancy was found in the gradient approach on the site A and B.

Table 3.2 Results of the 2-order polynomial fitting

Stn	a	b	c
A	25982.11	-313.77	4.667
B	28288.56	-301.73	2.833
B1	28275.37	-296.70	6.000
B2	28256.38	-291.97	5.667
B3	28273.67	-304.53	4.333
B4	28291.90	-312.67	6.667
B5	28289.87	-302.27	3.417
B6	28264.56	-299.53	5.583
W1	26714.51	-269.17	0.417
W2	26635.89	-271.13	6.083

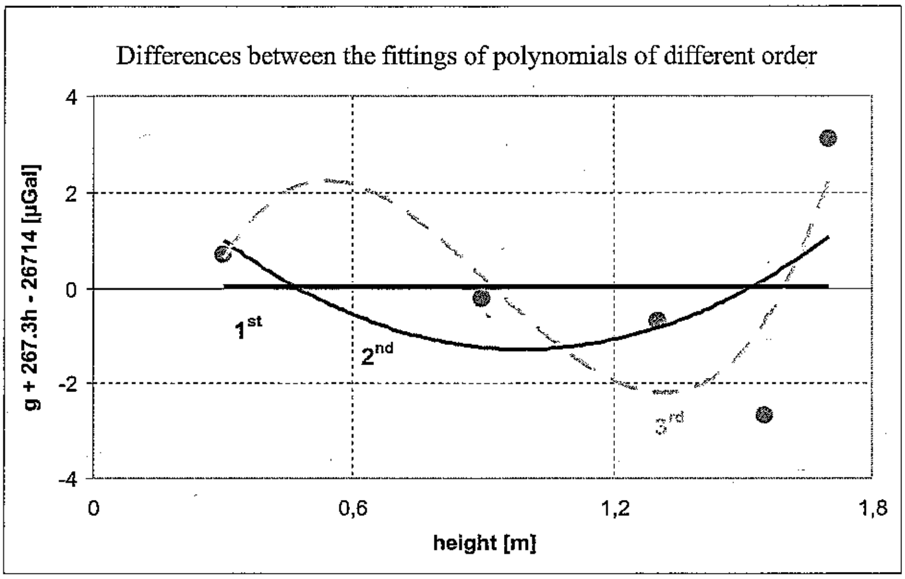


Fig. 3.2 Polynomial approaches with different orders on station W1 (unit in µGal, the x-axis is the height in m and y-axis is the g value with a linear trend removed)

The watt balance laboratory is located in the basement of the BIPM Obervatoire building which is on the foot of a hill. The existence of strong non-linearity in the gradient variations is no surprise. Higher order of the polynomial representation may be necessary to better fit the vertical gradient variations. Figure 3.2 demonstrates the effects of the high order polynomial approach to fit the 5 measurements on heights of 30 cm, 90 cm, 130 cm, 155 cm and 170 cm on the station W1. Here a linear trend $0.267.3\times h$-26714 µGal is removed from g to better show the non-linearity effect in the plot. It seems that a high order fitting gives smaller residuals and probably a better approach but it implies a lower redundancy adjustment. An optimal balance between the measurement uncertainty, weight and adjustment residual is achievable. Further investigation is in progress.

3.3 Measurement errors of a relative gravimeter given by adjusted residual analysis

The whole network was adjusted together with all 9 relative gravimeters' data. The residuals and their distribution demonstrate the noise level of the measurement of a gravimeter. Figure 3.3 displays the histograms of the adjusted residuals of the gravimeters ZLS B020 and Scintrex CG5 S539. The total number of the measured ties of ZLS B20 is 119 of which the RMS is 1.0 µGal. That of the Scintrex S539 is 143 and 1.3 µGal. These are the two best cases. Table 3.3 presents the statistics of the residuals of all the 9 gravimeters. The RMS varies from 1.0 to 2.7 µGal and on average 1.8 µGal with the total 1418 measured ties. In Table 2.2 above in the section 2.2, the total estimated uncertainty in a tie is 3.8 µGal and that the final uncertainty designed is better than or equal to 1 µGal. The residual analysis here and the following discussions prove that this basic requirement is achieved.

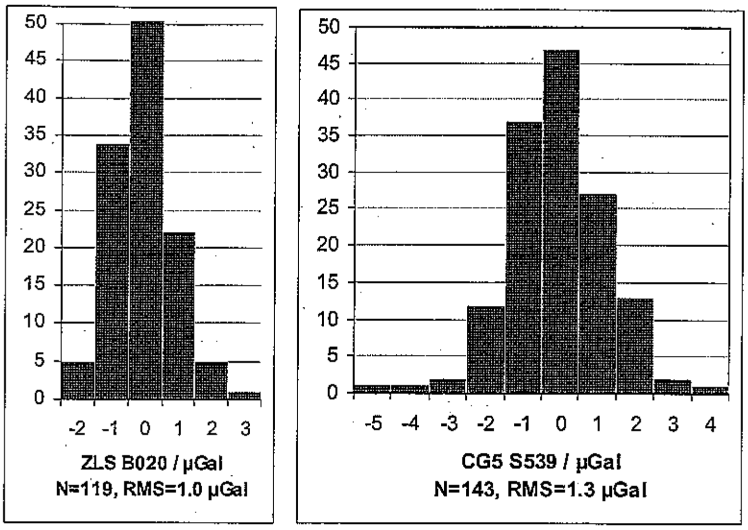


Fig. 3.3 Histograms of the adjusted residuals of the gravimeters ZLS B020 and Scintrex CG5 S539

Table 3.3 Residual statistics of gravimeters in the RGC 2009 [µGal]

gravimeter	number of ties	RMS of residuals
S008	115	2.3
S010	121	2.0
B020	119	1.0
B025	236	1.6
S028	69	2.1
S053	92	2.7
S105	211	1.7
S348	312	1.6
S539	143	1.3
ALL	1418	1.8

The two models of gravimeters ZLS and Scintrex had both a good performance and their results agreed with each other.

3.4 Raw measurement errors of a relative gravimeter by triangle closures

The measurement scheme was designed on the basis of the triangle-close measurement schedule. A non-zero-triangle-closure is considered a true error. The analysis of the amplitude of the closures of the raw measurement data provides a range of the measurement uncertainty. Table 3.4 presents the closures of the 11 triangles. The triangle closures were calculated the way that first we made the average of all the raw measurements of a tie and then made the sum the three ties which composed an independent triangle. The mean value equals 0.1 and the RMS equals 0.3 µGal. Similar as the section 3.3, this proves again the desired uncertainty of 1 µGal of a tie is achieved.

Table 3.4 Statistics of the triangle closures of the raw measurement data

#	Triangle			Closure [µGal]
1	B	B1	B2	0.2
2	B	B2	B6	0.6
3	B	B6	B3	-0.2
4	B	B3	B4	-0.2
5	B	B4	B5	-0.1
6	B	B5	B1	-0.3
7	W1	A	B	-0.4
8	W2	15	16	0.2
9	W2	21	22	-0.1
10	W2	19	20	-0.1
11	W2	17	18	0.7

3.5 Comparison of the results of absolute and relative measurements

Absolute-only (21 absolute gravimeters) and relative-only (9 relative gravimeters) measurements and data processing are completely independent. Comparison of the two results is helpful to estimate the uncertainties of both. At the time of preparing this paper, the absolute gravity values are not officially delivered and therefore confidential. The Table 3.5 lists the differences of the two sets of results and their uncertainties given by the least square adjustments. Here the decimal numbers of the *g*-values are replaced by "x". The mean value of the differences equals 0.46 µGal and the RMS equals 0.53 µGal. These two solutions agreed to each other perfectly and this implies that the uncertainties estimated and listed in the Table 3.5 are reasonable.

Table 3.5 Comparison of gravity values obtained by absolute-only and relative-only determinations

Unit in µGal (RG is relative gravimeter and AG absolute gravimeter)

No.	Stn	*g*/9RG	u	*g*/21AG	u	AG–RG
1.	B_.090	8018.x	±1.1	801x.x	±0.6	0.6
2.	B1.090	8012.x	±1.1	801x.x	±0.6	0.1
3.	B2.090	7997.x	±1.1	799x.x	±0.7	0.6
4.	B5.090	8020.x	±1.1	802x.x	±0.7	0.2
5.	B6.090	8009.x	±1.1	800x.x	±0.7	0.8

3.6 Offsets of the 21 absolute gravimeters

One of the goals of the CIPM key comparison is to determine the offsets of each absolute gravimeter. This can also be determined separately by using the data of the absolute-gravimeter-only (AG) and the relative-gravimeter-only (RG). Because at present the ICAG absolute offset result has not been officially delivered and is therefore confidential, in Figure 3.6, the absolute meter models and their instrument numbers are replaced by the sequential numbers. Only the differences of the offsets determined independently by AG-only and RG-only are displayed in the figure. The maximum difference of the offsets is 1.2 µGal. By a careful look at the figure, we notice that most of them are systematically negative. The mean value is -0.6 µGal. As mentioned above, the RG-only result was fixed to the ICAG 2005 g-value on the point 90 cm of the station B.

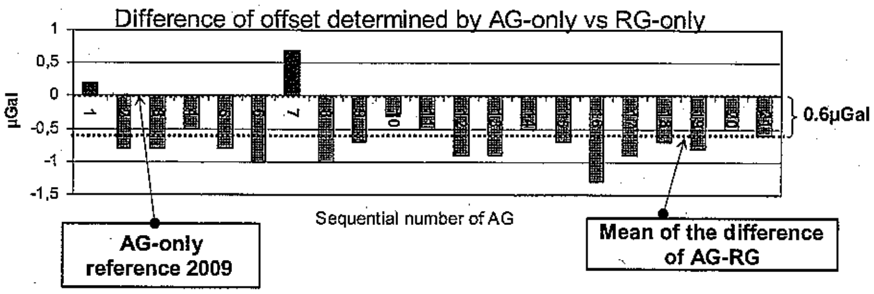


Fig. 3.6 Difference of the AG-offsets determined using the AG-only and RG-only data sets (RG and AG stand for relative and absolute gravimeters)

3.7 The preliminary results of the RGC2009

A series of least squares adjustments were carried out by changing the weightings, the outlier detection criteria, the number of meters or other parameters. Without giving all the details, table 3.7 lists the adjusted gravity difference values between the points which are defined at the height of 90 cm above the ground benchmark of the stations. As designed, the standard uncertainty of the gravity tie is about 1 µGal.

Table 3.7 The gravity differences between the points at the height of 90 cm above the network stations [μGal]

Pt	A	B	B1	B2	B3	B4	B5	B6	C1	C2	W1	W2
A	0.0	-2314.1	-2307.9	-2293.1	-2298.1	-2310.9	-2315.5	-2294.7	2424.2	-6334.0	-768.8	-693.3
B	2314.1	0.0	6.2	21.0	16.0	3.2	-1.4	19.4	4738.3	-4019.9	1545.3	1620.8
B1	2307.9	-6.2	0.0	14.8	9.8	-3.0	-7.6	13.2	4732.1	-4026.1	1539.1	1614.6
B2	2293.1	-21.0	-14.8	0.0	-5.0	-17.8	-22.4	-1.6	4717.3	-4040.9	1524.3	1599.8
B3	2298.1	-16.0	-9.8	5.0	0.0	-12.8	-17.4	3.4	4722.3	-4035.9	1529.3	1604.8
B4	2310.9	-3.2	3.0	17.8	12.8	0.0	-4.6	16.2	4735.1	-4023.1	1542.1	1617.6
B5	2315.5	1.4	7.6	22.4	17.4	4.6	0.0	20.8	4739.7	-4018.5	1546.7	1622.2
B6	2294.7	-19.4	-13.2	1.6	-3.4	-16.2	-20.8	0.0	4718.9	-4039.3	1525.9	1601.4
C1	-2424.2	-4738.3	-4732.1	-4717.3	-4722.3	-4735.1	-4739.7	-4718.9	0.0	-8758.2	-3193.0	-3117.5
C2	6334.0	4019.9	4026.1	4040.9	4035.9	4023.1	4018.5	4039.3	8758.2	0.0	5565.2	5640.7
W1	768.8	-1545.3	-1539.1	-1524.3	-1529.3	-1542.1	-1546.7	-1525.9	3193.0	-5565.2	0.0	75.5
W2	693.3	-1620.8	-1614.6	-1599.8	-1604.8	-1617.6	-1622.2	-1601.4	3117.5	-5640.7	-75.5	0.0

4. Conclusions

RGC 2009 was organised to support the ICAG 2009 which was the first CIPM metrological key comparison to further investigate the BIPM local gravity field and to backup the BIPM watt balance project. A 3D-grid network was set up by using relative and absolute gravimeters. High precision relative gravity and levelling observations were performed according to well designed measurement schedules. The RGC 2009 was the most laborious and rigorous RGC in the ICAG history. The required standard uncertainty is 1 μGal in the final adjusted gravity tie and this is achieved and proved by analysing the raw and adjusted data. The results of the RGC 2009 agree with absolute-only results both in view of the gravity values and of the offsets of the absolute gravimeters. By the time of preparing this paper, the final results of the ICAG 2009 is not delivered yet, the result of the RGC 2009 presented here is preliminary.

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COMPARISON OF NOISE LEVELS OF THE NEWEST GENERATION OF RELATIVE GRAVIMETERS

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Since the beginning of the Global Geodynamics Project in 1997, the number of superconducting gravimeters (SGs) has increased to reach about 25 operating sites today. Data from the network allow a comparison of the noise levels of the different contributing stations. Knowledge of the noise levels of each station is important in a number of studies that combine the data to determine global Earth parameters. We cite for example the stacking of the data to determine the period of the free core nutation and the Chandler wobble, and the use of the data in