Relative campaign during the International Comparison of Absolute Gravimeters ICAG-2005 and the strategy of data treatment combined with the absolute results

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Abstract

As a tradition following the first International Comparison of Absolute Gravimeters in 1981 (Becker and Groten, 1983), during the 7th International Comparison of Absolute Gravimeters (ICAG-2005) at the BIPM (Bureau International des Poids et Mesures), high precision relative gravity ties and vertical gradients were measured over the BIPM ICAG-network which includes sites with a gravity difference up to 9 mGal*. 12 institutes of 10 countries with 15 gravimeters of 6 different types were employed.

We report in this paper the organisation of the relative campaign, the raw data analysis, the relative-only measurement adjustment and the combined adjustment of the relative and absolute data. Related problems issued during the measurements and data processing are introduced.

When preparing the final version of this paper, the absolute g-values of the ICAG 2005 are not yet available (Vitushkin et al., IGFS2006). In consequence, results presented here are preliminary. The detailed analysis of adjusted g-values and gravimeter calibration etc. will be discussed in a forthcoming paper.

The relative gravimetry raw data analysis, the comparison between the relative-only adjustment and the absolute-only adjustment shows that the uncertainty of an adjusted gravity difference given by the relative campaign is of the order of 1~2 μGal, probably ±1.3 μGal, and that of the gradient is of the order of 1~2 μGal/m.

Keywords. Gravity values, gravimetry, absolute gravimeter, relative gravimeter

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* 1 Gal = 1 cm s^{-2}

1 Introduction

Since 1981, the comparisons of absolute gravimeters have been carried out every four years at the BIPM, Sèvres France. The 7th ICAG was held in 2005 at the BIPM, organised by the IAG Study Group 2.1.1 "Comparisons of Absolute Gravimeters" (SGCAG 2.1.1), the Working Group on Gravimetry of Consultative Committee on Mass (CCM WGG) and the BIPM. The steering committee of the ICAG-2005 consisted of L. Vitushkin (BIPM), M. Becker (IPGD, Germany), O. Francis (ECGS Luxemburg), A. Germak (INRIM Italy), Z. Jiang (BIPM), Wangxi Ji (NIM China). Totally 19 absolute gravimeters from 14 countries took part in the comparison. There were 7 types of absolute gravimeters made by different manufactures. As it is well known, different absolute gravimeters have different reference heights where the g-values are determined and at present the vertical gradient can not be derived from their observations with sufficient accuracy. In the recent comparisons absolute measurements are performed on multiple points to allow the determination of instrumental biases. The comparison is possible only when the gravity differences are well known. In consequence, the relative campaign is organised to measure the vertical gradients over every point and the gravity differences between the points. Traditionally, people take this change to make some special studies in relative gravimetry. This is changed since the 7th ICAG. During the 1st Joint Meeting of the CCM WGG and SGCAG 2.1.1 of the IAG on 25-26 May 2004, it was decided that the role of the relative campaign is as a service, in the sense of metrology, to the absolute gravimeter comparison. For this purpose, one of the investigations made during the ICAG2005 was the reachable uncertainty of relative measurements under the ‘laboratory’ conditions at BIPM (see below). 12 institutes of 10 countries with 15 gravimeters of 6 different types were participating in the campaign.

The organisation and the data analysis of the absolute measurements are reported by a parallel paper (Vitushkin et al., IGFS2006). We report in this paper only the relative campaign activities and the strategy of the data processing of the relative-only adjustment, the absolute-only adjustment and the combined absolute-relative adjustment. However, when preparing this paper, the absolute g-values of the ICAG 2005 have not been officially released. All results here are therefore preliminary. In consequence, a detailed analysis of the adjusted g-values and the gravimeter calibration etc. will be discussed in a forthcoming paper.

2 Optimal design of the BIPM network

The purpose of the optimal design is to look for the best reachable uncertainty of the gravity difference determination. Experiences based on the error sources’ analysis (Jiang et al. 2005) shows that the main disturbances of the relative measurement accuracy are due to calibration and the apparent zero-drift caused by: temperature change, transport vibration as well as operating errors and blunder or typing errors in gravimeter readings or instrument height measurements. The latter happens often and can be evaded by following a fixed and traceable schedule using the BIPM level-fixed tripods (Fig. 1). The first two error sources, calibration and zero-drift, can be greatly reduced with the so called quasi-zero technique, that is, small gravity difference, small distance, short, symmetric and equal time intervals with triangle-closing sequence of observations.

The BIPM ICAG-network is comprised of 12 points over 4 sites of A, B, C1 and C2 (Fig. 2). All points are precision levelling measured, absolute gravity determined and air-conditioned with maximal temperature variation of 0.5 °C. Having the gravity difference of 8.7 mGal, the new outdoor sites C1 and C2 were built in spring 2005 mainly for the relative meter calibration. The 10 indoor points, 3 over site A and 7 over site B, are used for the absolute meter comparison. Obviously, most of the comparisons are made separately within the site A or B but few between A and B. The gravity difference ties within a site (between A, A1, A2 and between B, B1 to B6) are the most favourable quantities in view of the optimal design. Most of the gravity differences are less than 10 μGal with a maximum of 23 μGal. The inter-point distances are 3 m at maximum. The average occupation takes about 3~4 minutes. All relative observations following the same scheme, over A site: A, A1, A2, A, A1, A2, A, A1, A2, and A; over B site: 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, ended at B. Each point has at least three occupations. The meters were always set up to be oriented to north. One of the advantages of the triangle-closed scheme is to better monitor the zero-drift behaviour of meter. A special program is developed to determine and reduce it. A normal drift is approximated by a polynomial while an abnormal drift (jumps for example) will be cut off into several drift periods. The outdoor ties are designed for mainly the relative meter calibration following the schedule: C1, C2, C1, B, A, B, C2, A, C1, C2 and C1.

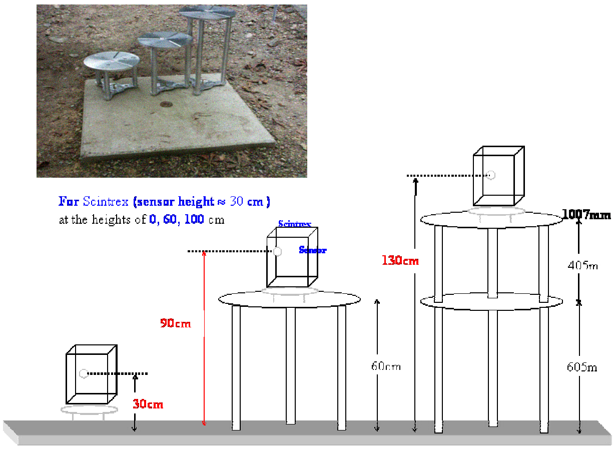

Fig. 1 The BIPM level-fixed tripods and its setting up for the gradient measurement by Scintrex CG gravimeter

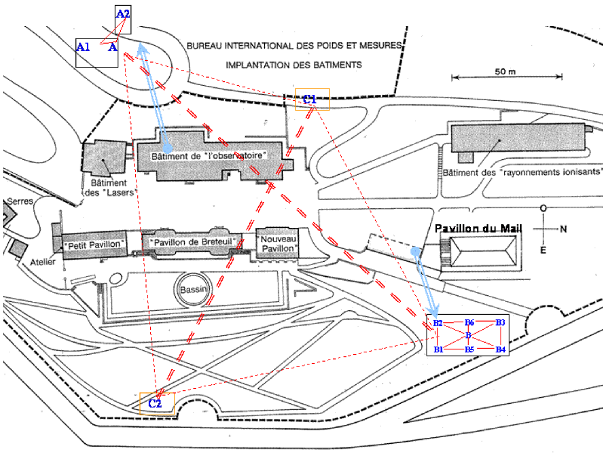

Fig.2 The BIPM ICAG horizontal network with 12 points over 4 sites: A and B indoor site, C1 and C2 outdoor

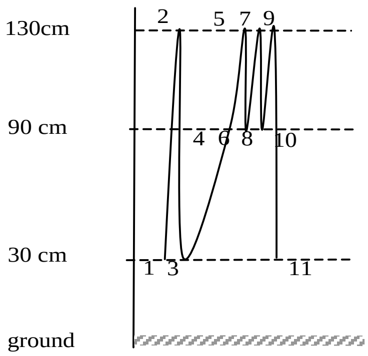

Fig. 3 The gradient measuring positions and the schedule with 11 occupations

The BIPM ICAG-network is consisting of the horizontal part and the vertical part. The comparison network is horizontally defined at 90 cm above the ground, about the average reference height of the different existing absolute gravimeter models. The vertical part serves for the gradient determination. Fig. 3 shows the gradient measuring schedule and the positions at 30, 90 and 130 cm above ground, knowing that the reference heights of all absolute gravimeters are between 30 and 130 cm. The gradient between 90 and 130 cm is strengthened due to the fact that the reference height of the most frequent absolute meter (FG5) is close to 130 cm. The BIPM level fixed tripod is designed (Fig. 1) to allow the instrument sensors of the LCR and Scintrex relative meters to be located within 1~2 cm w.r.t. the 30, 90 and 130 cm height levels above ground by different combination of the tripod towers. Slight eccentricities of the instrument sensor to the defined point (up to a few cm) are corrected by using the vertical and horizontal gradients obtained in an iteration procedure (cf. Fig. 9 and 10). The horizontal and vertical parts of the network are adjusted as a whole hence their accuracy is globally homogeneous. Over C1 and C2, only the gradient between 90 and 130 cm is measured. The gradient is approximated by a polynomial.

3 The relative gravity campaign and precision levelling measurements

The relative campaign was carried out during the 4th ~ 8th, the 24th ~ 28th July and on the 12th Sept. 2005. Totally 14 relative gravimeters from 12 institutes of 10 countries took part in it. Among them, there are 8 Scintrex (model CG-3 and CG-5) and 6 LaCoste-Romberg (model G, D and EG) as well as a ZLS model B, of which 11 meters performed the complete (or almost) measurement schedules that take about 15 to 18 hours for an experienced operator.

Tab. 1 Participants of ICAG relative campaign

Main Observers	Institute	Gravimeters
J. MRLINA	GI	LCR D188
M.RUYMBEKE, S.NASLIN	ORB	LCR G336
O. FRANCIS, M.FERRY	ECGS	CG-5 008
C.W. LEE, C.L. TSAI	ITRI	LCR EG184
P. JOUSSET F. DUPONT	BRGM	CG-3 245 CG-5 028
M. BECKER	IPGD	LCR D038
B. MEURERS	IMG	LCR D009
F. PEREIRA	SYRTE	CG-3 105
S. DEROUSSI L. METIVIER G. PAJOT	IPGP	CG-3 193 CG-3 323 CG-3 424
V. PALINKAS J. KOSTELECKY	GOP	ZLS B020
H. WILMES, R. FALK	BKG	CG-3 202
D. RUESS, M.C. ULLRICH	DMG	LCR D051

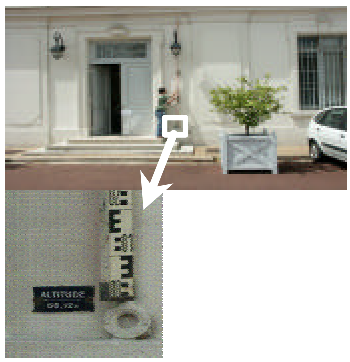

Fig. 4 The IGN69 precision levelling point served as the starting point of the height measurement

The height of the benchmarks of all the points are monitored by the repeated precision levelling carried out by BRGM of France. The reference point is the French IGN 69 levelling station located at the BIPM Observatory building (Fig. 4). The ICAG levelling measurement was performed the 6~7 July, 2005. For C1 and C2, it was the first time they were levelled. No detectable height change has been observed over the points on the sites A and B since ICAG 2001.

4 Strategy of data processing

The goal of the relative campaign is:
- Determination of gradients and *reachable* uncertainty: $dg/dh \pm U_d$: (14 relative meters)
- Determination of gravity values and *reachable* uncertainty $g \pm U_g$: (12 points with totally 34 positions at 30, 90 and 130 cm)
- Estimation of the offsets of absolute meters and their uncertainties: $d_k \pm U_d$: (N=19 absolute meters)
- Investigation of the detailed structures of the BIPM local gravity and gradient fields

Principally three different adjustments are made depending on the data introduced: the absolute-only, the relative-only and absolute-relative combined adjustment. The first two methods give the independent analysis of each data type and comparisons of them. The last gives the best estimations of the gravity values, gradient values at each point, relative meter calibration and absolute meters' offsets and their uncertainties.

The observation equations of the adjustments are described in brief as follows:

4.1 Absolute-only observation equation for meter *k* over point *i* :

$$V_i = g_{ki} - G_i + d_k$$

Offset condition: S $d_k = 0$, (k = 1, N), with
- V_i - adjustment residual
- g_{ki} - measured g value of meter *k* at point *i*
- G_i - adjusted g value at point *i*
- d_k - Offset of the meter *k* (*against the adjusted G*)
- N - Number of absolute gravimeters involved

4.2 Relative only observation equation for meter *q* between points *i* and *j*:

$$V_{qij} = s_q \times (R_{qi} - R_{qj}) - (G_i - G_j)$$

It is an unconstrained network adjustment with the absolute value of g fixed at the point B:

$$G_B = G_{B\text{-}absolute}$$

with
- V_{ij} - adjustment residual
- R_{qi}, R_{qj} - measurement reading of meter q at point *i* and *j*
- G_i, G_j - adjusted g value at points *i* and *j*
- S_q - Scale of a relative meter *q* w.r.t. a defined reference scale.

4.3 Combined Absolute and Relative observation equation with the adjusted gravity value **G** as common unknowns:

$$V_{qij} = s_q \times (R_{qi} - R_{qj}) - (G_i - G_j)$$
$$V_i = g_{ki} - G_i + d_k$$

with the Offset condition: S $d_k = 0$, (k = 1,N)

4.4 Weights in principle

Absolute observation equation (point *i* of meter *k*):

$$W_{i,k} = \mu^2_0 / (m^2_{i,k} + M^2_k)$$

Relative observation equation (the tie *j* of meter *q*):

$$w_{j,q} = \mu^2_0 / m^2_{j,q}$$

with:
- μ_0 - unit weight mean square error
- m - measurement error
- M - systematic error

4.5 The gradients

Suppose the adjusted gravity value G at a point can be approximated by a polynomial as function of the height H:

$$G(H) = a + bH + cH^2$$

Because the three positions of 30, 90 and 130 cm are measured, the coefficients *a, b, c* can be uniquely determined. The gravity difference and average gradient between H_1 and H_2 ($H_1 > H_2$) can be written:

$$dG = G(H_2) - G(H_1) = b(H_2-H_1) + c(H_2^2-H_1^2)$$
$$dG/(H_2-H_1) = b + c(H_2+H_1)$$

The gradient at height H: $dG/dH = b + 2cH$

5 Preliminary results

The results here are preliminary and may be subject to minor changes.

Fig. 5 is the histogram of the adjustment residuals of all the measured ties for the CG-5 008. The completed schedule gives 157 measured relative ties. The RMS (root of mean square) of the 157 residuals is ±1.5 μGal. This implies the most probable error of a measured gravity difference of this meter is ±1.5 μGal. For other meters, the RMS varies between 1.5 ~ 2.5 μGal. Table 2 lists the adjusted gravity differences of the combined adjustment between any two ICAG points.

```
µGal
-5| +
-4| ++                              N = 157
-3| +++++                           RMS = ±1.5 µGal
-2| ++++++++++++++++++
-1| +++++++++++++++++++++++++++++++++
 0| +++++++++++++++++++++++++++++++++++++++++++
 1| +++++++++++++++++++++++++++++++++++++
 2| ++++++++++
 3| ++++++
 4| ++
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Fig. 5 Histogram of the adjustment residuals for Scintrex CG-5 8 with observation number N=157, RMS=1.5 µGal

Fig. 6 presents the discrepancies of the two completely independent solutions. The relative solution is that of the unconstrained network adjustment with the gravity value at B fixed to the mean of the measured absolute g values and the scale is fixed to that of the CG-5 008. The maximum difference is 2 µGal at A2 with the RMS of the total differences being +/-1.3 µgal. Further investigation is required to explain the discrepancy at each point. Generally speaking, the discrepancy is within the uncertainties of the absolute and relative determinations. Here 14 absolute gravimeters out of the total 19 meters were used in this preliminary analysis. Further investigation should be made for using the results of other 5 meters.

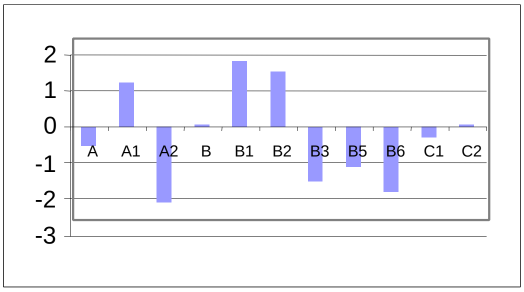

Fig. 6 Differences between the adjusted absolute-only (14 meters) and relative-only (14 meters) g values: RMS= +/-1.3 µgal (µGal, preliminary)

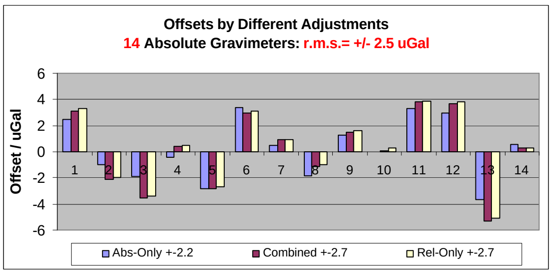

Fig. 7 Offsets of the 14 absolute meters computed by different adjustment methods (µGal, preliminary)

Fig. 7 shows the offsets of the 14 absolute gravimeters determined by the three different adjustment methods, they are close to each other and within the uncertainties. Fig. 8 gives the daily-variation of the offset of the FG5-108 belonging to BIPM. The FG5-108 followed a special schedule to occupy 6 points and 29 continuous one day-determinations (average of each full day measurements) were made in total. Further investigation is required to explain the offset determined at B point, of which the variation seems too big.

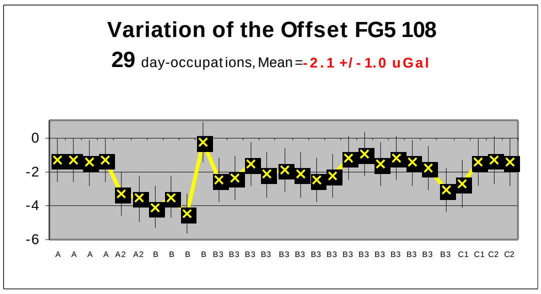

Fig. 8 Offsets of the daily-averaged gravity value by FG5-108 (µGal, preliminary)

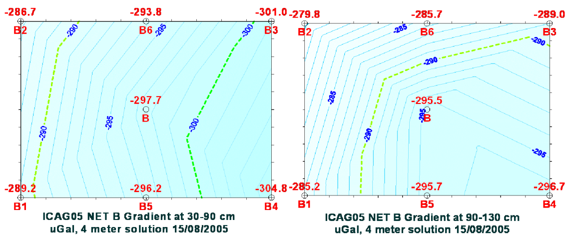

Fig. 9 B site vertical gradient between 30-90-130 cm (µGal/m, preliminary)

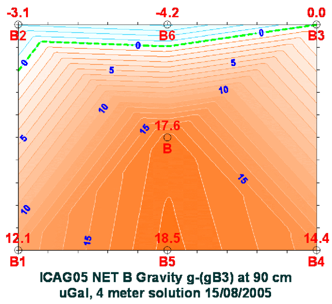

Fig. 10 Horizontal gravity variation over the B site at 90 cm w.r.t. B3 (µGal, preliminary)

Fig. 9 shows the non-linearity of the gradients between 30-90-130 cm at the 7 points over the site B, especially the points B2, B3, B4 and B6. Table 3 lists the polynomial coefficients of the gradients at the 12 points. Fig. 10 gives the horizontal gravity changes over the site B. Fig. 9 and 10 were plotted using a 4-meter solution which is slightly different to the 14-meter solution (Table 2).

Tab. 2 Gravity differences between the ICAG points at 90 cm (μGal, preliminary)

Point	A	A1	A2	B	B1	B2	B3	B4	B5	B6	C1	C2
A	0	11	-5	-2317	-2311	-2296	-2299	-2313	-2318	-2295	2420	-6338
A1	-11	0	-16	-2327	-2322	-2306	-2310	-2324	-2329	-2306	2410	-6349
A2	5	16	0	-2311	-2306	-2290	-2294	-2308	-2313	-2290	2426	-6333
B	2317	2327	2311	0	5	21	17	3	-1	21	4737	-4022
B1	2311	2322	2306	-5	0	16	12	-2	-7	16	4732	-4027
B2	2296	2306	2290	-21	-16	0	-4	-18	-22	0	4716	-4043
B3	2299	2310	2294	-17	-12	4	0	-14	-19	4	4720	-4039
B4	2313	2324	2308	-3	2	18	14	0	-5	18	4734	-4025
B5	2318	2329	2313	1	7	22	19	5	0	23	4739	-4020
B6	2295	2306	2290	-21	-16	0	-4	-18	-23	0	4716	-4043
C1	-2420	-2410	-2426	-4737	-4732	-4716	-4720	-4734	-4739	-4716	0	-8759
C2	6338	6349	6333	4022	4027	4043	4039	4025	4020	4043	8759	0

Tab. 3 Polynomial gradient coefficients and dG(gravity differences) between 90 and 130 cm (μGal/m, preliminary)

Point	a	b	c	dG/μGal
A	25983	-318	7.6	-120
A1	25975	-328	14.9	-118
A2	25989	-321	9.3	-120
B	28290	-305	4.4	-118
B1	28276	-295	3.4	-115
B2	28256	-293	6.0	-112
B3	28274	-309	7.3	-117
B4	28292	-312	6.2	-119
B5	28289	-299	1.4	-118
B6	28261	-295	3.6	-115
C1	23282	-315	-	-126
C2	32041	-287	-	-115

6. Conclusion

During the ICAG 2005, relative gravity difference and precision levelling measurements were carried out in addition to the absolute gravity determinations. An optimal design was developed for the relative campaign for the network and the scheme of observations. The uncertainty of the adjusted g-difference is of the order of 1~2 μGal, probably ± ***1.3*** μGal in the average. Consequently the uncertainty of the adjusted gravity gradient is about ± ***1.3*** μGal/m. The agreement of relative-only and absolute-only g values is about ± ***1.3*** μGal if the relative differences are referred to the mean absolute g-value; uncertainty of the g-values of the combined adjustment is about ± ***1*** μGal; the combined adjustment gives also the offset of the absolute meters with an uncertainty of about 1 μGal; the absolute g difference of ICAG 2005 to the previous comparison ICAG2001 is about ± ***1*** μGal.

Further investigation in the behaviour of each individual relative gravimeter will be discussed in a forthcoming paper after the ICAG 2005 absolute gravity values will be officially released. Only then a final statement on the benefits of a combined adjustment of absolute and relative gravity observations and the impact on offset determination, e.g. at points with few absolute occupations can be made. This will allow an assessment of the necessity of the huge efforts associated with the relative network observation scheme.

Acknowledgement

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