RESULTS OF RELATIVE GRAVIMETER MEASUREMENTS AT THE ICAG97 INTERCOMPARISON

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ABSTRACT

In Sèvres the fifth International Absolute Gravimeter Intercomparison was conducted in November 1997. In order to support the absolute measurements, the BGI Working Group 8: "Relative Networks at Absolute Gravimeter Comparison ICAG97" conducted a relative gravimeter campaign as well. Twelve LaCoste and Romberg and one Scintrex gravimeters measured the connections between absolute points and vertical gravity gradients at each point. In addition the calibration baseline installed in 1994 was re-measured as well to check or provide calibration factors for all gravimeters. The results show that the accuracy for single instruments is in the range of 3 to 8 μGal[1] for a gravity difference, for both the Scintrex and the LaCoste gravimeters. The campaign was also used to intercompare different ways of calibrating the gravimeter electrostatic feedback systems. The calibration platform of BKG, Frankfurt, was installed in Sèvres and the results can be compared to that of the calibration line. This paper gives results for the 1997 campaign.

INTRODUCTION

Since 1981, campaigns for the intercomparison of absolute gravimeters (ICAG) have been organized in Paris-Sèvres at the Bureau International des Poids et Mesures (BIPM). In support, working group 8 of the Bureau Gravimétrique International (BGI) entitled "Relative Networks at Absolute Gravimeter Comparison" was formed to conduct relative measurements for the determination of gravity differences and vertical gravity gradients between and above the pillars occupied by absolute gravimeters. These activities follow those of the former special study groups on relative gravimetry by the International Association of Geodesy and are well documented in publications, see (Becker and Groten, 1983, Boulanger et. al, 1983, Becker 1985, Becker et al. 1989, Boulanger et al, 1986, Becker et al. 1995). Generally a joint workshop is held to discuss the latest developments in instrumental design and gravimetry in general.

The 1997 intercomparison ICAG97 had quite a large number of participating groups with 7 FG5, 4 JILAG and 4 other type of gravimeters (Robertsson et al, in press). The observation strategy for the absolute instruments was changed so as to have each absolute instrument on the same two pillars in order to determine instrumental biases and also to be independent of ties measured by relative gravimeters to a certain extent. So, contrary to the previous comparisons, the absolute instruments did not observe in parallel, but sequentially. The change of strategy was thought to be necessary because of the increased accuracy and precision of the absolute instruments. However, due to time limitations, this could not be realized strictly and also points A3, A8 and L4 were used by some groups.

[1]For convenience the unit 1 μgal=$1*10^{-8}$ m/s^2 is used.

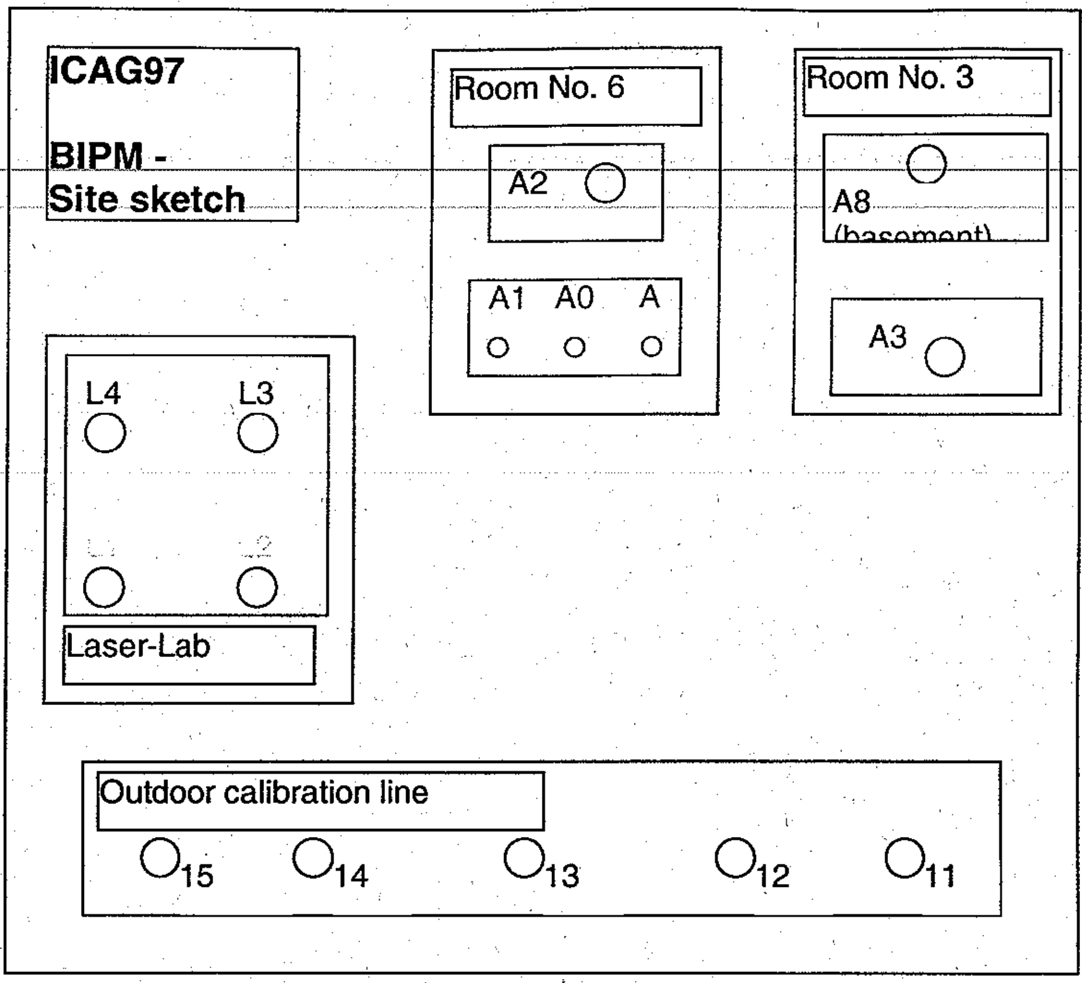

Fig. 1. Sites used for relative gravimetry in ICAG97.

The set of points chosen for relative measurements and given in the next section in detail was selected to include some points used in ICAG94 and also the outside calibration line in order to allow comparisons to previous campaigns. In order to generate data for further investigations of the calibration of relative gravimeters with feedback systems the calibration platform of BKG (Richter et al, 1995) was again installed at BIPM with some improvements as compared to 1994. The complete list of observations recorded on the platform is given in the appendix. The data is not used in this evaluation, but is available for interested people and further studies.

In addition to the relative measurements at ICAG97, O. Francis (Francis, 1998, pers. comm.) made available data of a Scintrex CG-3M microGal gravimeter S265 gathered in 1997 at BIPM. This turned out to enable the connection to some of the additional points, but on the other hand caused some problems in the combination with the LaCoste & Romberg instruments as the reference height of all levels of observation was different and no common height level was used. This led to rather large height reductions for the Scintrex and is the main reason why results for this gravimeter are given separately at its reference heights in addition to the combined adjustment where it was used as well.

THE GRAVITY NET

The majority of the relative gravimeters measured on sites 9008 (Sèvres A, not to be confused with A0 used in 1994 and labeled 108 in this paper), 9208 (A2), 9308 (A3), 949608 (L3), 949708 (L4) and the outside calibration line stations, see Fig. 1. The ties between the absolute sites were measured at a height of 0.9 m corresponding to the average value of the reference height for some absolute gravimeter measurements. Additional points were measured by the Scintrex S265 of ROB (Francis, pers. comm.).

In addition, the vertical gravity gradient, which is known to be non-linear inside the BIPM buildings, was measured between the heights of 0.05m, 0.9m and 1.3m (the latter being the reference height of the FG5 instruments). Table A1 in the appendix gives a list of instruments used.

Observations were made separately for the network ties, the gradients at each point and the calibration line. The height of the gravity sensor was brought close to the reference heights given above. However, the Scintrex CG-3M has quite a different sensor height, which is normally about 0.26 m above the floor. Therefore both network and gradient measurements had to be reduced to the reference height in an iterative procedure using the newly determined gradients at each point, the height reduction being up to 50 μGal. So a separate single adjustment for the Scintrex CG-3M was made using reference heights near the sensor heights during the measurements (0.26 m, 0.66 m and 1.56 m). These results give additional information about the local gravity field (Table 7).

	Owner-apriori		***ICAG97***		
Gravimeter	Linear	Quadratic	Linear	msd	Remarks
D028F	1.21511	-	1.21314	±0.0018	not used
D038F	-1.24440	-0.0007240	-1.18074	±0.0033	
G115F	-1.06947	-	-1.06049	±0.0014	
G258F	-1.04176	-0.0033000	-	-	not significant
S265F	1.00000	-	0.99825	±0.0005	not used
G298F	1.07527	-0.0005697	-	-	fixed
G402F	-0.01509	-	-	-	not significant
G487F	-2.93590	-	-	-	not significant
G625F	1.08248	0.0224484	1.08100	±0.0003	not used
G665F	1.01673	-	-	-	not significant
G709F	1.00793	-0.0003807	-	-	not significant

Table 1. Calibration factors of the feedback systems applied before the final combined adjustment.

Point	***Gravimeter***	***298***	***28***	***38***	***115***	***258***	***265***	***402***	***487***	***625***	***665***	***709***	***62***	***737***
No.	Name													
1	A0						13							
108	A0						3							
120	A0						3							
9000	A	6	6	7	6	6	25	5		6	3	6	6	2
9008	A	6	6	7	6	6	6	6		6	3	6	6	3
9012	A	3	3	3	3	3	6	3		2	3	2	3	
9100	A1						11							
9108	A1						3							
9112	A1						3							
9200	A2	6	6	6	6	6	11	6		3	3	5	6	2
9208	A2	7	6	6	6	6	3	6		5	3	5	6	
9212	A2	3	3	3	3	3	3	3			3	3	3	2
9300	A3	6	6	6	5	6	11	3		7		6	6	2
9308	A3	6	6	6	6	6	3	3		7	6	3	6	
9312	A3	3	3	3	3	3	3	3		3		3	3	3
9800	A8						10							
9808	A8						3							
9812	A8						3							
949600	L3	6	3	7	6	6	20		3	6	3	5	6	5
9496 8	L3	6	3	6	6	6	6			6	3	2	6	3
949612	L3	3	3	4	3	3	6		2	2	3	3	3	3
949700	L4	6	3	3		4	14			7	3	6	6	5
949708	L4	6	3	6	3	5	3			6	6	6	6	3
949712	L4	3	3			4	3			4	3	3	3	3
948011	cal. line	3	3	3	3	3	4			3	6	3	3	
948012	cal. line	3	3		2		3			3		3	3	
948013	cal. line	3	3	3	2	3	3			4		3	3	
948014	cal. line	3	2	3	2	3	3			3	2	2	3	
948015	cal. line	3	3	3	3	3	3			3	4	3	3	

Table 2. Observations from all gravimeters at each point.

ADJUSTMENT RESULTS FOR ICAG97

The basic ideas and methods of observations and data analysis are described in (Becker et al., 1995). Tidal corrections were applied using the observed factors as determined by the ROB from recordings in Sèvres. Height corrections were applied as described above so that all values refer to the reference heights.

For the determination of a uniform scale value a line observed by G298F of IFE was calibrated on the Hannover - Harz calibration line (Kanngieser et.al, 1983) after the campaign (Schmidt, pers. comm., 1998). The factor of this instrument was kept fixed in the adjustment and for all other instruments corrections to the factors given by the owners for their feedbacks were determined. Only the linear term was adjusted, the quadratic term was not changed. As can be seen in Tab. 1 for some gravimeters significant improvements could be achieved. For some other instruments there were indications of changes, however, due to the small gravity range covered and the formal errors they were considered to be non-significant and henceforth not used.

The adjustment was made based on the weights determined for single instruments and it can be clearly seen from Tab. 3, that there is a large variation in instrumental precision among the gravimeters. The errors of the adjusted gravity values are in the order of 2 to 9 µGal. This is somewhat inferior compared to the results of ICAG 94 and led to a wide range of weights.

Gravimeter	*Obs.(Raw)*	*Obs.(Adjust.)*	*msd*	*msd(dg)*	*msd(obs)*	*DoF*	*Weight*
D028F	77	77	±8.6	±10.8	±5.7	43	0.1
D038F	85	85	±9.4	±13.7	±6.7	47	0.1
D062	90	90	±2.2	±3.1	±1.5	48	not used
G115F	74	74	±4.6	±5.0	±2.6	50	0.5
G258F	85	85	±6.0	±9.0	±4.1	46	0.3
S265F	191	191	±3.3	±3.9	±1.9	134	0.9
G298F	91	91	±3.0	±4.3	±2.1	48	1.1
G402F	73	38	±6.2	±8.7	±4.4	19	0.3
G487F	33	5	±2.4	±2.4	±2.2	2	1.7
G625F	86	86	±3.3	±3.6	±1.9	57	0.9
G665F	57	57	±6.4	±6.7	±3.4	41	0.2
G709F	84	78	±5.8	±9.6	±4.3	34	0.3
G737	92	52	±4.7	±7.4	±3.6	22	not used
Combined		***867***	***±2.6***	***±2.1***	***±1.4***	***647***	-

Table 3. Statistics of single instrument adjustment, ICAG97 and weights for combined adjustment.

The final results can be taken from Tab. 3 and Tab.4. Formal error are in the order of 1-3 µGal for the adjusted gravity differences. About 900 readings were adjusted. The non –feedback instruments were not included to the combined adjustment because no information on periodic error corrections was available. Again it must be noted that the overall precision is worse than in ICAG94. As mentioned before, the Scintrex S265 is adjusted separately in addition and the results are given in Tab. 5. They refer to the approximate sensor heights of the Scintrex at each point and each height level as given in the table.

VERTICAL GRAVITY GRADIENTS

Vertical gradients can be obtained by using the gravity differences at the three different heights. Tab. 6 and 7 show the values computed by use of the results of the combined adjustment and by the Scintrex only adjustment.

Besides the well known fact that the gradient is considerably different at the different sites, a more or less systematic increase of the vertical gradient with increasing height could be determined. Up to now, function was fitted to the gradients, although a quadratic curve fit may be used for modeling. Vertical gradients converted to µGal/m are obtained with an accuracy of 1 to 3 µGal/m for the intervals from 5 to 90 and from 5 to 130 cm height, and with 2 to5 µGal/m for the interval between 90 and 130 cm. The nonlinearities in the gradient are also obvious when comparing the results of the Scintrex measured over different height-intervals to those of the combined adjustment.

Point	*Height in cm*	*Gravity values in μGal*	*Mean square deviation (msd) in μGal*
1	5	26017.0	±1.5
108	90	25737.6	±2.5
120	130	25616.2	±2.5
9000	5	26000.8	±0.9
9008	90	25734.4	±0.9
9012	130	25615.0	±1.2
9100	5	25991.3	±1.5
9108	90	25727.4	±2.5
9112	130	25612.1	±2.6
9200	5	26006.9	±0.9
9208	90	25743.3	fixed
9212	130	25625.2	±1.3
9300	5	25924.4	±1.0
9308	90	25676.9	±0.9
9312	130	25562.4	±1.4
949600	5	26884.2	±1.1
949608	90	26651.1	±1.0
949612	130	26542.8	±1.3
949700	5	26902.0	±1.2
949708	90	26669.3	±1.0
949712	130	26559.1	±1.5
9800	5	26556.4	±2.1
9808	90	26342.1	±2.9
9812	130	26244.3	±2.9
948011	5	26390.8	±1.1
948012	5	21491.2	±1.7
948013	5	27279.7	fixed
948014	5	28258.6	±1.2
948015	5	29503.5	±1.3

Table 4. Results of combined adjustment, ICAG97, 11 gravimeters, scale of G298 fixed.

Point	*Height in cm*	*Gravity values in µGal*	*Mean square deviation in µGal*
1	26	25123.5	±2.5
108	66	24997.2	±3.2
120	156	24725.8	±3.2
9000	26	25122.6	±2.6
9008	66	24996.8	±3.0
9012	156	24725.8	±3.0
9100	26	25113.5	±2.6
9108	66	24987.8	±3.3
9112	156	24718.3	±3.3
9200	26	25126.9	±2.0
9208	66	25000.0	fixed
9212	156	24731.7	±2.3
9300	26	25050.8	±2.6
9308	66	24932.8	±3.3
9312	156	24677.5	±3.3
949600	26	26013.1	±3.1
949608	66	25901.8	±3.4
949612	156	25655.4	±3.4
949700	26	26031.5	±3.1
949708	66	25923.2	±3.7
949712	156	25672.5	±3.7
9800	26	25691.9	±3.2
9808	66	25590.4	±3.8
9812	156	25368.5	±3.8
948011	26	26383.4	±3.1
948012	26	21486.5	±3.3
948013	26	27279.7	fixed
948014	26	28258.4	±3.3
948015	26	29511.5	±3.3

Table 5. Results Scintrex SC-3M 265 with reference heights near the sensor.

Point	*Gravity Difference (μGal)*		*Gravity Difference (μGal)*		*Vertical Gradient (μGal/m)*		
	dg(0.05-0.90)	*msd*	*dg(0.05-1.30)*	*msd*	*0.05 to 0.9*	*0.05 to 1.3*	*0.9 to 1.3*
1	279.5	±2.0	400.9	±2.1	328.8	320.7	303.5
9000	266.4	±0.8	385.8	±0.9	313.4	308.7	298.6
9100	263.9	±2.0	379.1	±2.1	310.5	303.3	288.1
9200	263.6	±0.9	381.7	±1.1	310.1	305.4	295.3
9300	247.4	±0.9	361.9	±1.3	291.1	289.5	286.2
949600	233.0	±0.8	341.4	±0.9	274.2	273.1	270.9
949700	232.6	±1.0	342.8	±1.1	273.7	274.3	275.5
9800	214.2	±2.0	312.0	±2.1	252.0	249.6	244.4

Table 6. Vertical gravity differences and gradients of combined adjustment.

Point	*Gravity Difference (μGal)*	*Gravity Difference (μGal)*	*Vertical Gradient (μGal/m)*		
	dg(0.26-0.66)	*dg(0.26-1.56)*	*0.26 to 0.66*	*0.26 to 1.56*	*0.66 to 1.56*
1	126.3	397.7	315.7	305.9	301.6
9000	125.8	396.8	314.5	305.2	301.1
9100	125.7	395.2	314.3	304.0	299.4
9200	126.9	395.2	317.3	304.0	298.1
9300	118.0	373.3	295.0	287.2	283.7
949600	111.3	357.7	278.2	275.2	273.8
949700	108.3	359.0	270.8	276.2	278.6
9800	101.5	323.4	253.8	248.8	246.6

Table 7. Vertical gravity differences and gradients of single adjustment of gravimeter Scintrex-CG3M (265) using reference heights near the position of the sensor.

COMPARISON TO RESULTS OF EARLIER RELATIVE MEASUREMENTS.

ICAG 94 and ICAG97 results are compared in Tab. 8. Gravity differences at the sites A0 (108) and A (9008) can not be directly compared, the difference was measured only by the Scintrex in 1997 and is therefore determined only very weakly. On the primary points of the network, the differences are in the order of 1 μGal at each height level and within the error limits of the adjustment. In the connection over the 1 mGal difference to the Laser-Lab, there seems to be a real change of about 4 to 8 μGal. The results of ICAG97 agree better with the differences determined by absolute instruments between Laser-Lab and point A. This seems to indicate a possible error in the ICAG 94 results for this difference.

The outdoor calibration line was not maintained or monumented in any way, so that larger discrepancies to 1994 occur. They are not related to a scale problem and probably due to point identification and height reference identification at some sites. Furthermore, real gravity changes may occur in the sites situated in the slopes of the hill where BIPM is located.

The gradient comparison gives quite an ambiguous picture. At some sites, like A2, A3,A8 and L3, the gradient seems to be stable. At others, like L4 and especially A0, there are large differences with respect to 1994 results. At A0, there is certainly a problem in the usage of the Scintrex data and this has to be investigated further. The gradients determined in ICAG94 for A0 and the ones determined in ICAG97 at A are rather close and fit better than those of A0 in '94 and '97. At L4, the difference occurs at the level of 90 cm and it is not clear what happened here.

CONCLUSIONS

Gravity differences and vertical gravity gradients could be determined with a formal accuracy of about 2 μGal during ICAG97 and are listed for further reference in Table 4.

Further comparisons with the results of the absolute measurements and the investigation of the larger discrepancies to 1994 have to be initiated in order to understand the errors and uncertainties in the relative measurements. The increased accuracy of absolute instruments may ask for a much

Point	*ICAG 1997*	*ICAG 1994*	*1997-1994*	*Remarks*
1	26017.0	26003.1	13.9	only Scintrex
108	25737.6	25739.3	-1.7	only Scintrex
130	25616.2	25621.5	-5.3	only Scintrex
9200	26006.9	26005.0	1.9	
9208	25743.3	25743.3	0.0	fixed
9212	25625.2	25623.9	1.3	
9300	25924.4	25926.3	-1.9	
9308	25676.9	25677.1	-0.2	
9312	25562.4	25563.3	-0.9	
949600	26884.2	26888.9	-4.7	
949608	26651.1	26656.8	-5.7	
949612	26542.8	26547.1	-4.3	
949700	26902.0	26910.5	-8.5	
949708	26669.3	26673.9	-4.6	
949712	26559.1	26564.7	-5.6	
9800	26556.4	26555.5	0.8	only Scintrex
9808	26342.1	26340.4	1.7	only Scintrex
9812	26244.3	26243.5	0.8	only Scintrex
948011	26390.8	26393.0	-2.2	
948012	21491.2	21505.6	-14.4	
948013	27279.7	27279.7	0.0	fixed
948014	28258.6	28267.9	-9.3	
948015	29503.5	29517.5	-14.0	

Table 8. Comparison to ICAG 94 (all values in μGal).

Year	dg/dh	msd	Source
1977	273	±3.0	Cannizzo et. al. ,1978
1980	273	±7.0	Sakuma
1981	284	±1.6	ICAG 81(exz.)
1981	294	±2.5	ICAG 81 (red.)
1984	275	±1.9	Ogier, 1986
1985	295	±1.2	ICAG 85
1985	296	±4.6	Ogier, 1986
1986	295	±1.2	Röder and Wenzel, 1986
1989	297	±0.7	ICAG 89
1994	293	±1.5	ICAG 94
1997	291	±1.0	ICAG 97

Table 9 Change in vertical gravity gradient at A3 in time, all values in µGal/m.

stronger effort in the relative campaigns. The concept of assembling an as large as possible number of gravimeters in order to minimize systematic errors may have to be replaced by a strategy to select a few, very well performing and very well calibrated instruments in order to get the utmost precision. Then a more comprehensive network measurement with observations at more than 3 height levels and possibly horizontal gradients at the pillars would be required to determine the complicated and nonlinear local gravity field at the BIPM to a sub-microGal level. Then relative ties will still be of value to absolute gravity determinations in future comparisons.

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Appendix:

Table A1. Observers and associated instruments

Name	*Institute*	*Gravimeter/ Instrumentation*	*Feedback -Type*
M. Becker, R. Falk, I. Nowak, B. Richter, H. Wilmes,	Bundesamt für Kartographie und Geodäsie, Germany (BKG)	Vertical Calibration Platform	
C. Gerstenecker, G. Läufer	Institut für Physikalische Geodäsie, TH Darmstadt. Germany (IPG)	LCR D038, G258	THD - Analog
J. Liard, C. Gagnon	Geodetic Survey Division, Geomatics Canada, Ottawa. Canada	LCR D028	ZLS - PWM
B. Meurers	Inst. für Metereologie und Geophysik, Univ. Vienna, Austria	LCR G-625	SRW
Stizza, J.E. Friederich	DMA Aerospace Center GGB St. Louis, SA, USA	LCR G115	LCR - Analog
M. van Ruymbeke, P. Vauterin, O. Francis	Observatoire Royal de Belgique, Dept. 1 Geodynamique, Bruxelles, Belgium (ROB)	LCR G402, LCR G-487, Scintrex CG-3M	VRL VRL Scintrex
A.G. Camacho, F.-J. Navarro	Instituto de Astronomia y Geodesia (CSIC-UCM) Madrid	LCR G665	VRL
G. Berrino, Malaspina, La Rocca, U. Riccardi	Osservatorio Vesuviano. Naples, Italy Dept. of Geophysics and Volcanology, Univ. of Naples Frederico II, Italy	LCR D-62, LCR G737	
F. Rehren, K. Schmidt, M. Schnüll	Institut für Erdmessung. Univ. Hannover, Germany (IFE)	LCR G298, G709	SRW-Extended

Table A2. Gravimeters calibrated on the calibration platform of BKG. All gravimeters were subjected to accelerations of periods T=200s, 300s, 480s, 600s, 750s, 900s and 1200s. For each period the feedback, CPI, position and time data for six full cycles were recorded.

Gravimeter	*Date of calibration*
G665	18.11.97
D136	18.11.97
D028	19.11.97
G298	19.11.97
G709	19.11.97
G115	19.11.97
G487	20.11.97
D038	20.11.97
G258	20.11.97
G625	20.11.97