Microgravimetric measurements at the 1994 International Comparison of Absolute Gravimeters

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Abstract. On the occasion of the fourth International Comparison of Absolute Gravimeters carried out at Sèvres in 1994 an extensive series of microgravimetric measurements was organized. In total, fifteen LaCoste, four Scintrex CG-3M and one Sodin gravimeter measured, within a small network, vertical gravity gradients and a calibration baseline. The results show that the accuracy for single instruments is in the range of 3 µGal to 5 µGal in gravity difference, for the Scintrex and the LaCoste meters. Data from the series were also used to intercompare different ways of calibrating the gravimeter electrostatic feedback systems. The calibration platform of the Institut für Angewandte Geodäsie, (IFAG), Frankfurt, and the calibration lift of the Observatoire Royal de Belgique (ORB) were installed at Sèvres and the results compared with those for the calibration line. This paper gives the first results and a review of the techniques used.

1. Introduction

Since 1981, the Working Group on the Intercomparison of Absolute Gravimeters of the International Gravity Commission (IGC) has organized meetings (ICAG) in Sèvres (Paris) at the Bureau International des Poids et Mesures (BIPM), at four-year intervals, for the intercomparison of different types of absolute gravimeters. In 1994, the Special Study Group on Techniques of Precise Gravimetry of the International Association of Geodesy (IAG) convened with a number of relative gravimeters to measure the differences in gravity at the absolute sites and the vertical gravity gradients at these sites [1-5]. As usual, a joint workshop was held to discuss the latest developments in instrument design and gravimetry in general.

For the 1994 intercomparison, ICAG94, requirements calling for increased accuracy were imposed on the relative measurements as more points for absolute instruments were introduced due to the large number of absolute gravimeters. The instruments were placed in two separate buildings with a gravity difference of more than 1 mGal. This means that the calibration of the relative gravimeters used had to be perfectly controlled in order to ensure that the accuracy was adequate to provide a check of the absolute gravity values. For this reason, it was decided to use only feedback gravimeters [6, 7] and to install a calibration line near the BIPM covering a range of 8 mGal.

In addition, Dr M. Van Ruymbeke of the Observatoire Royal de Belgique (ORB) and Dr B. Richter of the Institut für Angewandte Geodäsie (IFAG) in Frankfurt kindly agreed to install a calibration lift and calibration platform, respectively, at the BIPM for an additional check of the feedback calibration and the intercomparison of methods. Dr Csapó of the Eötvös Lorand Geophysical Institute (ELGI) in Budapest also made available to those interested his heavy mass calibration device, installed in a cave near Budapest.

Altogether, three different strategies of calibration were available and the data will be used to evaluate the accuracy of feedback calibration and the limitations of the methods and the instruments.

Among the equipment employed at Sèvres were quartz-spring gravimeters: one Sodin and a number of Scintrex CG-3M gravimeters of microgal* capability. These recently developed instruments are entering progressively into high-precision work due to their ease of use. In this way a direct comparison of the accuracy and precision of the two main types of gravimeter was feasible.

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* For convenience the microgal is used as the unit of acceleration: $1\ \mu\text{Gal} = 1 \times 10^{-8}\ \text{m} \cdot \text{s}^{-2}$.

2. The gravity net

As a large number of absolute gravimeters was present at ICAG94 and the BIPM FG5 absolute gravimeter is situated in the laser laboratory at the BIPM, four additional points were installed in the laser laboratory. This raised the maximum gravity difference to be measured by the relative instruments to 1 mGal. A five-point calibration line was therefore installed in the neighbourhood of the BIPM with one interval of about 4500 µGal and three intervals of 1000 µGal. In this way feedback systems with extended range (typically ± 4000 µGal to 10 000 µGal) and standard range of ± 500 µGal to 1000 µGal could both be calibrated. The site locations are shown in Appendix 1.

As no absolute measurements have yet been made at the points of the calibration line, the scale had to be transferred by well-calibrated instruments, see Section 3.

Altogether four points in the main BIPM building and two points in the laser laboratory were used during ICAG94: some additional points were measured using only one instrument. The connecting measurements between the absolute sites were measured at a height of 0,9 m, corresponding to the average value of the reference height for the absolute gravimeter measurements.

In addition, the vertical gravity gradient, which is known to be strongly nonlinear inside the BIPM buildings, was derived from measurements at heights of 0,05 m, 0,9 m and 1,3 m (the reference height of the new FG5 absolute meter). Appendix 2 lists the instruments and feedback types used.

Observations were made separately for the network connections, 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, due to the different constructions, height corrections of up to 50 µGal had to be applied by use of the best approximation to the actual gradient at each point and height. Here the Scintrex CG-3M turned out to be difficult to handle on the tripods due to its size, its weight and the height of its sensor, which is normally about 0,27 m above the floor. For this reason, gradient measurements at 1,3 m could not be carried out using this instrument.

3. Adjustment results for ICAG94

The basic ideas, and methods of observation and data analysis, are described in Becker [8] and Becker et al. [4]. Tidal corrections were applied using the observed factors as determined by the ORB from recordings at Sèvres. Height corrections were applied as described above so that all values refer to the reference heights.

The functional model used for ICAG94 and the corresponding observational equation for each gravimeter reading is as follows:

$$\begin{aligned} r_{\mathrm{g,i}} = {} & G_{\mathrm{j}} + O_{\mathrm{g,k}} + D_{\mathrm{g,p,e}}(t) + K_{\mathrm{g,m}}(Z_{\mathrm{g,i}}) \\ & + A_{\mathrm{g,n}} \sin\left(Z'_{\mathrm{g,i}} + B_{\mathrm{g,n}}\right) + F_{\mathrm{g,l}}\left(V_{\mathrm{g,i}}\right). \end{aligned}$$

$r_{\mathrm{g,i}}$	Reading i of instrument g
G_{j}	Gravity value of station j
$O_{\mathrm{g,k}}$	Common offset of a group k of readings of gravimeter g
$D_{\mathrm{g,p,e}}(t)$	Driftpolynomial of a group p of readings of gravimeter g, e = degree of polynomial, t = time of reading
$A_{\mathrm{g,n}}$, $B_{\mathrm{g,n}}$	Amplitude and phase-lag of periodic screw error n of period T_{n} of instrument g
$F_{\mathrm{g,l}}$	Polynomial of degree l for the feedback-calibration function
$V_{\mathrm{g,i}}$	Feedback voltage reading of instrument g and reading i
$K_{\mathrm{g,m}}$	Calibration function for the readings of gravimeter g, in general a polynomial of degree m
$Z'_{\mathrm{g,i}}$	$2\pi\, Z_{\mathrm{g,i}}/T_{\mathrm{n}}\, Z_{\mathrm{g,i}}$ = gravimeter counter reading i.

The number of parameters that are actually introduced to the vector of unknown parameters $x = x\,(G, O, D, A, B, F, K)$, depends on the number of observations available, the gravity range, known absolute gravity values, etc. In the case of ICAG94, as we used feedback observations only, the parameters O, D, F and G were estimated.

The adjustment was made using a robust estimation technique developed for high-precision gravimetry. By iteratively re-weighted least-squares solutions the effects of observations with large residuals are minimized. For details see [8]. In this way all original observations are included in the adjustment, but observations that result in gross errors, or are erroneous in some way, are labelled so that distortions of the parameters to be estimated are reduced.

For the determination of a uniform scale value a calibration line was observed by four instruments, two being calibrated on the Hannover line and two on the Karlsruhe line directly prior to or after the ICAG94 meeting. These two lines are based on absolute measurements and are determined independently. The uncertainty in the gravity values on the calibration line is about 2 µGal, see Table 1. The relative error of the calibration should therefore be around 0,05 %.

Results for combined and single adjustments are given in Tables 1 and 2. Due to the large number of observations the standard uncertainty is about 1 µGal for the adjusted gravity differences. Single instruments gained 2 µGal to 5 µGal for the adjusted differences. Figure 1 summarizes the comparison of single instrument versus combined adjustment. It shows that the general noise level exceeds that for a single instrument.

Most differences are in the range ± 2 µGal to 5 µGal, but a considerable number of instruments show

Table 1. Results of combined adjustment. Absolute level arbitrarily assigned to be 980 926 005,0 µGal at point 9200.

Point	Gravity values/ µGal	Mean square deviation/µGal	Name of point, height/m		Remarks
9200	26 005,00	0,00	A2	0,05	
9000	26 003,14	0,96	A0	0,05	
9300	25 926,32	1,05	A3	0,05	
9800	26 555,55	1,09	A8	0,05	
949600	26 888,87	1,05	L3	0,05	Laser laboratory
949700	26 910,45	1,07	L4	0,05	Laser laboratory
949400	26 900,17	2,74	L1	0,05	Only one instrument adjusted
949500	26 891,83	2,66	L2	0,05	Only one instrument adjusted
9008	25 739,28	1,01	A0	0,90	
9208	25 743,30	0,99	A2	0,90	
9308	25 677,06	1,09	A3	0,90	
9808	26 340,44	1,10	A8	0,90	
949608	26 656,79	1,10	L3	0,90	Laser laboratory
949708	26 673,89	1,09	L4	0,90	Laser laboratory
949408	26 663,37	4,71	L1	0,90	Only one instrument adjusted
949508	26 657,33	3,80	L2	0,90	Only one instrument adjusted
9012	25 621,53	1,37	A0	1,30	
9212	25 623,89	1,24	A2	1,30	
9312	25 563,31	1,49	A3	1,30	
9812	26 243,50	1,40	A8	1,30	
949612	26 547,12	1,44	L3	1,30	Laser laboratory
949712	26 564,70	1,38	L4	1,30	Laser laboratory
949412	26 556,63	4,51	L1	1,30	Only one instrument adjusted
949512	26 549,47	3,80	L2	1,30	Only one instrument adjusted
948011	26 392,97	1,94	BIPM11	0,05	Calibration line
948012	21 505,59	2,07	BIPM12	0,05	Calibration line
948013	27 279,74	2,02	BIPM13	0,05	Calibration line
948014	28 267,85	1,98	BIPM14	0,05	Calibration line
948015	29 517,50	2,01	BIPM15	0,05	Calibration line

Table 2. Statistics of single instrument adjustments (msd is the mean square deviation; msd(dg) is the mean square deviation of adjusted gravity differences; msd(obs) is the mean square deviation of adjusted observation; DoF is the number of degrees of freedom).

		Unforced adjustment/µGal				Fixed *g*-value/µGal		
Instrument	No. obs.	msd	msd(dg)	msd(obs)	DoF	msd	msd(obs)	DoF
LCR-D	80	3,5	3,0	1,8	68	6,6	1,9	84
LCR-D	130	3,0	3,9	1,9	78	3,3	1,6	97
LCR-D	56	3,1	3,5	1,9	35	3,2	1,1	49
LCR-D	24	4,4	9,4	4,3	9	5,5	3,8	16
LCR-G	109	6,2	5,9	3,3	78	6,7	2,0	98
LCR-G	101	5,5	4,7	2,9	73	4,0	1,9	91
LCR-G	86	4,1	5,6	2,7	50	4,0	1,8	66
LCR-G	772	3,8	4,6	2,4	42	4,0	1,8	56
LCR-G	159	4,3	3,1	1,8	129	4,7	1,2	148
LCR-G	16	4,8	3,9	2,9	10	4,7	2,0	13
LCR-G	18	5,1	3,9	2,9	12	5,3	2,1	15
LCR-G	100	3,3	4,4	2,0	62	3,7	1,6	81
SCG-3M	35	5,8	5,9	3,5	22	6,2	2,3	30
SCG-3M	46	5,7	9,2	3,3	30	6,4	2,1	41
SCG-3M	44	3,3	5,1	2,0	28	4,1	1,3	39
SCG-3M	80	4,1	3,7	2,1	58	5,1	1,7	70
Sodin	138		6,3	2,7				
Sodin	26		6,1	4,8				

larger discrepancies of up to 15 µGal. This may indicate that there are systematic effects in some instruments, in particular the presence of strong magnetic fields, which is very likely to induce errors in some of the gravimeters used.

The results in Table 1 were obtained by fitting a linear term, and, in cases where the gravity range measured on the calibration line was sufficient, a quadratic term. Changes in the factors given by the owners a priori are of order a few parts per thousand in most cases, see Table 4.

Table 2 shows the uncertainty and statistics for single instrument adjustments. In the case of the unforced adjustment, where only one gravity value is fixed, the errors show the precision and inner consistency of the instrument. This is about 3 µGal to 6 µGal for the adjusted gravity differences, as can be expected for this type of high-precision measurement. Interestingly, the Scintrex gravimeters, used for the first time in an ICAG series, do not show a significant difference in precision with respect to the LaCoste instruments.

The Sodin gravimeters used by Dr Kopaev are also comparable in precision, as can be seen from the msd of the adjusted values given in Table 2. The accuracy (fixed *g*-value adjustment) is not given because data evaluation was made in a different way. Nevertheless the differences in adjusted gravity values between Sodin instruments and the common adjustment of ICAG94 are about 3 µGal in most cases. Occasionally larger discrepancies of up to 15 µGal occur, but in most cases these are related to strong microseismic noise. The Sodin instrument, due to its lever arm construction with horizontal torsion wires in addition to the main spring, is rather sensitive to microseismic noise so cross-coupling effects of the magnitude noted above may occur. Tilt calibrations made in Moscow prior to and after ICAG94 for the two Sodin instruments agree to about 0,05 % with the values obtained on the BIPM calibration line.

The second part of Table 2 shows the results of an adjustment with all *g*-values fixed to the value obtained in the combined adjustment. The only parameters for which solutions were obtained are drift, common offset and a scale factor for each gravimeter. The uncertainties therefore represent the accuracy of each instrument. It is remarkable, and probably due to the exclusive use of feedback instruments, that for the majority of gravimeters there is almost no difference in precision and accuracy, i.e. within the individual noise level they agree to the ensemble of all meters. Some meters, which show larger discrepancies, see also Figure 1, have obviously experienced systematic errors at some of the stations.

4. Vertical gravity gradients

Vertical gradients can be computed from the gravity differences between three different heights. Table 3 shows the values computed from the results of the combined adjustment.

Besides the well-known fact that the gradient differs considerably between sites, a more or less systematic increase of the vertical gradient with increasing height was measured. Vertical gradients converted to µGal/m are obtained with an accuracy of 1 µGal/m to 3 µGal/m for the main points.

5. Calibration of electrostatic feedback systems

During ICAG94 the calibration of the feedback systems was of special interest. In the case of a microgravimetric network with gravity differences of 1 mGal or more, measurement of the calibration parameter stability is essential. One of the major objectives of the ICAG94

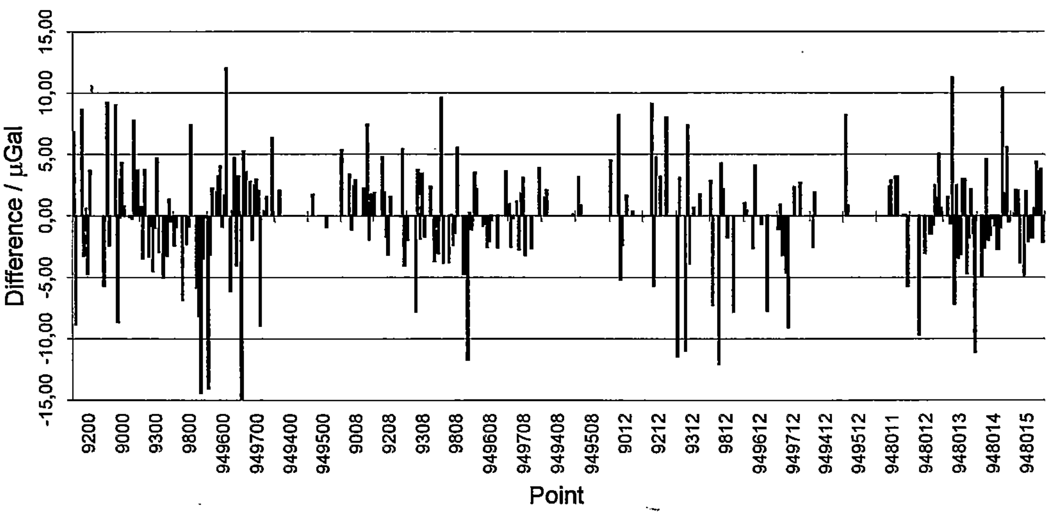

Figure 1. Comparison of combined and single instrument adjustments at ICAG94.

meeting was to compare different methods of calibration. The methods used were as follows:

(a) Calibration line adapted to the requirements of feedback instruments, see for example Kanngieser et al. [9].

(b) Heavy mass calibration device generating a well-known gravitational attraction by movement of a suspended cylindrical ring [10, 11].

(c) Calibration lift or platform producing a well-defined acceleration by a sinusoidal vertical motion of the gravimeter [12, 13].

Table 4 summarizes the advantages and problems associated with each method. A detailed analysis and intercomparison of results obtained by the three different methods and different mechanizations during ICAG94 will be the subject of a separate paper.

Table 5 lists the improvements to the calibration factors given by the owners as determined on the BIPM calibration line in combination with the network and gradient data of each gravimeter during ICAG94. They are a few parts in 10^3, which, if ignored, may introduce a significant error in the gravity differences. The correction of scale factors demonstrates the need for a frequent check of feedback scale factor stability. For closer data evaluation, the absolute values determined during ICAG94 for a scale-factor improvement will be treated in a future paper.

Table 3. Vertical gravity differences and gradients of common adjustment.

	Gravity difference/µGal		Gravity difference/µGal		Vertical gradient (µGal/m)		
Point	d*G*(0,05-0,90)	msd	d*G*(0,05-1,30)	msd	0,05 to 0,9	0,05 to 1,3	0,9 to 1,3
9200	261,70	1,00	381,11	1,00	307,89	304,88	298,50
9000	263,86	1,51	381,62	1,67	310,43	305,29	294,39
9300	249,27	1,51	363,01	1,82	293,26	290,41	284,36
9800	215,11	1,52	312,05	1,77	253,07	249,64	242,35
949600	232,07	1,52	341,75	1,78	273,03	273,40	274,18
949700	236,55	1,52	345,75	1,78	278,30	276,60	272,99
949400	236,80	5,40	343,54	5,27	278,59	274,83	266,85
949500	234,50	4,60	342,36	5,23	275,88	273,89	269,66

Table 4. Calibration methods and limitations for feedback gravimeters (typical values).

Type	Range/mGal		Accuracy/%	Advantages	Problems
Calibration line	2 to 7	1 to 5	< 0,1 to 0,01	Measurements as in field procedure	Initialization, stability, fixed location
Heavy mass calibration	0,110		< 0.1	Static gravimeter, well-defined attraction	Fixed location, small range, magnetic effects
Lift/platform	< 1		< 0,1	Portable, well-known acceleration	Movement of gravimeter, transfer function required

Table 5. Calibration factors of gravimeters determined at ICAG94.

	Original factor				ICAG94 factor				Difference
Instrument	Linear	msd	Quadratic	msd	Linear	msd	Quadratic	msd	Linear
D006	1,039 064				1,032 71	0,002 27	n.s.	n.s.	–0,006 35
D009	1,116 112		0,000 783		1,114 876	0,000 634	n.s.	n.s.	–0,001 24
D021	1,136 147		0,000 349		1,134 872	0,000 195	0,000 154	0,000 159	–0,001 28
D038	–1,24 115		0,000 724		–1,244 40	0,002 225	–0,003 25	0,001 49	–0,003 25
D126	–46,652	0,1	(µGal/kHz)		–46,535	0,065	n.s.	n.s.	0,117
D136	–0,161 2	(unfiltered)	0,157 5	(filtered)	–0,163 9	0,002 8 (unfiltered output)			0,002 7
G115	–1,056 4				–1,055 4	0,001 1	n.s.	n.s.	0,001
G126	–1,073 95				-1,071 13	0,001 9	n.s.	n.s.	0,002 825
G156	1,071 917	0,000 201	0,006 607	0,000 09	fixed				
G249	1,068 822	0,000 292	0,000 180	0,000 15	fixed				
G258	–1,035 32		0,005 55		–1,041 76	0,001 016	0,003 997	0,001 337	–0,006 45
G298	1,073 58		0,000 63		fixed				
G709	1,001 833		0,000 341		fixed				
G1919	1,180 185				1,186 794	0,001 416	0,000 15	0,000 316	–0,002 18
S112	1				1,000 314	0,000 59			0,000 314
S193	1				0,998 88	0,000 65			–0,001 12
S2136	1				0,997 2	0,000 43			–0,002 8
S233	1				0,997 41	0,000 4			–0,002 59

6. Comparison with results of earlier relative measurements

Röder and Wenzel [14] give a summary of previous results at the BIPM: here these values are used and updated with the latest data. For gravity differences, only sites A0 and A3 can be compared, see Table 6.

It appears that when the uncertainties of the adjusted values are considered, there has been no significant change in the difference A0 to A3 since 1981. The same holds true for the vertical gradient if the different epochs since 1977 are compared, see Table 7. If the eccentricity as determined by Röder and Wenzel [14] is taken into account, and the observations of Ogier [15] are disregarded, the standard deviation of the six values since 1981 is 1,4 µGal/m only.

When comparing these results, it looks as if both the gravity difference between BIPM A0 and BIPM A3, and the vertical gradient at A3, have been stable since 1981. Between 1978 and 1981 the gravity at A0 changed due to the construction of the laser laboratory at the BIPM [14]. The staff of the BIPM are carrying out additional studies of gravity variations and the results of repeated measurements.

Table 6. Change in gravity difference A0 – A3 over time.

Year	dg/µGal	msd/µGal	Source
1976	–90,1	7	Cannizzo et al., 1977
1977	–90,6	0,6	Marson
1978	–91	7	Poitevin
1981	–79,6	1,5	ICAG81(exz.)
1981	–72	1,9	ICAG81(red.)
1985	– 70,6	0,4	ICAG85
1986	–68,2	0,6	Röder/Wenzel, 1986
1989	–73,4	2,2	ICAG89
1994	–77,1	2,5	ICAG94

Table 7. Change in vertical gravity gradient at A3 over time.

Year	dg/dh/(µGal/m)	msd/(µGal/m)	Source
1977	273	3	Cannizo et al., 1977
1980	273	7	Sakuma
1981	284	1,6	ICAG81 (exz.)
1981	294	2,5	ICAG81 (red.)
1984	275	1,9	Ogier, 1986
1985	295	1,2	ICAG85
1985	296	4,6	Ogier, 1986
1986	295	1,2	Röder/Wenzel, 1986
1989	297	0,7	ICAG89
1994	293	1,5	ICAG94

7. Conclusions

Gravity differences and vertical gravity gradients could be determined with an uncertainty of about 2 µGal during ICAG94. The use of Scintrex quartz spring gravimeters in addition to the feedback LaCoste meters improved the reliability of the results. The Scintrex CG-3M turned out to be of a precision comparable to a regular LaCoste meter. This is corroborated in other investigations using this device, see for example Falk [16] and Liard et al. [17].

The calibration line established at the BIPM during ICAG94 has allowed an improved determination of scale factors for all gravimeters.

Due to the large number of gravimeters used, and considering the accuracy of the absolute gravimeters, the use of relative gravimetry to connect the absolute sites is still a valuable tool. Furthermore, due to the need for relative measurements in connection with absolute g-determinations, e.g. for gradients, for excenters, etc., studies of how to improve relative meters are required. This is even more important as the accuracy of the absolute meters also increases and makes greater demands on relative gravimetry. Systematic errors identified in some instruments at ICAG94 have to be studied with a view to eliminating them in the future.

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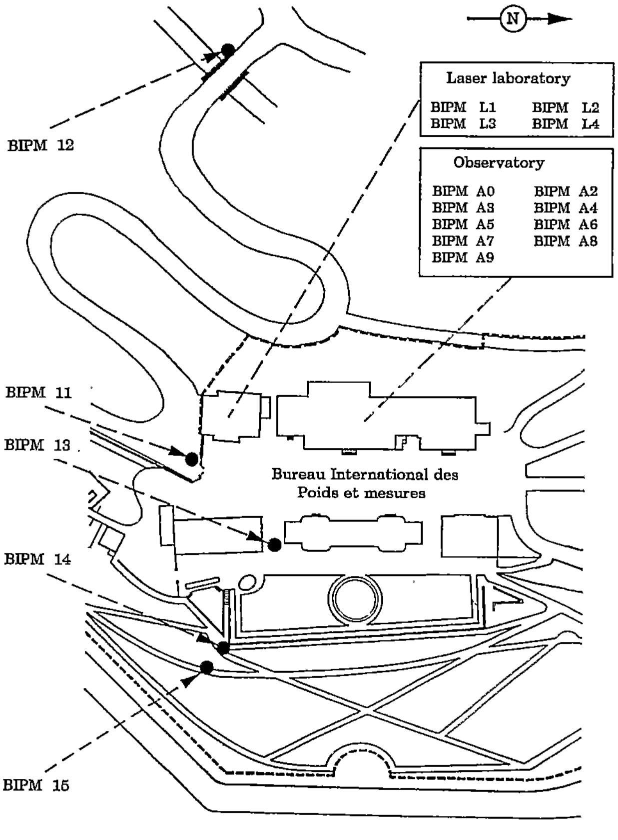
Appendix 1. Calibration line and location of points at the BIPM.



Appendix 2. Observers and associated instruments.

Name	Institute	Gravimeter	Feedback-Type
L. Balestri, M. Zucchi	Osservatorio Geofisico dell Universita, Modena, Italy	Scintrex CG-3M 112	Scintrex
M. Becker, A. Lothammer, I. Nowak, B. Richter, H. Wilmes	Institut für Angewandte Geodäsie, Frankfurt, Germany	LCR D021	SRW-extended
G. Berrino, M. D'Errico	Osservatorio Vesuviano, Naples, Italy	LCR D126 LCR D136	MVR-PWM LCR-analogue
G. Csapó, G. Szatmári	Eötvös Lorand Geophysical Institute, Budapest, Hungary	LCR G1919	ELGI-analogue
M. Diament, S. Bonvalot, P. Jousset	Institute de Physique du Globe, Gravimétrie et Geodynamique, Paris, France	Scintrex CG-3M 91110193 and 2136	Scintrex Scintrex
C. Gerstenecker	Institut für Physikalische Geodäsie, TH Darmstadt, Germany	LCR D038, G258	THD-analogue
J. Liard, C. Gagnon	Geophysical Division, Geological Survey of Canada, Ottawa, Canada	LCR D006 LCR D028	GSC-PWM ZLS-PWM
A. Kopaev	Astronomical Institute, Moscow University, Moscow, Russia	Sodin 312 (February) Sodin 313 (June)	—
B. Meurers	Institut für Meteologie und Geophysik, University of Vienna, Austria	LCR D009	SRW-analogue
S. Nakai	National Astronomical Observatory, Mizusawa, Japan	Scintrex CG-3M 233	Scintrex
W. Spita, R. Bartell	DMA Aerospace Center, GGB St Louis, USA	LCR G115, G126	LCR-analogue
M. Van Ruymbeke, A. Somerhausen	Observatoire Royal de Belgique, Dept. 1 Geodynamique, Brussels, Belgium	LCR G487	VRL
F. Rehren, M. Schnüll	Institut für Erdmessung, University of Hannover, Germany	LCR G298, G709	SRW-extended
H.-G. Wenzel, W. Zürn	Geodätisches Institut, University of Karlsruhe, Germany	LCR G156, G249	SRW-analogue

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