metrologia

Performance of two Scintrex CG3M instruments at the fourth International Comparison of Absolute Gravimeters

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Abstract. Two Scintrex CG3M gravimeters were calibrated and compared with other relative meters (LaCoste-Romberg and Scintrex meters) at the fourth International Comparison of Absolute Gravimeters at Sèvres, France (30 May to 2 June 1994). LaCoste-Romberg meters were used as reference. Three main experiments were carried out at the Bureau International des Poids et Mesures. First, a calibration of the two Scintrex CG3M meters on a new baseline of five points, spanning a range of about 8 mGal. It is shown that both Scintrex meters provide results similar to within 0,005 mGal, even in noisy places, and that Scintrex results are similar to those of LaCoste-Romberg instruments to within an accuracy better than 0,010 mGal. Second, measurements of vertical gradient at four points were carried out. The results for the Scintrex meters lie within 0,007 mGal/m and are similar to those of LaCoste-Romberg meters to within an accuracy of around 0,010 mGal/m. Third, a series of continuous records (each of about 10 minutes) was carried out with three LaCoste-Romberg and the Scintrex meters at four adjacent points. A repeatability of better than 0,005 mGal was obtained for one Scintrex meter. There is a difference of 0,010 mGal with LaCoste-Romberg data. These results confirm that the Scintrex meter is suitable for measuring small gravity differences, similar to those observed on active volcanoes.

1. Introduction

In the framework of the International Comparison of Absolute Gravimeters and of the relative gravimeter feedback calibration, we compare the results of two Scintrex CG3-M relative meters, fully electronic, with those of LaCoste-Romberg relative meters. The aim of this study is to check whether the results obtained with the Scintrex meters 9002136 (belonging to ORSTOM, shipped in November 1990) and 9110193 (belonging to IPGP, shipped in November 1992) are comparable with those of LaCoste-Romberg meters. Three experiments were carried out at the Bureau International des Poids et Mesures (BIPM), Sèvres, France:

(a) calibration of the meters on a newly designed baseline with fourteen LaCoste-Romberg results;
(b) measurement of vertical gradients at four absolute gravity points;
(c) detection of small spatial gravity variations and comparison of the repeatability of measurements from the Scintrex meters with those of three other LaCoste-Romberg meters. The method consists in recording Earth tides during a series of about ten minute steps on a small network of four absolute points, with a distance of less than 2 m between them.

For convenience, we use the mGal (1 mGal = 10^{-5} m · s^{-2}) as the unit of measurement throughout the paper.

2. Setup of Scintrex CG3M meters

Before carrying out measurements, the Automated Scintrex CG3M meter requires some software adjustments, as advised by Scintrex Ltd [1].

2.1 Gravity readings

Each gravity reading consists of an automatic average of samples (we usually choose sixty) with a fixed acquisition interval of 1 s. For each sample, the standard

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deviation of the running average is computed by the meter software. A rejection criterion is applied which allows filtering of very noisy samples, those which are more than four times the standard deviation. The uncertainty, $s(\overline{q})$, of the mean, $\overline{q}$, of the experimental readings is related to the experimental standard deviation, $s(q_k)$, of the n samples by:

$$s(\overline{q}) = n^{-1/2} \cdot s(q_k), \qquad (1)$$

where n is the number of the non-rejected samples (less or equal to sixty), and $s(qn)$ is the standard deviation of the mean $\overline{q}$.

2.2 *Tilt compensation*

Before beginning the measurements we checked the tilt meter compensation of the Scintrex meters according to the Scintrex user's manual [1]. The error introduced in records by possible unadjusted levelling within the range –10 arc second to 10 arc second (i.e. –50 μrad to 50 μrad) is thus much less than 0,001 mGal.

2.3 *Earth Tide Correction (ETC)*

Recorded values are corrected for Earth tides. The Earth Tide Correction (ETC) is calculated by the meter software using the Longman algorithm [2] for which one input is the location at which the measurements are carried out.

2.4 *Drift correction*

The Scintrex software allows the correction of a gravity reading for a linear drift computed from previous continuous temporal series. However, there is often a discrepancy between the actual and the estimated drift of the meter. For this study, neither Scintrex meter was automatically corrected (correction constant fixed at zero) to get an idea of the actual drift of the spring. A linear drift was computed later, during data processing, by a least-squares adjustment through the observed data.

3. Baseline calibration of two Scintrex CG3M meters

3.1 *Data acquisition*

We used five new points, especially chosen for calibration of relative meters [3, 4]. The baseline range is about 8 mGal. We included some of the absolute points available at the BIPM for providing a future absolute control of the baseline. The height of the gravimeter above ground at each station was measured so as to remove the effect of variation in the height of the sensor. Tables 1 and 2 give the main characteristics of the field procedure for the Scintrex meters 9002136 and 9110193.

The experimental standard deviation of the mean of the sixty samples at each baseline point is less than 0,005 mGal, for both meters. The error is low, thanks to the rejection of bad values by the meter software. Data rejection is higher for point 12, because of higher noise from passing traffic.

3.2 *Data processing*

We apply the following method for data calibration:
(a) application of accurate tide correction;
(b) height reduction to a common reference level (ground, using vertical gradient);
(c) drift computation and correction;
(d) linear regression with reference values (data from fourteen LaCoste-Romberg meters) to get the calibration scale factor and finally computation of calibrated Scintrex records.

3.2.1 *Accurate tide correction*

The algorithm of Longman [2] is not sufficiently accurate for our purposes. Indeed, the difference between accurate tides based on the Cartwright and Tayler computation [5] and the Scintrex software ETC is as high as 0,004 mGal, during our field work. We thus first remove the ETC value and then apply an accurate correction, based on the algorithm of Cartwright and Tayler [5].

3.2.2 *Height reduction: effect of vertical gradient*

Between two measurements, the levelling of the meters may cause variation in height of up to 0,038 m because of the screw range. This results in a variation which may cause an error of about 0,012 mGal. At baseline points, the observed height maximum difference is around 0,028 m. As we did not measure vertical gradient, we applied the value 0,295 mGal/m according to Becker [3, 4] and calculated the gravity value at ground. We supposed that the error introduced by a difference between actual and common gradient values is negligible at Sèvres. This hypothesis requires that the vertical gradient should not differ from one point to another by more than 0,03 mGal/m.

3.2.3 *Linear drift*

We compute here the instrumental drift using stations where two or more sets of measurements were carried out. For example, for station 11, we plot (Figure 1) the

Table 1. Field procedure of the calibration line for the Scintrex 9002136 meter.

Baseline point number	Universal Time*	Gravimeter to ground height/m	Internal temperature /mK	Remarks Scintrex 9002136
Base L3	13:14 to 13:18	?	0,38	Many people inside the room
948011	13:29 to 13:31	0,490	0,33	Measure at 0,22 m from the wall
948012	13:42 to 13:44	0,483	0,40	Many cars
948011	13:52 to 13:54	0,489	0,36	
948014	14:02 to 14:05	0,508	0,36	Measure at 0,10 m from the wall
948015	14:20 to 14:24	?	0,40	Measure at 0,27 m from the wall
948014	14:31 to 14:33	0,511	0,33	
948013	14:40 to 14:42	0,498	0,32	Measure at 0,11 m from the second step
Base A3	14:49 to 14:51	0,500	0,35	
948011	14:56 to 14:58	0,495	0,33	

Table 2. Field procedure of the calibration line for the Scintrex 9110193 meter.

Baseline point number	Universal Time*	Gravimeter to ground height/m	Internal temperature /mK	Remarks Scintrex 9110193
Base A1	15:36 to 15:39	0,489	0,06	
948011	15:45 to 15:50	0,487	0,06	Measure at 0,22 m from the wall
948012	15:58 to 16:01	0,489	0,12	Many cars
948011	16:10 to 16:12	0,486	0,11	
948014	16:17 to 16:19	0,506	0,10	Measure at 0,10 m from the wall
948015	16:25 to 16:28	0,494	0,07	Measure at 0,27 m from the wall
948014	16:34 to 16:36	?	0,00	
948013	16:42 to 16:45	0,487	-0,03	Measure at 0,11 m from the second step
948011	16:51 to 16:53	0,487	-0,03	
Base L3	16:59 to 17:01	0,485	-0,01	

differences between two successive measurements at the same station as a function of the time between the two measurements. We obtain a regression value of (0,332 ± 0,075) mGal/day for meter 9002136 and (0,701 ± 0,043) mGal/day for meter 9110193. We remove these drifts for both meters. The difference between the two values arises from the age difference of the meters.

3.2.4 Calibration of the two Scintrex meters against fourteen LaCoste-Romberg meters

We average the drift corrected data for one station to obtain a final value relative to station 11, arbitrarily set at 0. The error is calculated as described in the Appendix. The reference baseline values are those obtained by a set of fourteen LaCoste-Romberg meters (fixed scale factors: G248, G709, G156, G249, D9; adjusted scale:

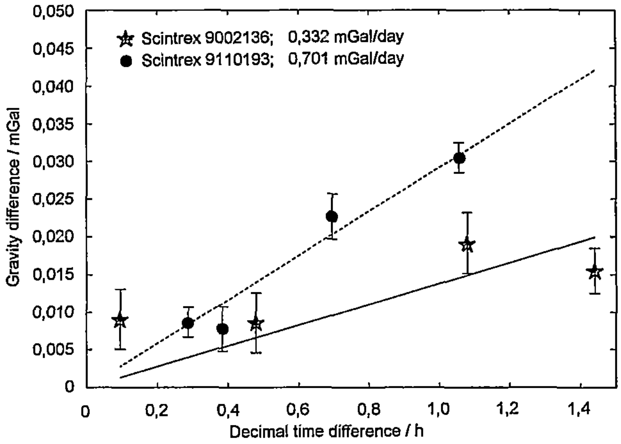

Figure 1. Linear drift for both Scintrex CG3M meters during the baseline field work. The drift correction of the Scintrex software is switched off, in order to obtain the actual drift value. As usual the older Scintrex 9002136 drift (0,332 ± 0,075 mGal/day) is less than the drift of the newer Scintrex 9110193 (0,701 ± 0,043 mGal/day). In the long term, the drift value should be of order 0,2 mGal/day [1, 8].

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* hh:mm.

D6, G115, G127, D126, D136, D38, G258, D21 and G919) which were calibrated just before or after the series of measurements on a baseline determined by absolute instruments [3, 4]. We compute a calibration coefficient a by a regression (2) between the set of baseline values $\Delta g_{\mathrm{Scintrex}}$ (uncalibrated units) and the reference Δg_{LCR} (mGal), for each meter:

$$\Delta g_{\mathrm{LCR}} = a \cdot \Delta g_{\mathrm{Scintrex}} + b. \qquad (2)$$

The Earth Tide Correction was applied here for uncalibrated readings. This could introduce an error which may affect the calibration factor, which we did not take into account. The calibration coefficient is given in Table 3 forcing b to be zero. We did not use network adjustment, as proposed by Reilly [6], because of the simplicity of the network.

3.3 Results

Table 4 and Figure 2 show the difference, for both Scintrex meters, between the calibrated data and the reference baseline values. There is good coherence between the two Scintrex meters, the data being within 0,004 mGal. Differences may be attributed to bad temperature compensation, which should be checked more precisely. Internal temperature variations are less than 0,11 mK for meter 9002136 and 0,22 mK for 9110193 (Tables 1 and 2). The influence of the external temperature variations on gravity readings has already been shown [7-9]. Our previous laboratory and field tests also confirm this effect [10-12]. The difference between Scintrex results and the reference is less than 0,009 mGal and is within the error bars, except at point 948013 for the Scintrex 9002136 meter and at point 948014 for both meters.

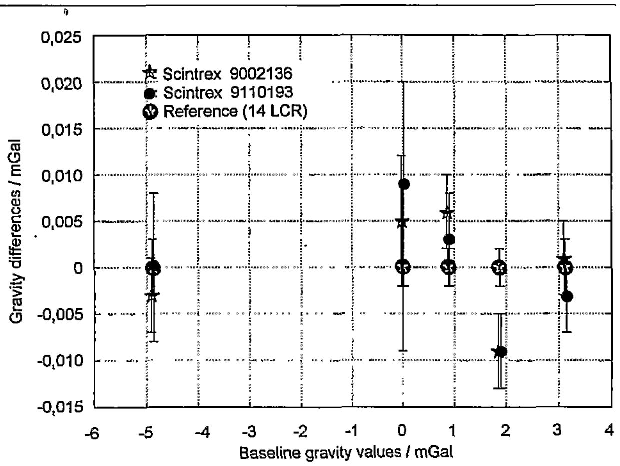


Figure 2. Differences between the calibrated results of the Scintrex meters and the reference. Scintrex meters results are similar to the reference (fourteen LaCoste-Romberg meters, from [4], except at point 948013 (Table 4).

Table 3. Results of the calibration of both Scintrex meters relative to the reference (fourteen LCR meters): uncertainties* are shown in parentheses.

	Scintrex 9110193	Scintrex 9002136
a/mGal (uncalibrated unit)$^{-1}$	0,99964 (0,0019)	0,99888 (0,0014)
b (fixed)/mGal	0,000 (0,0117)	0,000 (0,0087)
RMS/no unit	0,999996	0,999992

* All uncertainties are represented by standard deviations.

Table 4. Baseline results for Scintrex meters 9110193 and 9002136. Uncertainties (computation in appendix) are given in parentheses. The reference is the average of the results obtained for fourteen LaCoste-Romberg meters [4]. The last two columns show the difference between the results given by the individual meters and the reference baseline values. They are better than 0,009 mGal.

Point	Scintrex 9002136 /mGal	Scintrex 9110193 /mGal	LCR reference /mGal	Difference 9002136 LCR /mGal	Difference 9110193 LCR /mGal
948011	0,005 (0,007)	0,009 (0,011)	0,000 (0,009)	+0,005	+0,009
948012	–4,889 (0,004)	–4,886 (0,008)	–4,886 (0,003)	–0,003	0,000
948013	0,889 (0,004)	0,886 (0,005)	0,883 (0,002)	+0,006	+0,003
948014	1,867 (0,004)	1,867 (0,004)	1,876 (0,002)	–0,009	–0,009
948015	3,126 (0,004)	3,122 (0,004)	3,125 (0,003)	0,001	–0,003

4. Vertical gradient measurements

4.1 Data acquisition

We measured the vertical gradient at four of the six points designed for that purpose [3, 4]. We proceeded as we usually do in the field with these meters [11, 13, 14]. We start by measuring on the ground then on a tripod (about 1 m high) then back on the ground, and this twice for drift estimation. In order to make it easier, quicker and more accurate, we install two of the Scintrex tripods, one on the ground and the other on the main tripod. Before starting the measurements, we level the meter at low and high positions. The total duration of the gradient measurement at one site never exceeds 10 min. The gradient values obtained are thus integrated values of the vertical gradient between the low and high levels of measurements.

4.2 Data processing and results

We first remove the Earth Tide Correction computed by Scintrex meter software and we apply to the measurements the scale-factor obtained from the baseline (see Section 2). We then remove the accurate Earth tides and calculate the linear drift with the three measurements we have on the ground at each point and apply it to the measurements done at the upper level. Table 5 gives the different linear short-term drifts. The drift for meter 9110193 remained stable from 22:01 to 23:04 and changed by more than 0,1 mGal/hour afterwards. The drift for meter 9002136 decreased by about 0,04 mGal/hour (between 00:28 and 00:44) and changed again (between 01:19 and 01:34) by an amount of 0,07 mGal/m. One can discuss whether these short-term variations can be interpreted as perturbations of the long-term linear drift of the spring.

After removing the drifts, we obtain three values for the ground measurements and two for the tripod measurements. We average these values and estimate their standard deviation (see Appendix). We measured the height of the Scintrex meters at ground and on the top position. This difference is about 0,85 m, and is from (0,25 ± 0,05) m to (1,10 ± 0,05) m (the sensor is at (0,22 ± 0,01) m from the cover meter top).

Table 6 gives the results of the vertical gradient for both meters, for the four points measured (A0, A2, A3 and A8, renamed 9000, 9200, 9300 and 9800, respectively, in [4]). We estimated the error of height difference

Table 5. Linear drifts for the two Scintrex meters during vertical gradient measurements.

Universal Time	Linear drift for meter 9110193 /mGal · hour^{-1}	Linear drift for meter 9002136 /mGal · hour^{-1}
22:01 to 22:09	–0,007(0,026)	No data
22:27 to 22:36	0,012(0,020)	No data
22:57 to 23:04	–0,026(0,007)	No data
23:19 to 23:26	–0,140(0,021)	No data
00:21 to 00:28	No data	0,062(0,020)
00:44 to 00:54	No data	0,020(0,003)
01:11 to 01:19	No data	0,027(0,007)
01:34 to 01:40	No data	0,094(0,020)

Table 6. Results of vertical gradient for the two Scintrex meters (mGal/m). The comparison of Scintrex values is made easier with an estimation of a weighted average with the heights for the LaCoste-Romberg values [3]. The difference between the two Scintrex meters is less than 0,004 mGal/m, except at point A8 (difference is 0,007 mGal/m). The last two columns show the difference between the results given the individual meters and the reference estimated gradient values. They are less than 0,006 mGal/m except at point A8 (difference is 0,013 mGal/m for Scintrex 9110193). Uncertainties are shown in parentheses.

Point	Vertical gradient for meter 9002136 /mGal · m^{-1}	Vertical gradient for meter 9110193 /mGal · m^{-1}	LaCoste-Romberg vertical gradient data 1) 0,05 to 0,90 m 2) 0,05 to 1,30 m /mGal · m^{-1}	Estimation of weighted average 0,25 to 1,10 m /mGal · m^{-1}	Difference 9002136 LCR /mGal · m^{-1}	Difference 9110193 LCR /mGal · m^{-1}
A0 9000	0,308 (0,009)	0,308 (0,009)	0,3119 0,3048	0,310 (0,002)	-0,002	-0,002
A2 9200	0,314 (0,014)	0,310 (0,012)	0,3105 0,3045	0,309 (0,003)	+0,005	+0,001
A3 9300	0,290 (0,009)	0,289 (0,009)	0,2926 0,2872	0,291 (0,003)	-0,001	-0,002
A8 9800	0,257 (0,009)	0,264 (0,010)	0,2511 0,2492	0,251 (0,003)	+0,006	+0,013

Table 7. Meter schedule during loop experiment. Between each location L1, L2, L3 and L4, the meters are moved (loop) from one location to the next.

Universal Time	Scintrex S2 location	Height to ground /m	Scintrex S1 location	Height to ground /m	LaCoste LCR1	LaCoste LCR2	LaCoste LCR3
01:35 to 02:01	L3 sup	1,143	L4 sup	1,136	No record	No record	No record
02:04 to 02:10			L4 inf	0,434			
02:11 to 02:15			L4 sup	1,114	L1	L3 inf	L2
02:17 to 02:24							
02:24 to 02:27							loop
02:27 to 02:29						loop	
02:29 to 02:30					loop		L4 inf
02:30 to 02:32						L2	
02:32 to 02:40					L3 inf		
02:40 to 02:41							loop
02:41 to 02:43						loop	
02:43 to 02:44	loop	loop			loop		
02:44 to 02:46						L4 inf	L1
02:46 to 02:48	L3 inf	0,436					
02:48 to 03:01					L2		
03:01 to 03:02	loop	loop					
03:02 to 03:04							loop
03:04 to 03:05						loop	
03:05 to 03:06	L3 sup	1,143			loop		
03:06 to 03:16							L3 inf
03:16 to 03:18						L1	
03:18 to 03:25					L4 inf		
03:25 to 03:26							loop
03:26 to 03:28						loop	
03:28 to 03:31			loop	loop	loop		
03:31 to 03:32			L4 inf	0,432			
03:32 to 03:33						L3 inf	L2
03:33 to 03:42					L1		
03:42 to 03:45			loop	loop			loop
03:45 to 03:48						loop	
03:48 to 03:51					loop		
03:51 to 03:54			L1	0,433			L4 inf
03:54 to 03:56						L2	
03:56 to 04:08					L3 inf		
04:08 to 04:12			loop	loop			loop
04:12 to 04:14						loop	
04:14 to 04:15					loop		
04:15 to 04:17							L1
04:17 to 04:18			L3 inf	0,432		L4 inf	
04:18 to 04:19							
04:19 to 04:30					L2		
04:30 to 04:32			loop	loop			
04:32 to 04:35					loop	loop	loop
04:35 to 04:37							L3 inf
04:37 to 04:39			L2	0,433		L1	
04:39 to 04:47					L4 inf		
04:47 to 04:48			loop	loop			
04:48 to 04:49							loop and recording problem
04:49 to 04:50						loop	
04:50 to 04:52					loop		
04:52 to 04:54						L3 inf	
04:54 to 04:56			L4 inf	?			
04:56 to 05:10					L1		
05:10 to 05:11							L2
05:11 to 05:13			loop	loop			
05:13 to 05:14							loop
05:14 to 05:15						loop	
05:15 to 05:16					loop		
05:16 to 05:18							L4 inf
05:18 to 05:21			L1	0,434		L2	
05:21 to 05:29					L3 inf		
05:29 to 05:30			loop	loop			

Universal Time	Scintrex S2 location	Height to ground /m	Scintrex S1 location	Height to ground /m	LaCoste LCR1	LaCoste LCR2	LaCoste LCR3
05:30 to 05:32	L3 sup	1,143	loop	loop	L3 inf	L2	loop
05:32 to 05:33						loop	
05:33 to 05:36					loop		
05:36 to 05:38			L3 inf	0,432			
05:38 to 05:39						L4 inf	L1
05:39 to 05:52					L2		
05:52 to 05:55			loop	loop			
05:55 to 05:56							loop
05:56 to 05:58					loop	loop	
05:58 to 06:00							L3 inf
06:00 to 06:03			L2	0,433			
06:03 to 06:16					L4 inf	L1	
06:16 to 06:18			loop	loop		loop	loop
06:18 to 06:20					loop		
06:20 to 06:21			L4 inf	0,433			L2
06:21 to 06:23						L3 inf	
06:23 to 06:30					L1		
06:30 to 06:38	off	off			off	off	off

as about 0,002 m; the error of gravity difference is the sum of the errors at low and high position. This leads to an error in the vertical gradient of about 0,01 mGal/m, except at point A2, which was noisier. The results are similar for the two Scintrex meters to within an accuracy of better than 0,007 mGal/m. As a reference, the values of the vertical gradient obtained with the fourteen LaCoste-Romberg meters are given in [4]. In order to compare the results more easily, a vertical gradient from the LaCoste-Romberg values was estimated by averaging: the weighted average was calculated with both values of vertical gradient (from 0,05 m to 0,90 m and from 0,90 m to 1,30 m) for 0,25 m to 1,10 m, corresponding to the Scintrex measurements positions of the sensor. The results of the Scintrex meter are very close to those of the LaCoste-Romberg meters, for most points within 0,006 mGal/m, but a wider spread was found at point A8 for meter 9110193.

For comparison, we had already measured the vertical gradient at point A3 with both Scintrex meters in January 1993, using the same method. For both Scintrex meters we obtained the same value of the vertical gradient (0,291 ± 0,015) mGal/m. The high level of error was linked to high microseismic noise caused by a storm.

5. Small baseline gravity measurements with Scintrex CG3M and LaCoste-Romberg meters

5.1 Objectives and procedure of the study

In order to test the ability of Scintrex CG3M and LaCoste-Romberg meters to detect small variations of gravity, i.e. less than 0,03 mGal, on very short baselines, we used the four points L1, L2, L3 and L4 located in the laser laboratory at the BIPM, where the temperature remains more stable than in field conditions. These points are well known because absolute measurements were carried out [15] and some of them were also measured by fourteen LaCoste-Romberg meters during the calibration [4]. Their geometric disposition is a square of about 2 m side (Figure 3).

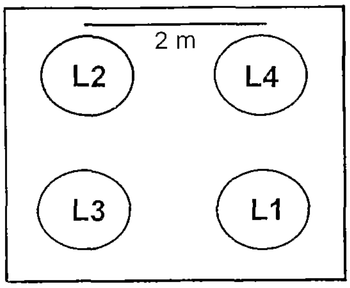


Figure 3. Schematic map of the four points L1, L2, L3 and L4 in the quiet and thermally stable laser room at the BIPM.

The unusual new procedure that we used was to take continuous records of gravity during short periods, successively at the different points. As we had four gravity stations, we chose to use three LaCoste-Romberg meters (designated LCR1, LCR2 and LCR3) and one of our two Scintrex meters (designated S1). Due to the short schedule, we recorded simultaneously with the four chosen meters, one on each point, and we rotated them at each step of the experiment.

The acquisition rate for all meters was 1 datum/min and each point was occupied for about 10 min. Throughout the experiment, data for the LaCoste-Romberg meters were continuously recorded by a digital acquisition system designed by Van Ruymbeke [16, 17] with final data recorded into a computer, even during the

Figure 4a

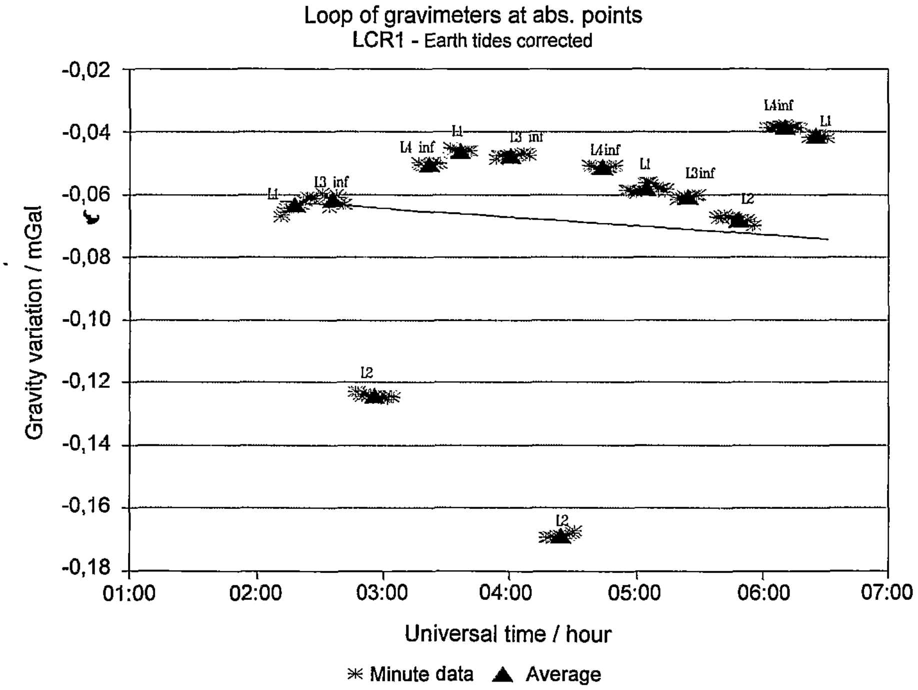


Figure 4b

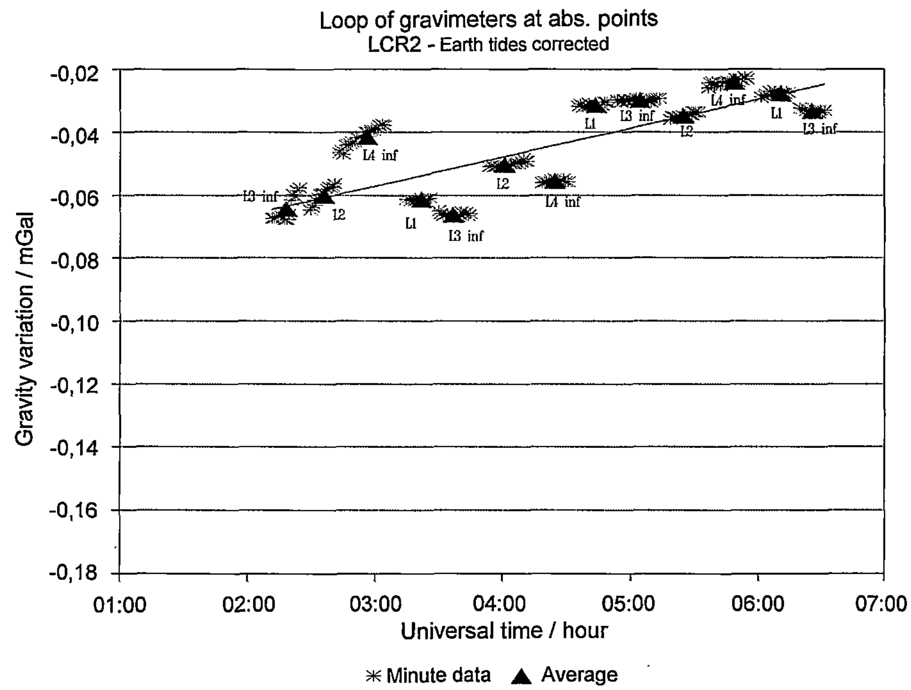


Figure 4. Earth Tide Corrected continuous records of four meters (three LaCoste-Romberg and one Scintrex) at the four points (L1, L2, L3 and L4) and the linear regressions (black lines) computed through all data, except for meter LCR1. Stars represent the average of sixty or less samples and filled triangles are average of stars of each step at a point. The location of the records are referenced close to the filled triangle. (a) LCR1 meter; (b) LCR2 meter; (c) LCR3 meter; (d) Scintrex CG3M meter S1. Data for point L4 sup are not shown for coherency with the scale of the other graphs.

Figure 4c

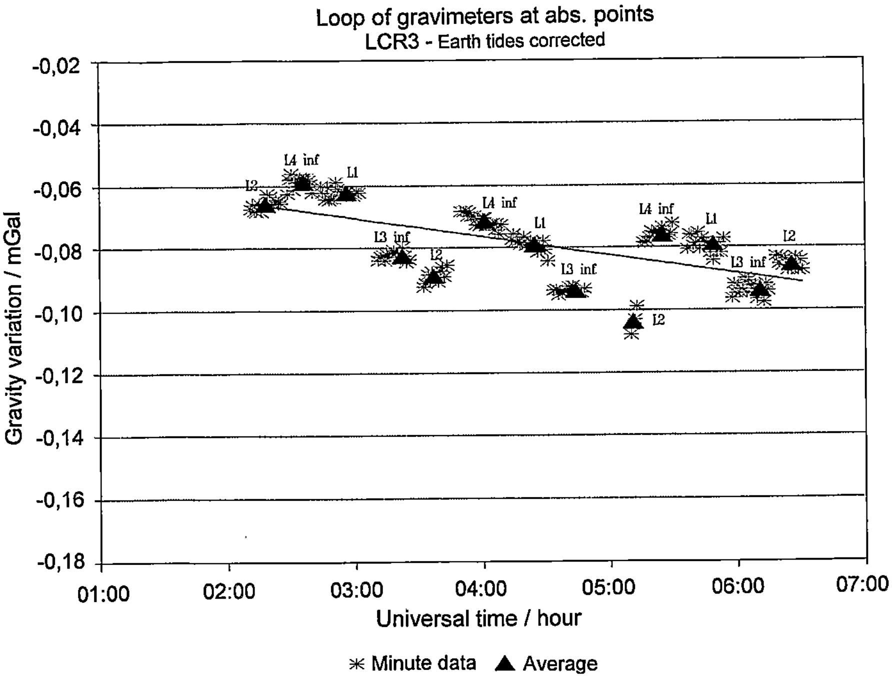
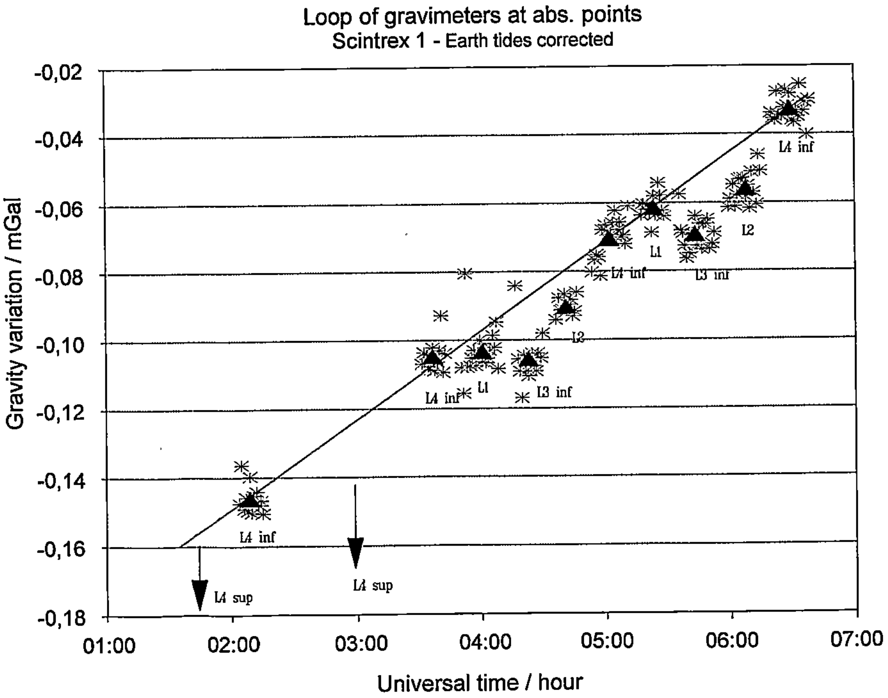


Figure 4d



change of recording location. An external supply power was also provided to the LaCoste-Romberg meters throughout the experiment. The Scintrex meter was settled in continuous mode giving a series of 1 min samples, each being the average of sixty 1 s samples. When changing the recording location, the Scintrex meter recording was stopped. The external ac power supply was also removed for 2 to 3 min due to a practical problem. Note that the Scintrex meter has an internal battery for use when the external power is switched off.

For each meter, we thus obtained series of small continuous records (about ten samples of 1 min each), corresponding to the different steps at one point. Table 7 gives the schedule of the experiment. After data processing as described below, the final results are compared with the reference baseline [4].

As we wanted to establish the relatively long-term drift variation of the Scintrex meters and compare it with the drift obtained during the baseline and vertical gradient measurements we installed two tripods over points L3 and L4, and thus added two locations (L3 sup and L4 sup), each about 1 m above ground. As described in Table 7, the second Scintrex meter (designated S2) recorded continuously between L3 sup (on the tripod) and L3 inf (on the ground) and the Scintrex meter S1 recorded for over 1 h at point L4 sup (Table 7).

5.2 *Data processing and results*

5.2.1 Calibration of the meters

As the resolution of the Scintrex meters is 0,001 mGal and as the variations between the points are expected to be less than 0,03 mGal, an error of calibration between the meters of less than 3 % is insignificant for this study. Thus, for the Scintrex meters, we used the automatic calibration values given by the manufacturer, which we previously checked to be accurate to better than 0,2 %. For the LaCoste-Romberg meters, the calibration carried out at Brussels is better than 0,1 %. Figures 4a to 4c show the calibrated records of all meters corrected for Earth tides.

5.2.2 Linear drift computation

The drift was computed in two ways for each meter: first, through data for all steps at each point, and second, through all data. We show in Table 8 that the individual linear drift value varies within 12 %, 100 %, 40 % and 24 %, for S1, LCR1, LCR2 and LCR3, respectively, depending on the point. The computation of a linear regression within all data gives a drift value close to the average of the four drift values for individual points, with differences of 7 %, 6 %, 1 % and 14 %, for S1, LCR1, LCR2 and LCR3, respectively. For each meter we removed the linear value from all data. For the LCR1 meter the strong jumps (described below) in the data introduce a distortion in the drift values. Suppressing the evident out-of-range data, we obtain a linear regression value of –0,066 mGal/day, which we applied to the data.

Scintrex meter S1 also recorded data at L4 sup for about 2 h. It is of interest to note that the linear drift computed from this record at L4 sup is close to those given in Table 8: we found (0,622 ± 0,014) mGal/day. The difference between this value and the average of the four drift values (Table 8) is less than 3 % and is less than 5 % with the drift computed through all data, i.e. within the error bars. However, for meter S2, Figure 5 clearly shows that a change of drift occurred after the change of location. The drift value is first (0,945 ± 0,06) mGal/day and then becomes (1,42 ± 0,009) mGal/day after moving the meter from L3 sup to L3 inf and back, revealing a change of about 40 %. Note that in Figure 5, the second drift value is removed from all data because it was computed from a longer duration.

5.2.3 Results

As there are no standard deviations for LaCoste-Romberg samples (minute values), we decided, for S1, not to take into account the standard deviation on the minute sample data given by the Scintrex software. We show in Figure 4 that the dispersion of the minute samples for one step is highest for the Scintrex meter (standard deviation around 0,005 mGal, up to 0,008 mGal). The dispersion is better for LCR3 (standard deviation around 0,002 mGal), and better for LCR2 and LCR1 (standard deviation around or less than 0,001 mGal).

Once the linear drifts are removed, we average the corrected data for each meter at each step. We thus obtain, for each meter, the average of about ten samples (minute values) during each step at a point and the corresponding simple standard deviation. Concerning LaCoste-Romberg meters, there are four step values at the point where each meter began the loop series, and three for the other points. To obtain the final values at each point relative to point L4, we average all data measured at one point for the different steps (Table 9). Figures 6a to 6d give these results relative to point L4. The uncertainties given are the standard deviations computed from all data at one point. The reference of the four points is given by the fourteen LaCoste-Romberg results for L3 and L4 and by only one LaCoste-Romberg meter (D21) for L1 and L2 [3, 4].

S1 and LCR3 final values are the closest to the reference, despite showing the highest dispersion of the minute samples at each step. LCR1 data jumps make the results very noisy at point L1.

Table 8. Linear drift (mGal/day) calculated (linear regression) for each meter either at each point or through all data. Values in parentheses are standard deviation (mGal/day) on the slope of the linear regression.

Meter	Drift at point L1 /mGal · m^{-1}	Drift at point L2 /mGal · m^{-1}	Drift at point L3 /mGal · m^{-1}	Drift at point L4 /mGal · m^{-1}	Average /mGal · m^{-1}	Drift (all data) /mGal · m^{-1}
S1	0,714 (0,040)	0,574 (0,023)	0,636 (0,042)	0,622 (0,009)	0,637 (0,080)	0,590 (0,014)
LCR1	0,085 (0,014)	0,459 (0,091)	0,014 (0,025)	0,109 (0,011)	0,167 (0,175)	0,177 (0,046)
LCR2	0,278 (0,023)	0,213 (0,006)	0,240 (0,019)	0,133 (0,027)	0,216 (0,045)	0,214 (0,012)
LCR3	-0,144 (0,011)	-0,113 (0,020)	-0,094 (0,009)	-0,144 (0,009)	-0,124 (0,014)	-0,142 (0,011)

Table 9. Final values for each point relative to point L4. Values in parentheses are the standard deviations.

Station	Scintrex S1 average /mGal	LCR1 average /mGal	LCR2 average /mGal	LCR3 average /mGal	Ref. /mGal
L1	–0,003 (0,006)	-0,007 (0,045)	–0,003 (0,007)	–0,003 (0,004)	–0,010 (0,003)
L2	–0,013 (0,004)	–0,075 (0,043)	–0,005 (0,002)	–0,015 (0,011)	–0,019 (0,003)
L3	–0,018 (0,007)	–0,012 (0,007)	–0,008 (0,009)	–0,017 (0,004)	–0,022 (0,001)
L4	0,000 (0,007)	0,000 (0,009)	0,000 (0,012)	0,000 (0,003)	0,000 (±0,001)

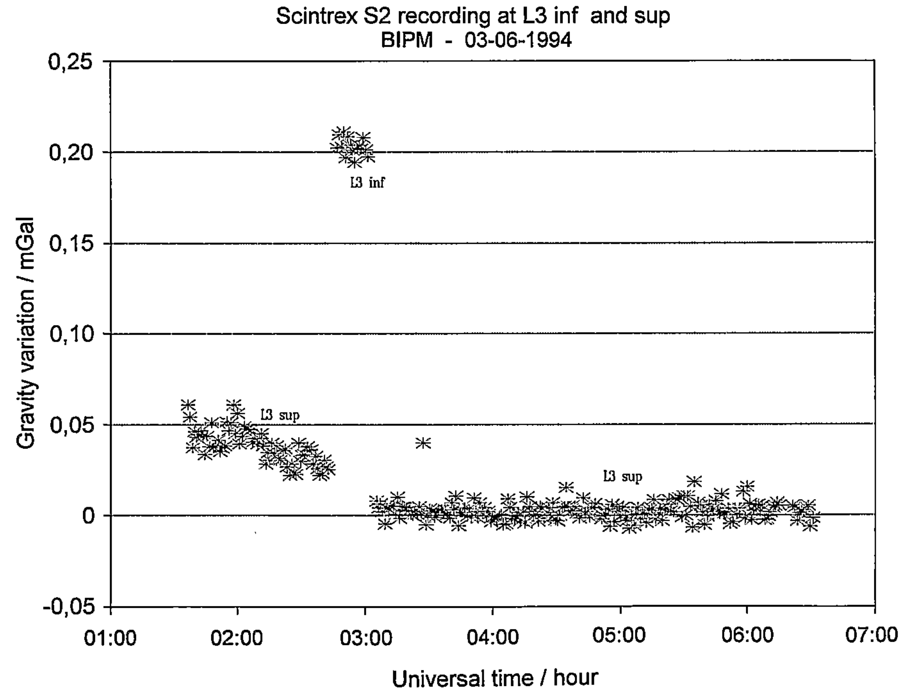


Figure 5. Records at low position L3 inf (on ground) and high L3 sup (on a tripod) with Scintrex CG3M meter 9002136. The shift corresponds to the change of location recording (from L3 sup to L3 inf and back, see Table 7). The applied drift correction is that of the second part of the recording, showing from about 3:00 a linear curve. This shows a bad linear correction for the first part of the recording (from starting to 2:40), revealing a change of linear drift, due to the change of location. No data post-filtering has been applied: higher spikes correspond to small shocks on the tripod due to our displacements around it.

Figure 6a

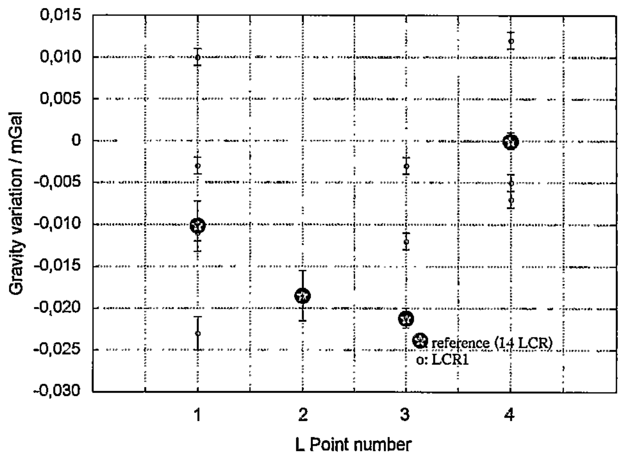


Figure 6b

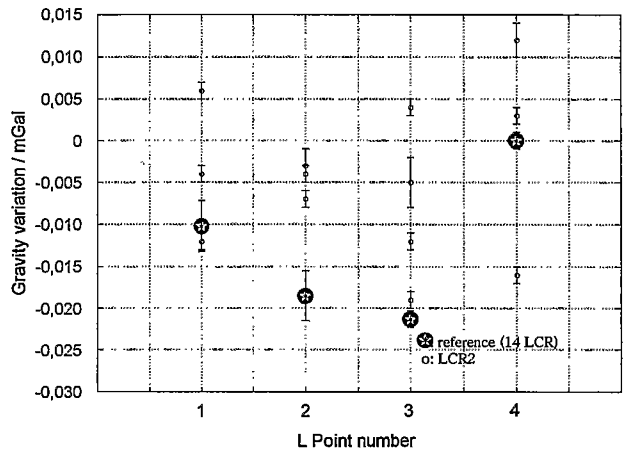


Figure 6c

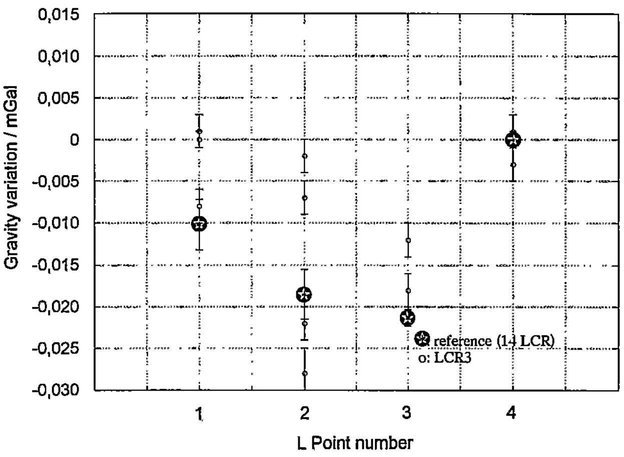


Figure 6d

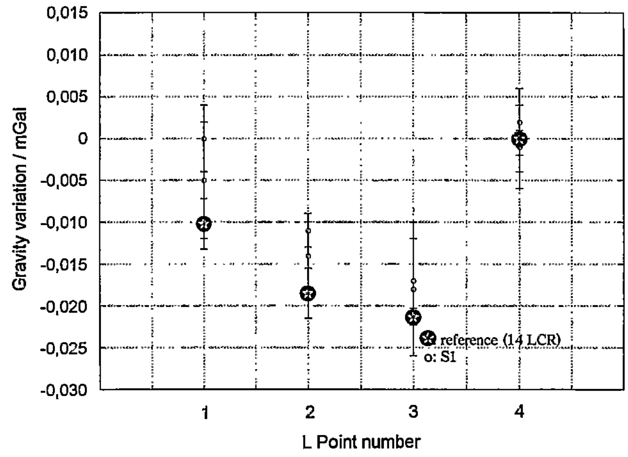


Figure 6. Results for each meter: (a) LCR1; (b) LCR2; (c) LCR3; (d) Scintrex CG3M meter S1, for each point of the loop session relative to point L4. The reference value is given in [4]. LCR1 and LCR2 results are very disperse; LCR3 and S1 results are more confident to the reference.

6. Discussion

We show in these three experiments that Scintrex meters 9110193 and 9002136 give results similar to those obtained by LaCoste-Romberg meters.

The baseline calibration work shows that the two Scintrex meters provide results lying within the error bar of the fourteen LaCoste-Romberg meters, except at point 948014 (Table 4). At that point the results for the two Scintrex meters are, however, the same, within the uncertainties. This suggests that local conditions may have affected Scintrex and not LaCoste-Romberg meters or vice versa.* Better results could probably be obtained if the ground at the baseline stations were to be consolidated. The effect of microseismic noise (which may greatly affect data for vertical spring meters) could thus be attenuated. Moreover, the baseline range is small. In future, it would be useful to construct stable underground sites for the calibration line, and to investigate the upper part of the hill at Sèvres so as to obtain a wider range of values.

Concerning the loop experiment, we have shown that the dispersion of individual minute samples is smaller for LaCoste-Romberg meters (Figure 4). This may be due to the higher number of samples for each minute value. Each minute data requires the integration of a frequency as high as 60 kHz over 1 min for LaCoste-Romberg meters [16, 17], whereas Scintrex minute data are the average of 60 1 s samples [1]. The repeatability of two successive steps at a point is better

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* The locations of the baseline points were often close to or on metallic drainpipes. Scintrex springs are made of fused quartz whereas LaCoste-Romberg springs are metallic. Some magnetic effect may therefore be suggested.

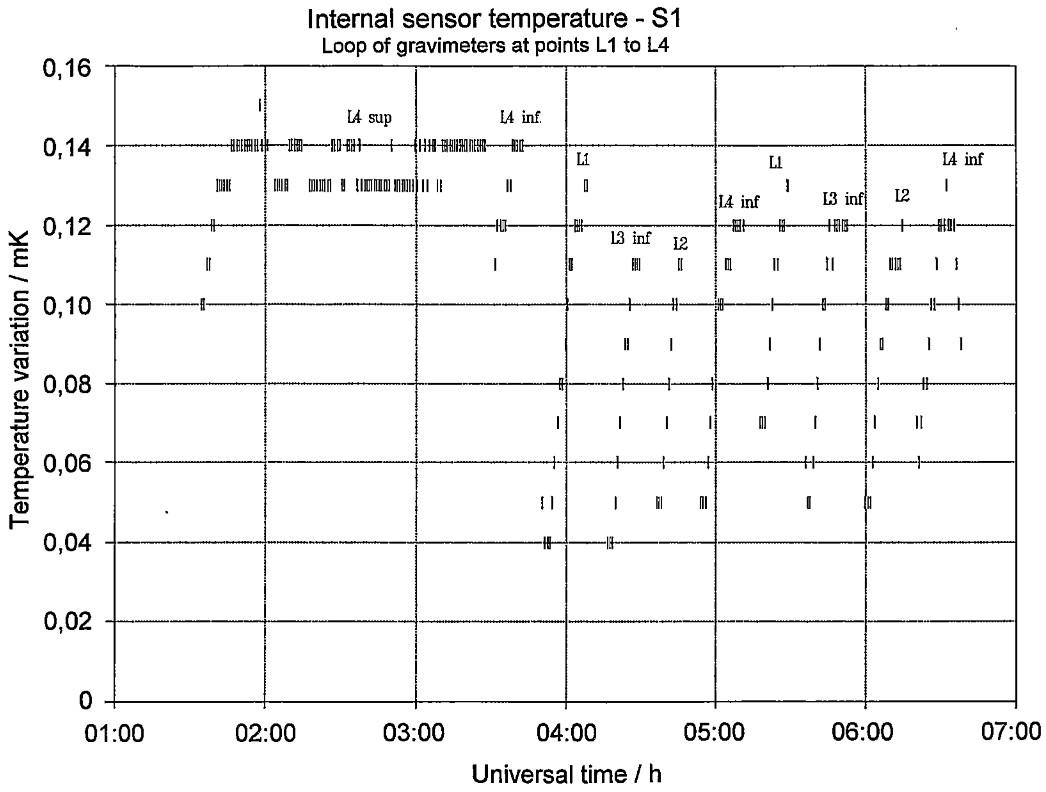

Figure 7. Temperature variations of the meter sensor 9110193. The periodic variations correspond to the change of locations during the loop, for which the electrical power supply also changed (external ac supply to battery and back).

for tilt-corrected data for S1 compared with LaCoste-Romberg data (Figure 4). LCR2 and LCR3 were fixed on an additional stable base that allows more accurate levelling than that achieved using the original levelling screws. LCR1 was levelled using original screws so giving the worst possible repeatability: this may explain data jumps from one point to another of up to 0,1 mGal. Moreover, for LCR3, the sign of the gravity variation between points L3 inf and L2 can be opposite for different loops. Indeed, at the first (03:06 to 03:42), second (04:17 to 4:47) and third (05:36 to 06:16) steps, the sign of the gravity variation is, respectively, negative, negative and positive (Table 7). Other examples can be found for LCR1 and LCR2, whereas no such change of sign arises for Scintrex meter loops* (Figure 4). The reason is probably the clamping of the spring between steps on LaCoste-Romberg meters, while the Scintrex spring remains free. It is well known that relaxing the spring may produce an hysteresis effect. As the dispersion of the LCR1 minute samples is the smallest (standard deviation less than 0,001 mGal), this suggests that meter LCR1 could be suitable for long-term Earth tide recording, without displacement.

The linear drift of the Scintrex meter S1 computed from the continuous recording on L4 sup is the same as that for the loop points. This good result is probably due to the fact that the change of meter location is performed slowly, which prevents a change of drift. This is not always the case in the field because of the ruder conditions. Even in quiet conditions, we have mentioned an evident change of drift (about 40 %) for Scintrex meter S2, after relocation (Figure 5). Vertical gradient measurements show that the short-term drift may change, probably due to meter displacement.

The temperature variation inside meter S1 is systematically the same for any step (Figure 7). These variations are probably due to the change of power supply: each time we relocated the meters, we removed the Scintrex ac power, the meter S1 being supplied with an internal battery during 1 to 2 min. This shows that the influence of battery voltage variations may be a source of error through the temperature correction. Poor temperature compensation may influence the short-term drift value [7, 8]. Concerning the temperature variation during the baseline measurements, no conclusion can be drawn yet. We recently made additional temperature and pressure tests both in the laboratory and in the field, and these confirm the strong influence of temperature correction in the final gravity value of Scintrex meters [12].

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* We must, however, note that only two complete loops were carried out using the Scintrex meters whereas three were used for the LCR meters.

Scintrex results also show good repeatability under field conditions on volcanoes [11, 13, 14, 18]. The repeatability obtained is however not as good as that described here, because the influence of external parameters is greater (wind, effects of higher temperature variations, microseismicity, etc.). The precision of the data is good enough, however, to record the classical gravity variations expected on active volcanoes (up to more than 0,1 mGal [19]) for which measurements with an uncertainty of less than 0,015 mGal [19, 20] are required.

Even if the dispersion of Scintrex continuous recordings is higher than that of LaCoste-Romberg meters, Scintrex meters could also be used for continuous recording of gravity on volcanoes. Two further advantages may be recalled. First, as the spring is vertical, earthquakes will not jam the meter. Second, as tilt effects are automatically corrected, maintenance is simplified.

7. Conclusions

From this study, we confirm that Scintrex CG3M gravity meters are able to measure microgravity variations in stable laboratory conditions.

(a) Results from the two Scintrex meters used are consistent to within 0,005 mGal.

(b) The observed repeatability of both instruments can be better than 0,005 mGal under stable conditions. The main limit to the accuracy seems to be, first, imperfect knowledge of the instrumental drift and, second, imperfect correction of external temperature variations.

(c) Even if Scintrex data are more dispersed than those of LaCoste-Romberg meters, their averages are in most cases close to the reference data, within the error bars (less than 0,010 mGal).

(d) Recording gravity over several minutes tends to improve the results compared with a single measurement.

These considerations confirm that the Scintrex CG3M meter has good potential for field work in microgravity studies, both in network surveys and in continuous recording.

Note. IPGP Contribution No. 1397.

Appendix

Computation of the standard deviation of a series of values with individual standard deviation

Let us consider a series of m measurements which are defined as the average of n unknown samples X_i. For each measurement we know the average μ_j and the standard deviation σ_j of the n samples. By definition we have

$$\sigma_j^2 = 1/n \sum\nolimits_{i=(j-1)n+1}^{j \cdot n} \left(X_i - \mu_j\right)^2 . \qquad (3)$$

As final value for the m measurements, we take the average of the μ_j:

$$M_m = 1/m \sum\nolimits_{j=1}^{m} \mu_j . \qquad (4)$$

As the samples X_i are unknown, we look for the standard deviation Γ_m expressed from the σ_j:

$$\Gamma_m^2 = 1/m \cdot n \sum\nolimits_{k=1}^{m \cdot n} \left(X_k - 1/m \sum\nolimits_{j=1}^{m} \mu_j\right)^2 . \qquad (5)$$

It is possible to show that this term may be written as

$$\Gamma_m^2 = 1/m \sum\nolimits_{k=1}^{m} \left(\mu_k^2 + \sigma_k^2\right) - M_m^2 . \qquad (6)$$

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