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An intercomparison of LaCoste and Romberg Model-D gravimeters: results of the International D-meter Campaign 1983

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Summary. The LaCoste and Romberg Model-D gravimeter has found many applications in studies of geophysical processes around the world. To assist in evaluating the results of these studies the performance of 13 Model-D gravimeters from seven countries was determined during a two-week observing campaign in 1983 on calibration ranges in the Federal Republic of Germany. Independent analyses of the data were carried out by the Institute of Physical Geodesy (IPG), Federal Republic of Germany, the Earth Physics Branch (EPB), Canada, and the International Latitude Observatory of Mizusawa (LOM), Japan. All instruments were found to have significant non-linear calibration functions (10–60 μGal corrections) and periodic error terms (2–7 μGal amplitudes). Calibration functions for most gravimeters were expressible in terms of third-order polynomials but a few instruments exhibited shorter wavelength structure. The calibration results appear to be similar to those obtained by the manufacturer's laboratory method, Cloudcroft Junior. Redundant observations taken at different reset-screw positions were used to estimate the uncertainties of the calibration functions. It is shown that the accuracy of a D-meter can be expressed in terms of the repeatability of readings and the uncertainty of its calibration function. For the average D-meter the present calibration error exceeds that associated with repeatability when gravity differences are greater than about 26 mGal. Although variations in precision and residual drift of the D-meters could not be clearly linked to environmental factors, the best results were obtained by D21 which was distinguished from the other gravimeters by having an extra thermostatized enclosure. Instruments transported in the manufacturer's cases without a special suspension system tended to give inferior precision. It is estimated that if two or more D-meters are employed in a well-designed network spanning a range of 100 mGal, 1σ errors of 3–4 μGal can be achieved with respect to the network mean.

Key words: high-precision gravimetry, gravimeter calibration, precise-gravity networks, gravity-survey accuracy, periodic error

Introduction

High precision gravimetry plays an important role today in the study of crustal processes around the world. Recent applications of this technique have been made in the studies of earthquake processes (e.g. Chen, Gu & Lu 1979; Hagiwara *et al.* 1980; Dragert, Lambert & Liard 1981; Jachens *et al.* 1983), mass movement associated with geothermal fields and reservoirs (e.g. Denlinger, Isherwood & Kovach 1981; Lambert, Liard & Mainville 1986), movements of magma (e.g. Jachens & Eaton, 1980; Torge & Kanngieser 1980) and post-glacial rebound (e.g. Becker *et al.* 1984), among others. For the purpose of carrying out high-precision gravity measurements a number of research institutes and agencies around the world have acquired LaCoste and Romberg (LCR) Model-D gravimeters. The LCR Model-D gravimeter, introduced in the mid-1970s, was designed to provide a precision of a few microgals (one microgal (μGal) = 10 nm s^{-2}) over a range of about 200 milligals (one milligal (mGal) = 10 μm s^{-2}). Apart from isolated studies of individual instruments (McConnell, Hearty & Winter 1975; Lambert, Liard & Dragert 1979; Steinhauser 1978; Kaidzu 1981; Götze & Meures 1983) there has been no comparative study of the performance and accuracy of the LCR Model-D gravimeter.

Under the sponsorship of special study group 3.37 of the International Association of Geodesy, 'Special Techniques in Gravimetry', a number of owners of LCR Model-D gravimeters agreed to participate in an international campaign to field test several instruments simultaneously. The joint measurements and the intercomparison of the data were carried out with the aim of resolving some of the key instrumental problems encountered in using the D-meter for precise gravity work (cf. Groten 1983 for more details on the instruments and for a review of the 'state of the art' in precise gravimetry). The main objectives of the campaign were (1) determination of the non-linear calibration function of the D-meter, (2) determination of the effect of reset changes on the calibration function, (3) determination of periodic errors associated with irregularities in the measuring screw and gear box, (4) investigation of the drift behaviour of the D-meter, and (5) determination of the accuracy obtainable with the D-meter. The campaign took place in 1983 April 14 to May 1 on two baselines in Germany. Thirteen D-meters and one G-meter from 12 different institutions participated in the measurements (see Appendix A).

Model-D gravimeter

The LaCoste and Romberg Model-D gravimeter is almost identical in appearance and operating principle to the more familiar Model-G gravimeter. Both instruments are spring-suspension instruments that are manually nulled using a galvanometer. The null is achieved by adjusting a reading dial that is connected through a gear box to a measuring screw. The measuring screw moves a system of levers that act on the upper end of a 'zero-length' spring attached to the gravimeter beam. In the Model-D the internal mechanism has been modified to give a reading resolution of 1 μGal and a range of 200 mGal rather than the 10 μGal resolution and 7000 mGal range of the Model-G. A reset screw on the D-meter allows it to be used over its limited range anywhere on the globe. Improvements to the original Model-D gravimeter adopted by various users and now offered by the manufacturer include the use of an external analogue or digital voltmeter for nulling the system, and the addition of electronic levels, a calibrated reset screw, and an extra thermostatized enclosure.

Design of the measurements

The determination of the calibration function required measurements that spanned the whole range of the instruments, whereas the determination of periodic errors required measurements that sampled more densely over a short range of the measuring screw. To satisfy these different needs the calibration line Hannover–Harz, described in detail in Kanngieser *et al.* (1983), was chosen for the study of the calibration functions, and the staircase calibration line of the Institute of Physical Geodesy (IPG), Darmstadt, was chosen for the study of periodic errors.

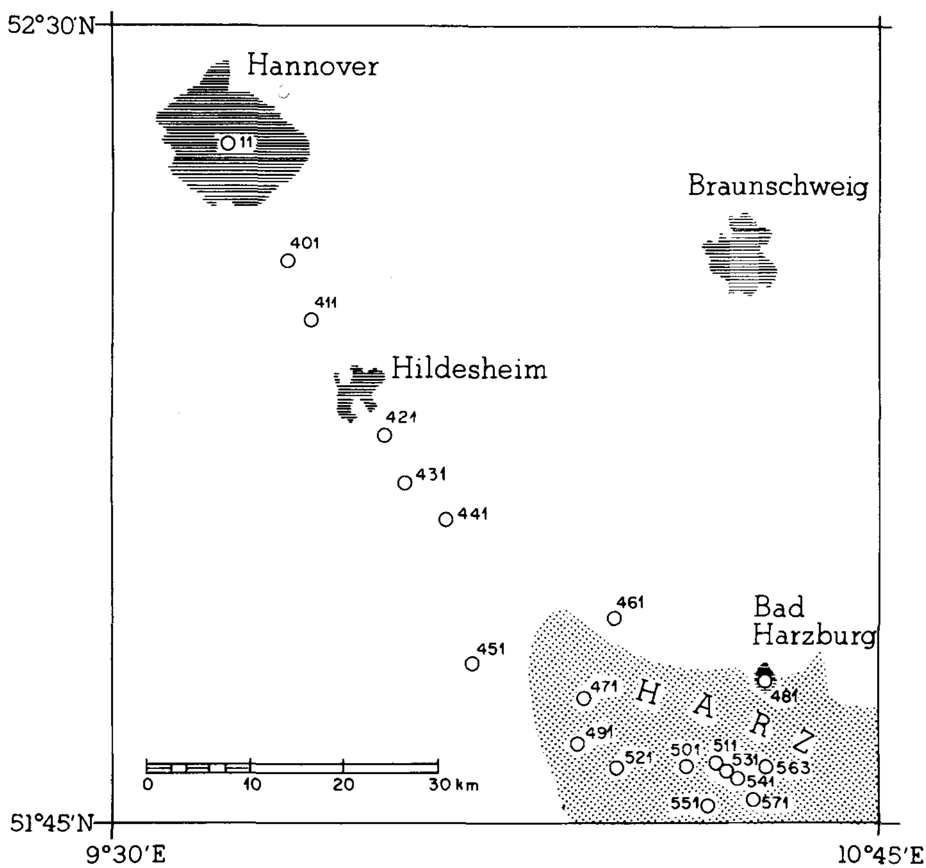


Figure 1. Location of the stations of the Hannover–Harz calibration line (Kanngeiser *et al.* 1983) used in the international D-meter campaign. The numbers identify stations at Hannover (11), Gleidingen (401), Giesen (411), Barienrode (421), Detfurt (431), Nette (441), Bilderlahe (451), Langelsheim (461), Lautenthal (471), Bad Harzburg (481), Wildemann (491), Altenau (501), Oberharz (511, between Altenau and Torfhaus), Oberharz (541, between Altenau and Torfhaus), Oderteich (551), Torfhaus (563), Oberharz (571, between Torfhaus and Oderbruck). Change in gravity is provided by variations in latitude in the north and by variation in elevation in the south.

1 DETERMINATION OF CALIBRATION FUNCTIONS

The calibration function of a gravimeter expresses the relationship between gravity and dial reading. An ideal calibration line for the determination of calibration functions for D-meters should fulfil certain requirements.

(1) The entire measuring range of the D-meter should be covered (approximately 200 mGal).

(2) The stations should subdivide the measuring range into a series of equal gravity differences.

(3) Distances between the stations should be small in order to keep the driving times short.

(4) The sites should allow a simultaneous reading of several (two to four) instruments.

(5) The sites should be stable and durable to allow the repetition of the campaign at some later time.

(6) Gravity values for the stations should be available with sufficient accuracy to determine the scale of the gravimeters.

The Hannover–Harz calibration line (Fig. 1) provides a maximum gravity difference of 192 mGal and gravity intervals of approximately 10 mGal (Table 4). Each station consists of a concrete pillar whose top surface measures 0.42 by 0.42 m. At the time of writing no absolute gravity measurements had been made on the line. Nevertheless, the absolute values for these stations are well determined because of the connection with the German Base Gravity Net 1976 (Boedecker & Richter 1981) and a great number of observations with gravimeters calibrated on the European Absolute Calibration Line (Cannizzo, Cerutti & Marson 1978) (see Kanngieser *et al.* 1983 for details).

In order to optimize the resolution of the calibration function and to minimize the effect of errors associated with a particular station, all of the 10 mGal gravity intervals were used in the campaign (station 1 in Hannover was not required). To facilitate the determination of the effect of reset changes the line was observed in two parts: stations 11–481 and stations 481–571. Each part has a range of approximately 100 mGal (see Appendix B for the gravity differences and the observation scheme). Within each of the two parts, neighbouring points as well as the end and mid points were connected by observations using the step-like scheme A–B–A–B–C–B–C..... This scheme allows the short-term drift of the instruments to be well determined. For the investigation of the effects of reset changes on the calibration function both parts of the line were observed by each instrument. They were then re-observed at different reset positions as shown in Table 1.

All precautions necessary in precise gravimetry were taken. These included driving prior to the first observation in the morning, keeping the instruments in a room where temperatures are close to outside temperatures, keeping a fixed orientation towards north on

Table 1. D-meter reset scheme.*

Reset-screw Position	Station 11 (C.U.)	Station 481 (C.U.)	Station 571 (C.U.)
	Nominal D-meter readings		
R1	195.0	100.0	5.0
R2	100.0	5.0	-
R3	-	195.0	100.0

*Example for D-meter with constant calibration function equal to 1 mGal c.u.$^{-1}$.

Table 2. Grouping of instruments in the D-meter campaign.

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
D8	D6	D27	D18	D16	D21
D14	D37	D38	D60	G317	
D23	D77	D73			

Groups 2 and 3 used the spring-suspensions with open carrying cases, shown in Fig. 2 (see also Appendix A).

every pillar, etc. (see Groten 1983). The instruments were transported in groups as listed in Table 2. Groups 2 and 3 used the IPG spring suspension with open carrying cases, shown in Fig. 2 (see Appendix A for details of methods used by other groups).

2 DETERMINATION OF PERIODIC ERRORS

Periodic errors result from imperfections in the measuring screw and from eccentricities in the toothed wheels of the gear box. Their periods which can be computed from the number of teeth on the different wheels are 6.5, 3.25, 1.625, 0.722, 0.361 and 0.1 counter units (c.u.). One counter unit is defined as 10 turns of the D-meter dial (approximately 1 mGal) for consistency with the LCR G-meter.

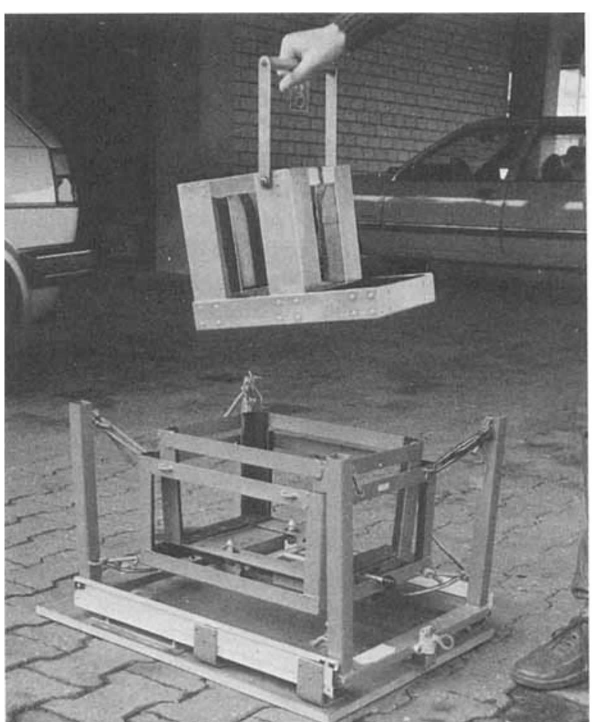


Figure 2. Spring suspension for the transport of gravimeters constructed by the IPG. The gravimeter and battery are hand-carried in an open carrying case (upper unit) which, for vehicle transport, fits into a frame suspended by elastic cords (lower unit). The suspended frame is loaded with more than 20 kg in order to obtain a low eigenfrequency and a reduction in vibration amplitudes.

It is known from the G-meter that the largest amplitudes of the periodic errors are associated with full and half turns of the measuring screw. Therefore, it was decided to concentrate on the corresponding periods in the D-meter, namely 3.25 and 1.625 c.u. or 32.5 and 16.25 turns, respectively, of the D-meter dial. From the points on the staircase calibration line of the IPG (Becker 1981), 14 points were chosen with eight spacings of about 0.4 mGal and five spaces of about 0.8 mGal leading to a maximum gravity difference of 7.4 mGal. Two series of measurements were conducted. Between the first and second series the reset screw was changed by

$$5.68 + 2n(3.25)\ \text{c.u.},$$

where $n = 1, 2, \ldots$, in order to maximize the changes in the observed gravity values produced by the periodic errors (see Appendix B, Section 4 for the number of observations and the gravity differences on the staircase calibration line).

Method of data analysis

The data observed during the campaign were analysed independently by EPB, LOM and IPG.

1 IPG AND LOM MODELS

The procedures applied by LOM and IPG are basically very similar; minute differences occur in the computation of corrections and in the mathematical model. For example, in the present analysis LOM used only linear drift terms whereas IPG used polynomials up to degree 3. A brief description of the IPG-model is given here; details are given in Nakagawa *et al.* (1983) and Becker (1984).

Prior to adjustment the raw readings of the instruments are modified by applying the following corrections: (1) a conversion to milligals by multiplication of the readings in c.u. by the manufacturer's (or a previously determined) linear calibration factor, (2) a height reduction to a reference mark (in this analysis no actual gradients were used, the normal gradient of 0.3086 mGal m^{-1} was applied), (3) an air-mass correction equal to $\Delta g_p = (p - p_n) \cdot r$, where p is the actual air pressure, p_n is the standard pressure at the height of the station and $r = 0.35\ \mu$Gal mbar^{-1}, (4) a correction for known periodic errors, and (5) a tidal correction.

The tidal correction is computed by the Cartwright–Taylor–Edden expansion (Cartwright & Edden 1973). In this analysis the amplitude factors and phase lags observed at the Earth-tide station, Hannover (Kanngieser *et al.* 1983, p. 13) were used. The observed Ocean-tide values agree with those computed by Schwidersky's maps (Schwidersky 1980) and the programme of C. Goad (Goad 1980) to better than 20 per cent for the M2 wave. On the basis of test computations it was shown that the remaining uncertainties in the tidal corrections lead to errors in the adjusted gravity values of less than 0.5 μGal for a single gravity meter.

The corrected readings are then used as observables in a least squares procedure to solve for the gravity values of the stations and the unknown calibration parameters. The observation equations are of the form:

$$\sqrt{W_g}\,[g_j + O_{g,k} + d_{g,p,e}(t) + K_{g,q}(R_{g,m}) + A_{g,n} \sin(R'_{g,m} + B_{g,n}) = \epsilon_{g,m}], \quad (1)$$

where g_j is the unknown gravity value of the jth station, $O_{g,k}$ is the offset unknown of series number k (usually over one day), $d_{g,p,e}(t)$ is the drift polynomial for the pth group of readings (e = degree of polynomial, t = time relative to the mean time of all readings in group p), $A_{g,n}B_{g,n}$ are the amplitude and phase of the nth term of the periodic error with the period T_n, $R_{g,m}$ is the mth corrected counter reading of the gth gravimeter. $R'_{g,m}$ is equal to $R_{g,i} \cdot 2\pi T_n$, $K_{g,q}$ is a polynomial of degree $q = 1-3$ for the approximation of the calibration function, and $\epsilon_{g,m}$ is the observational error in $R_{g,m}$. W_g is the weight of the gth instrument.

If absolute determinations of gravity or gravity values of a previous adjustment are available the corresponding observational equation reads:

$$\sqrt{W}(g_j - a = \epsilon), \qquad (2)$$

where a is the given value of gravity at the station, and W is the weight given to the gravity value.

In the initial adjustment the maximum number of parameters is introduced in the observation equation. The significance (95 per cent level) of each parameter is tested and the number of parameters for each instrument is reduced accordingly.

As a first step every instrument is adjusted separately and checks are made for tares, gross errors and drift behaviour. In the second step the instruments are combined in a common adjustment where the final gravity values and the instrumental parameters are determined. In the calculations of this report each instrument was weighted on the basis of an average accuracy obtained in the separate adjustments.

In the least squares adjustment of gravity values, a rank defect in the matrix of the normal equations occurs unless at least one gravity value is kept fixed. A solution is possible using the 'pseudo-inverse' for the inversion of the normal equations. This is equivalent to minimizing the sum of the squared gravity values or the introduction of a mean datum. Such an adjustment will be referred to as a 'free network adjustment'. It should be noticed that the adjusted gravity *differences* computed from a free network adjustment are the same as those computed from an adjustment with one fixed gravity value. The latter adjustment is called an 'unconstrained adjustment'.

2 EPB MODEL

The model adopted by the Earth Physics Branch (EPB) considers the differences of successive gravity readings as the observable that is input to the network analysis scheme (McConnell & Gantar 1974). In this model error is considered to be generated mainly during the transport of the instrument between readings. In so far as the drift of the instrument can be modelled as a low-order polynomial function of time, the remaining errors are considered to be uncorrelated.

Prior to the network adjustments, the raw readings of the instruments were corrected for the best available linear calibration function for the instrument, for known periodic errors, and for Earth tides. The corrected reading differences were then used as observables in a standard least-squares procedure to solve for the gravity values of the stations, with respect to a designated reference station. The observational equations are of the form:

$$\sqrt{W_g}\,[g_i - g_j - K_{g,q}(\Delta R_{g,m}) - d_{g,p,e}(\Delta t_{g,m}) = \epsilon_{g,m}], \qquad (3)$$

where g_i is the unknown value of gravity at the ith station, g_j is the unknown value of gravity at the jth station, $\Delta R_{g,m}$ is the mth corrected reading difference of the gth gravimeter, $K_{g,q}$ is a calibration function for the gth gravimeter which normally takes the form of a table of interval factors multiplied by a scale factor, can also be a polynomial function of $R_{g,m}$ of degree $q = 1-3$, but in the case of this analysis is a constant scale factor corresponding to a linear calibration function, $d_{g,p,e}$ is normally the unknown linear drift rate for the gth instrument for the pth group of readings but can be a polynomial function of time of degree $e = 1$ or 2, $\Delta t_{g,m}$ is the time difference associated with the mth observed gravity difference by the gth instrument (station i is observed before station j), $\epsilon_{g,m}$ is the observational error in $\Delta R_{g,m}$, and W_g is the weight of the gth instrument.

The unknowns computed in the fitting procedure are actually corrections to *a priori* values of the above unknowns.

The observations with each gravimeter are assumed to form separate populations with different variances. We take $W = 1$ and reject no data for the first cycle of the adjustment and then calculate new weights $W_g = S_0^2/S_g^2$ where

$$S_g^2 = \sum_m^l W_g \epsilon_{g,m}^2/(l-1)$$

is the standard error associated with the l observations of the gth instrument and

$$S_0^2 = \sum_m^n W_g \epsilon_{g,m}^2/(n-r)$$

is an estimate of the standard error of unit weight for n observations and r unknowns. The adjustment is then recycled with these weights. Measurements are rejected if $\epsilon_{g,m}\sqrt{W_g} > 3S_0$, where S_0 is taken from the previous cycle.

In the EPB analysis of the D-meter campaign data no corrections for instrument height or atmospheric pressure were made. In accordance with a policy of keeping the analysis as simple as possible, no drift terms were included in the final least squares network adjustments. The raw readings were corrected for Earth tides using the simple formulation of Longman (1959). These corrections assume a gravimetric factor of 1.16 for both the degree 2 and degree 3 tidal distribution. In contrast to the more sophisticated Earth-tide correction scheme applied by IPG no account was taken of the effect of the Ocean tides in the EPB tidal corrections. A comparison of the Earth-tide correction with the readings of D27 during the first part of the campaign shows differences between the two methods of up to 5 μGal with differences of 1–2 μGal in most cases. The discrepancies in the differences of successive readings are smaller. The importance of the Earth-tide corrections in the analysis of the campaign data was judged by comparing the mean observed gravity differences for a typical instrument, such as D27, where corrections were made according to the different IPG and EPB methods. It was found that as a result of averaging, most of the discrepancies in the observed ties before adjustment are of the order of 0.1–0.2 μGal. The maximum discrepancy in the mean value of the observed ties was found to be 0.5 μGal or less.

Network analysis results

The network analysis was carried out in two stages: (1) data for individual D-meters were adjusted separately to establish the internal consistency of each instrument and the weights for the second stage of the analysis, and (2) combined adjustments involving all D-meters were carried out to derive the gravity values of the stations on the calibration lines, the periodic errors, the drift and the calibration functions of the D-meters. In (2), the approach of EPB differed from that of IPG and LOM in that a combined adjustment was done only to establish the gravity values of the stations. The calibration functions of the D-meters were then determined by comparing station gravity values derived from adjustments of individual instruments with the values derived in the combined adjustment.

1 PRECISION OF THE D-METER

IPG, LOM and EPB carried out separate adjustments for each D-meter to determine general data quality and the precision of each instrument. Although slightly different corrections were applied and different drift removal methods were employed, similar results were obtained by all three institutions.

In the preliminary analysis carried out by EPB, for example, the data for each D-meter were adjusted separately keeping Bad Harzburg (station 481) fixed at 981 165 278.0 μGal. Available periodic error corrections were applied to all instruments but only the nominal linear scale factors (Table 6) were applied. Adjustments of D27 data with and without a linear drift term showed negligible effect on station values and only a slight increase in the standard deviation of unit weight. Consequently, drift terms were not included in the analysis of the campaign data.

Separate adjustments for all 13 instruments were carried out for each of three different reset positions described in Table 1. The results of these adjustments are given in Table 3. Most of the instruments achieve standard deviations of unit weight between 4 and 10 μGal. D21 achieves the smallest standard deviation of unit weight. D60 and D73 have a higher than average standard deviation.

2 DETERMINATION OF D-METER PARAMETERS

(a) Station gravity values

Gravity values for the stations on the Hannover–Harz calibration range were determined independently by IPG, LOM and EPB using the observations of all 13 D-meters of the campaign. The results of these determinations are presented and compared to the pre-campaign values (Kanngieser *et al.* 1983) in Table 4.

IPG carried out combined adjustments of 2142 observations from the Hannover–Harz line and 793 observations from the IPG staircase calibration line while solving for periodic errors. The individual instruments were weighted according to the results of separate adjustments. Two different adjustments were carried out: (1) a free net adjustment based on D-meter observations only, and (2) an adjustment involving D-meter observations and the predetermined station values. In the first adjustment a formal accuracy of 0.9–1.9 μGal was obtained for the gravity values with respect to the mean value of the stations. In the second adjustment the pre-campaign station values (Kanngieser *et al.* 1983) were given a higher weight than the D-meter observations. For a weight ratio of 10:1 a formal accuracy of 6 μGal was obtained for the station gravity values. The root mean-square error of gravity *differences* in this case was found to be 1–3 μGal (i.e. the errors of station gravity values were well correlated). IPG adopted the gravity values computed with a 10:1 weight ratio as the values to be used for further calibration studies. The accuracy of a 10 mGal interval is about 9×10^{-5} and the largest interval of 190 mGal is accurate to about 1.1×10^{-5}.

LOM computed gravity values for the stations of the Hannover–Harz line using all D-meter observations with the condition that the sum of the corrections to the pre-campaign values equals zero and that the sum of squares of the corrections is minimized (Nakagawa *et al.* 1983).

EPB carried out a combined, unconstrained adjustment of the Hannover–Harz D-meter data. No periodic error corrections were applied, instruments were weighted by a factor inversely proportional to their rms deviations from the combined solution, and the station values were shifted to give them the same mean as the pre-campaign gravity values.

Table 4 shows that there is reasonable agreement among the results of IPG, LOM and EPB

Table 3. Results of free-adjustments for individual D-meters at reset position R1, R2 and R3

Instrument	Number of Observations			Number of Rejections			Standard deviation of unit weight (μGal)			Mean standard error of station values (μGal)		
	R1	R2	R3	R1	R2	R3	R1	R2	R3	R1	R2	R3
D6	82	36	41	0	0	0	5.6	6.3	5.9	3.–	3.–	3.–
D8	69	35	33	0	1	0	8.3	11.8	6.2	5.–	7.5	4.–
D14	69	36	33	0	0	0	7.5	10.7	11.3	5.–	7.–	7.–
D16	79	47	37	0	0	2	10.9	10.6	10.5	6.–	6.–	5.5
D18	73	37	41	0	0	0	6.0	8.0	5.5	3.5	5.–	3.–
D21	66	32	36	3	1	0	2.3	1.4	2.4	1.5	1.0	1.5
D23	69	33	33	0	3	0	4.8	5.1	4.6	3.0	3.–	3.5
D27	80	47	38	1	0	0	5.9	4.9	8.3	3.–	3.–	4.0
D37	82	36	41	0	0	0	6.3	7.0	5.5	3.5	4.5	3.0
D38	80	47	37	0	0	1	4.4	5.1	4.3	2.5	3.0	2.0
D60	73	37	41	1	0	0	17.7	15.9	12.7	11.–	10.–	7.–
D73	80	37	37	1	0	1	23.7	12.3	16.1	13.–	7.–	10.–
D77	80	36	41	2	0	0	8.4	5.7	7.1	4.–	3.–	3.5

Table 4. Gravity values of the Hannover–Harz line determined by IPG, LOM and EPB compared with gravity values of Kanngieser *et al.* (1983).

Station	Gravity Values				Difference from Kanngieser et al. values			
	IPG P = 10 : 1* (μGal)	IPG free net-adjustment (μGal)	LOM (μGal)	EPB (μGal)	IPG (μGal)	IPG free net-adjustment (μGal)	LOM (μGal)	EPB (μGal)
11	981261909.5±5.9	981261910.0±1.9	981261909.0	981261910.1	− 0.5	− 0.0	− 1.0	0.1
401	981250843.7±5.9	981250844.7±1.8	981250842.8	981250845.5	1.7	2.6	0.8	3.5
411	981241708.4±5.9	981241709.2±1.7	981241708.3	981241709.1	0.4	1.1	0.3	1.1
421	981232560.6±5.9	981232560.7±1.5	981232559.2	981232562.3	− 4.4	− 4.3	− 5.8	− 2.7
431	981219904.5±5.9	981219905.1±1.3	981219903.5	981219904.4	− 0.5	+ 0.0	− 1.5	− 0.6
441	981210129.8±5.9	981210130.3±1.1	981210130.8	981210132.0	− 1.2	− 0.7	− 0.2	1.0
451	981200874.7±5.9	981200875.0±1.1	981200876.0	981200876.2	− 1.3	− 1.0	0.0	0.2
461	981190374.8±5 0	981190376.2±0.9	981190376.3	981190379.4	1.8	3.1	3.3	4.4
471	981173849.1±5.9	981173850.8±0.9	981173851.8	981173852.9	4.1	5.7	6.8	7.9
481	981165274.2±5.9	981165272.6±0.6	981165274.5	981165274.2	− 3.8	− 3.4	− 3.5	− 3.8
491	981152427.3±5.9	981152429.2±1.0	981152429.6	981152426.9	5.3	7.1	7.6	4.9
501	981141753.1±5.9	981141754.2±2.9	981141754.5	981141753.4	0.1	1.1	1.5	0.4
511	981129263.5±6.0	981129263.9±1.1	981129262.8	981129263.3	− 3.5	− 3.1	− 4.2	− 3.7
521	981122744.8±5.9	981122745.2±1.1	981122746.0	981122745.0	− 1.2	− 0.8	0.0	− 1.0
531	981110163.0±6.0	981110162.6±1.3	981110161.8	981110160.5	− 4.0	− 4.4	− 5.2	− 5.5
541	981103370.5±6.0	981103371.1±1.3	981103371.9	981103372.5	− 0.5	0.0	0.9	1.5
551	981089985.7±6.0	981089985.7±1.6	981089985.1	981089983.2	− 5.6	− 1.3	− 0.9	− 3.8
563	981080036.4±6.0	981080035.4±1.8	981080037.1	981080034.8	− 5.6	− 6.6	− 4.9	− 7.2
571	981072101.2±6.0	981072102.0±1.8	981072103.1	981072100.2	4.2	4.9	6.1	3.2

**P* indicates the average proportion of weight between the predetermined (Kanngieser *et al.* 1983) gravity values and the observations of the D-meter campaign.

in spite of small differences in calibration functions used, periodic errors applied, different drift functions and data rejection criteria. For example, the differences between the LOM and the IPG gravity values have a mean of 0.5 μGal and a standard deviation of 1.2 μGal. The observation scheme employed in the D-meter campaign appears to have randomized all these influences to produce a relatively unbiased estimates for the gravity values. The gravity values determined in the D-meter campaign do differ, however, from the predetermined values by up to ± 7 μGal (Table 4). IPG found that even if the predetermined values are weighted 100 times higher than the average D-meter reading, differences of more than ± 3 μGal remained. These differences are probably due to the fact that some of the pillars of the Hannover–Harz line were established only recently and their gravity values were determined by tying them to only one point of the existing line. Also, short-period gravity changes may have taken place as a result of changes in ground-water conditions.

The adjusted gravity values of the IPG staircase calibration line are listed in Appendix B, Section 4. The values were computed by IPG based on all D-meters except D8, D14 and D23 which did not participate in the staircase calibration.

(b) Periodic-error corrections

Additive corrections to take into account periodic errors arising from imperfections in the gearbox system of the gravimeter were determined independently by LOM and IPG. IPG constrained the periods determined in the adjustment to those being larger than twice the smallest gravity difference on the staircase calibration line (Appendix B, Section 4). LOM used four periods for all instruments. IPG and LOM used both the observations gathered on the Hannover–Harz line and those from the staircase calibration line at IPG to determine amplitudes and phases. Results are given in Table 5.

D37 and D77 show relatively large amplitudes of more than 4 μGal. Other instruments have magnitudes consistent with those found in earlier investigations (Becker 1981; Kanngieser 1982). D8, D14 and D23 did not take part in the measurements on the IPG staircase calibration line; the values given in Table 5 were determined on the staircase calibration line in Hannover by the University of Hannover. More extensive measurements at different reset positions revealed an amplitude of about 1 μGal for D21 and D38 at a period of 6.5 c.u.

The LOM and the IPG results are in reasonable agreement; most of the discrepancies are within the error bounds given by IPG. Larger differences, such as those for D37 or D38, could possibly be explained by aliasing effects resulting from the introduction or neglect of periods. In the case of D8, D14 and D23 the results of LOM and IFE are based on different data. LOM had only the Hannover–Harz measurements at its disposal.

To investigate the possible presence of periods other than the ones expected theoretically a least-squares spectral analysis (Vanicek 1971) was performed by IPG for all instruments used on the IPG staircase line in Darmstadt. Only D18 yielded a significant unexpected peak; a single peak at the period of 2.78 c.u. A tentative adjustment introducing solely the period of 2.78 resulted in an amplitude of 1.9 ± 0.6 μGal and a phase-lag of $40^\circ \pm 18^\circ$, which is almost the same magnitude as found for the period of 3.25 c.u. Further measurements are required to clarify whether the unexpected period is real or whether the signal is caused, for example, by an amplitude modulation of normally expected periods.

The investigation of the series of measurements of D21 and D38 indicate a possible change of the amplitude of the periodic errors at different parts of the screw. More measurements are needed but a variation of ± 1–1.5 μGal seems possible (see Becker 1984).

Table 5. Periodic errors computed by LOM, IPG and IFE*

Instrument	Source	Period 0.3611 C.U. A	Period 0.3611 C.U. Φ	Period 0.7222 C.U. A	Period 0.7222 C.U. Φ	Period 1.625 C.U. A	Period 1.625 C.U. Φ	Period 3.25 C.U. A	Period 3.25 C.U. Φ	Period 6.5 C.U. A	Period 6.5 C.U. Φ
D 6	LOM	1.3	230	1.0	258	2.1	156	0.9	165	–	–
	IPG	–	–	–	–	1.6±0.7	142±23	–	–	–	–
D 8	LOM	2.2	265	4.2	163	3.2	53	1.8	323	–	–
	IFE	–	–	1.6	60	–	–	1.7	17	–	–
D 14	LOM	3.3	282	4.0	26	3.4	213	1.9	98	–	–
	IFE	–	–	–	–	1.4	207	–	–	–	–
D 16	LOM	0.4	74	1.4	289	2.0	158	2.5	92	–	–
	IPG	–	–	–	–	–	–	2.0±0.9	87±25	–	–
D 18	LOM	1.8	187	1.0	293	1.1	78	2.0	122	–	–
	IPG	–	–	–	–	–	–	2.2±0.6	147±15	–	–
D 21	LOM	1.2	300	0.7	156	2.6	257	1.6	9	–	–
	IPG	–	–	–	–	2.8±0.5	260±11	1.5±0.5	65±18	1.2±0.6	14±26
D 23	LOM	1.0	137	3.6	234	1.5	135	2.6	210	–	–
	IFE	–	–	–	–	–	–	3.0	212	–	–
D 27	LOM	2.0	216	1.4	130	2.2	318	1.7	299	–	–
	IPG	–	–	–	–	1.9±0.7	328±20	2.2±0.7	296±16	–	–
D 37	LOM	1.6	177	1.6	132	1.8	108	8.0	171	–	–
	IPG	–	–	–	–	3.4±0.7	132±11	6.8±0.7	170±6	–	–
D 38	LOM	0.9	143	0.1	281	3.8	124	0.2	114	–	–
	IPG	–	–	–	–	3.6±0.4	142±7	1.9±0.4	46±15	1.0±0.4	214±27
D 60	LOM	2.9	175	0.4	217	0.9	132	3.0	341	–	–
	IPG	–	–	–	–	0.9±0.9	278±54	0.8±0.9	355±66	–	–
D 73	LOM	2.4	301	7.5	92	3.2	190	2.6	77	–	–
	IPG	–	–	–	–	–	–	–	–	–	–
D 77	LOM	1.5	175	1.3	370	5.7	128	3.7	88	–	–
	IPG	–	–	–	–	6.0±0.8	125±8	2.6±0.7	72±16	–	–

*Institüt für Erdmessung, Universität Hannover,
Amplitudes (A) are in μGal; phases (Φ) are in degrees.

(c) Instrument drift

The observational models described by equations (1) (IPG and LOM) and (3) (EPB) require an adequate parameterization of the systematic or 'drift' component of the gravity changes sensed by each instrument.

The long-term drift of the gravimeters is determined from the daily offset unknowns of equation (1). These data show that D6, D18, D21, D23, D27, D37 and D38 drifted about 10 μGal day^{-1} and D8, D14, D16 and D77 drifted about 20–30 μGal day^{-1}. An exception was D60 which drifted at a rate of 180 μGal day^{-1}. Except for D18 and D77, instruments transported in a special suspension box had a lower long-term drift rate than those that were not.

Over the course of one day's observations most instruments showed a non-linear drift behaviour. No abnormal drift rate or degradation of precision was seen as a consequence of a reset change, although D6, D23 and D38 showed a change in sign after one of the reset changes. Daily drift rates did not appear to correlate with particular gravity stations or with a particular observing day; nor did instruments transported together show a similar drift rate. There was no obvious correlation between gravity residuals and temperature or air pressure. The gravimeters seem to react individually, i.e. every instrument in a different way.

(d) Calibration functions

Calibration functions were determined by IPG and LOM (Table 6) by fitting all the observations for each D-meter to the reference gravity values of the Hannover–Harz line calculated by each institution, respectively (Table 4; column 1, IPG; column 3, LOM). The calibration term or reading correction term in equation (1) takes the form

$$K_{g,q}(R) = (L \cdot R + Q \cdot R^2 + C \cdot R^3) - F \cdot R, \tag{4}$$

where R is in c.u. and $K_{g,q}(R)$ is in mGals. Since nominal scale factors (F) were already available from the manufacturer and from other experiments, the calibration polynomials given in Table 6 represent corrections to these nominal scale factors. All instruments were found to have significant non-linear calibration components giving rise to corrections of the order of 10–60 μGal.

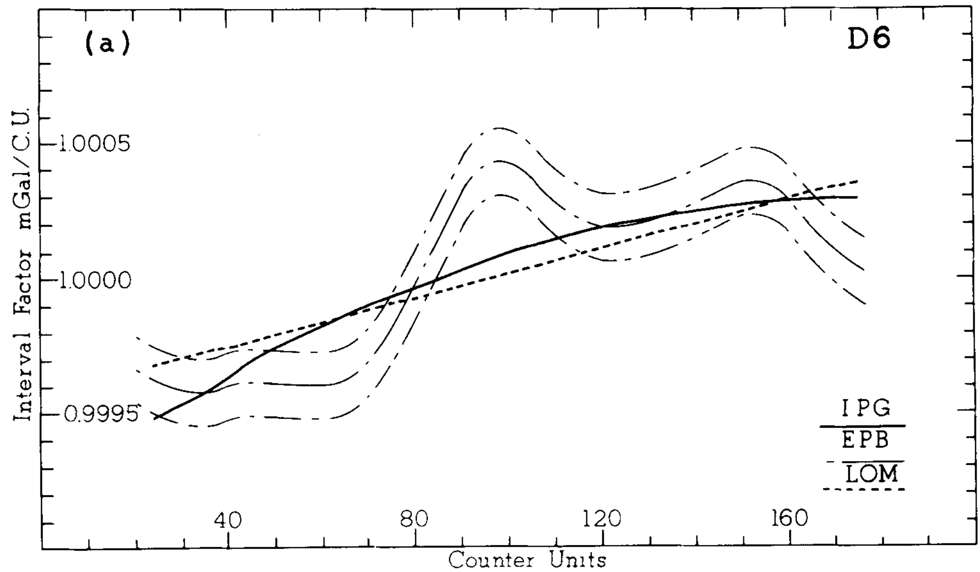
The presence of fine structure in the calibration curves not resolvable with polynomials alone was investigated by EPB. Calibration functions were determined in the form of interval factors [calibration term of equation (3)] by dividing adjusted gravity differences for each D-meter on the Hannover–Harz line into the EPB reference gravity differences (Table 4, column 4). Two sets of 18 interval factors and corresponding standard errors were computed for each instrument: one set for reset position R1 and one combined set for reset positions R2 and R3. Using a curve-fitting method developed by Vondrak (1969), a pair of smooth curves and associated error envelopes were determined for each gravimeter by fitting the two sets of interval factors (points centred in each 10 c.u. interval). Curves were fitted before and after the application of periodic-error corrections (Table 5); the corrections produced significantly smoother curves. The stiffness and the associated variance of the two curves were further increased where necessary until there was no significant difference at the 90 per cent confidence level. Then, a mean curve and associated error envelope were calculated.

Figs 3–6 compare the calibration curves computed by IPG, LOM and EPB for the 13 D-meters in the form of interval-factor curves. The calibration functions determined by IPG and LOM (Table 6) were expressed in the form of interval-factor curves by differentiating expression (4). At a 90 per cent confidence level the EPB curves for D6, D8, D27, D38, D77

Table 6. Coefficients of calibration polynomials obtained on the Hannover–Harz calibration line.

Instrument	Institution	Nominal scale factor F	Linear term $L \cdot 10^4$	Quadratic term $Q \cdot 10^6$	Cubic term $C \cdot 10^8$
D 6	LOM	1.0388*	2.72	2.39	–
	IPG		6.54 ± 1.32	-6.48 ± 1.59	1.22 ± 0.53
D 8	LOM	1.085	-10.02	-8.04	-4.41
	IPG		-10.86 ± 1.30	9.71 ± 1.86	-5.17 ± 0.68
D 14	LOM	1.114	-14.20	-20.48	-6.58
	IPG		-13.73 ± 1.31	20.10 ± 2.08	-6.48 ± 0.80
D 16	LOM	1.2495	-12.20	–	–
	IPG		– 5.15 ± 1.08	– 3.21 ± 0.48	–
D 18	LOM	1.3563*	– 6.34	3.70	–
	IPG		– 6.27 ± 0.77	3.53 ± 0.38	–
D 21	LOM	1.12023*	12.99	-10.60	2.41
	IPG		13.37 ± 1.50	-11.43 ± 1.80	2.70 ± 0.60
D 23	LOM	1.1828	13.93	-16.13	4.78
	IPG		14.92 ± 1.11	-17.46 ± 1.66	5.33 ± 0.66
D 27	LOM	1.10757*	– 4.41	–	–
	IPG		– 1.55 ± 1.59	– 1.17 ± 0.75	–
D 37	LOM	1.1646	– 0.78	2.62	–
	IPG		– 6.37 ± 1.91	8.21 ± 2.17	-1.55 ± 0.70
D 38	LOM	1.24667*	– 0.09	–	–
	IPG		3.30 ± 0.71	– 1.19 ± 0.33	–
D 60	LOM	1.0725	8.39	– 2.84	–
	IPG		15.17 ± 2.03	-12.84 ± 2.54	3.63 ± 0.84
D 73	LOM	1.126	26.13	-34.79	9.59
	IPG		27.47 ± 4.06	-34.04 ± 5.0	8.79 ± 1.71
D 77	LOM	1.1092	12.63	– 2.48	–
	IPG		11.77 ± 0.68	– 2.03 ± 0.32	–

* Nominal scale factors improved by earlier calibration measurements.



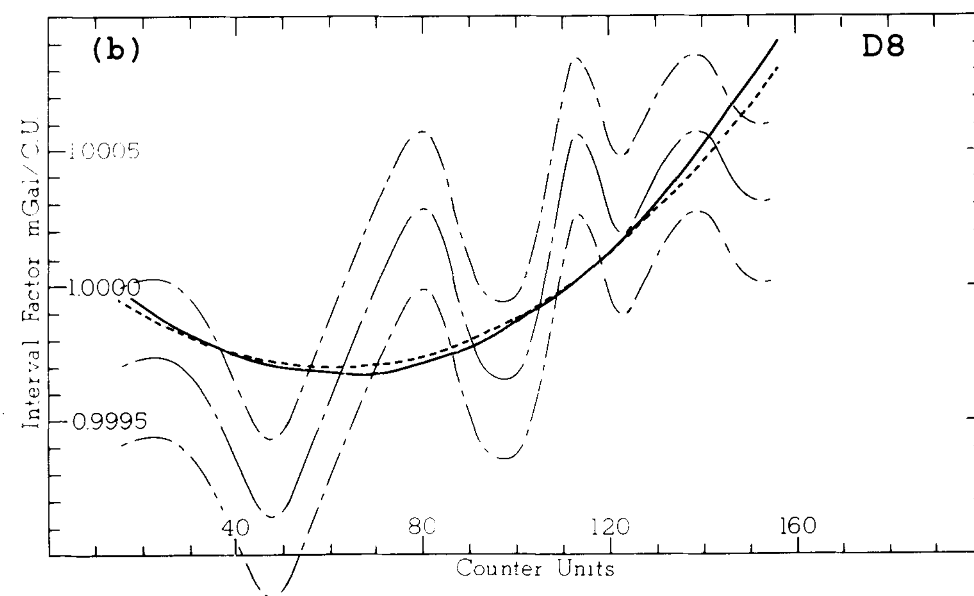
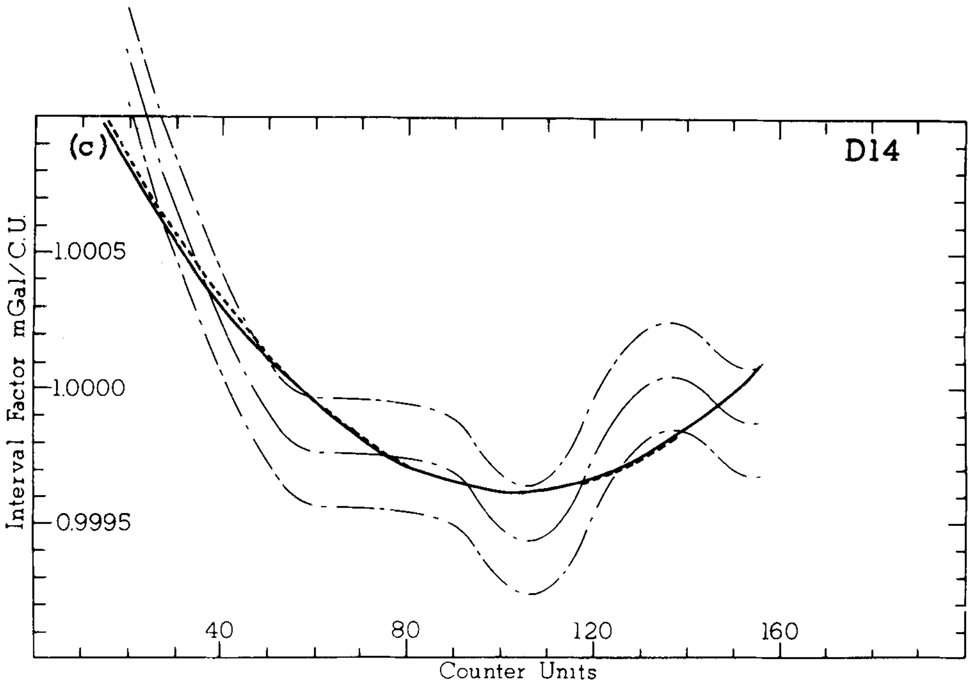


Figure 3. Interval factor curves for gravimeters D6 (a), D8 (b), D14 (c), D16 (d), assuming linear scale factors of 1.038 998, 1.085 846, 1.113 723 and 1.250 625, respectively. A 1σ error-envelope for the EPB-calculated curves is denoted by light dashed lines.

differ significantly from the smoother polynomial curves. Error bounds given for the IPG polynomial coefficients (Table 6) are not easily converted to errors in interval-factor curves because the coefficients are correlated. However, the similarity of the error in the EPB and polynomial calibration functions can be demonstrated by comparing the calibration error for a 100 mGal gravity difference for four typical instruments (Table 7). The IPG errors, for example, are calculated from the errors in the polynomial coefficients using the rules of



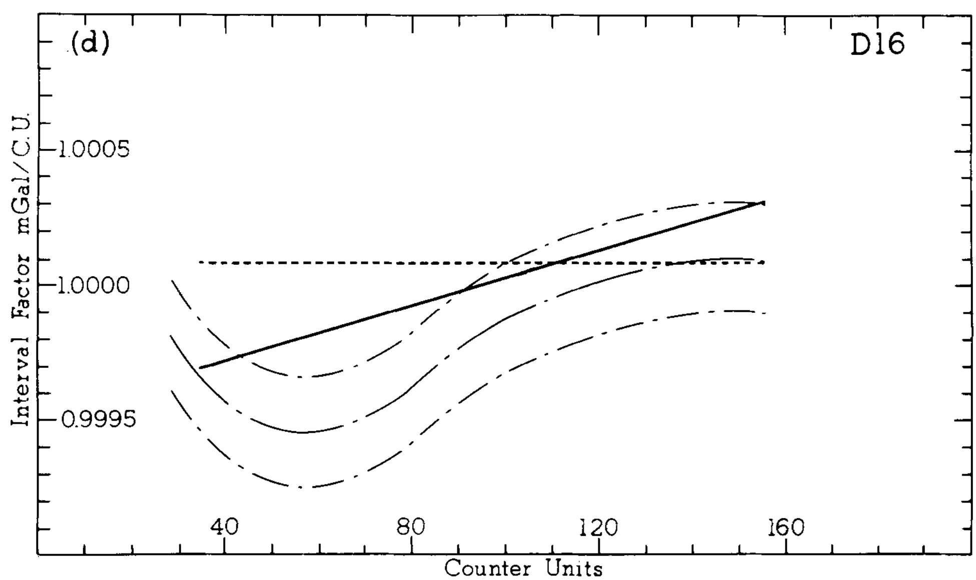


Figure 3–*continued*

Table 7. Comparison of calibration function error over 100 mGal.

Instrument	IPG Error	EPB Error
D 6	3.6	3.8
D21	2.4	3.8
D38	3.4	3.8
D60	7.1	8.8

error propagation, and the EPB errors are calculated by integrating the error envelopes of the appropriate interval-factor curves (Figs 3–6).

Discussion and conclusions

The calibration functions for the 13 LCR model-D gravimeters (Figs 3–6) were derived from data observed on the Hannover–Harz line at three different settings of the reset screw.

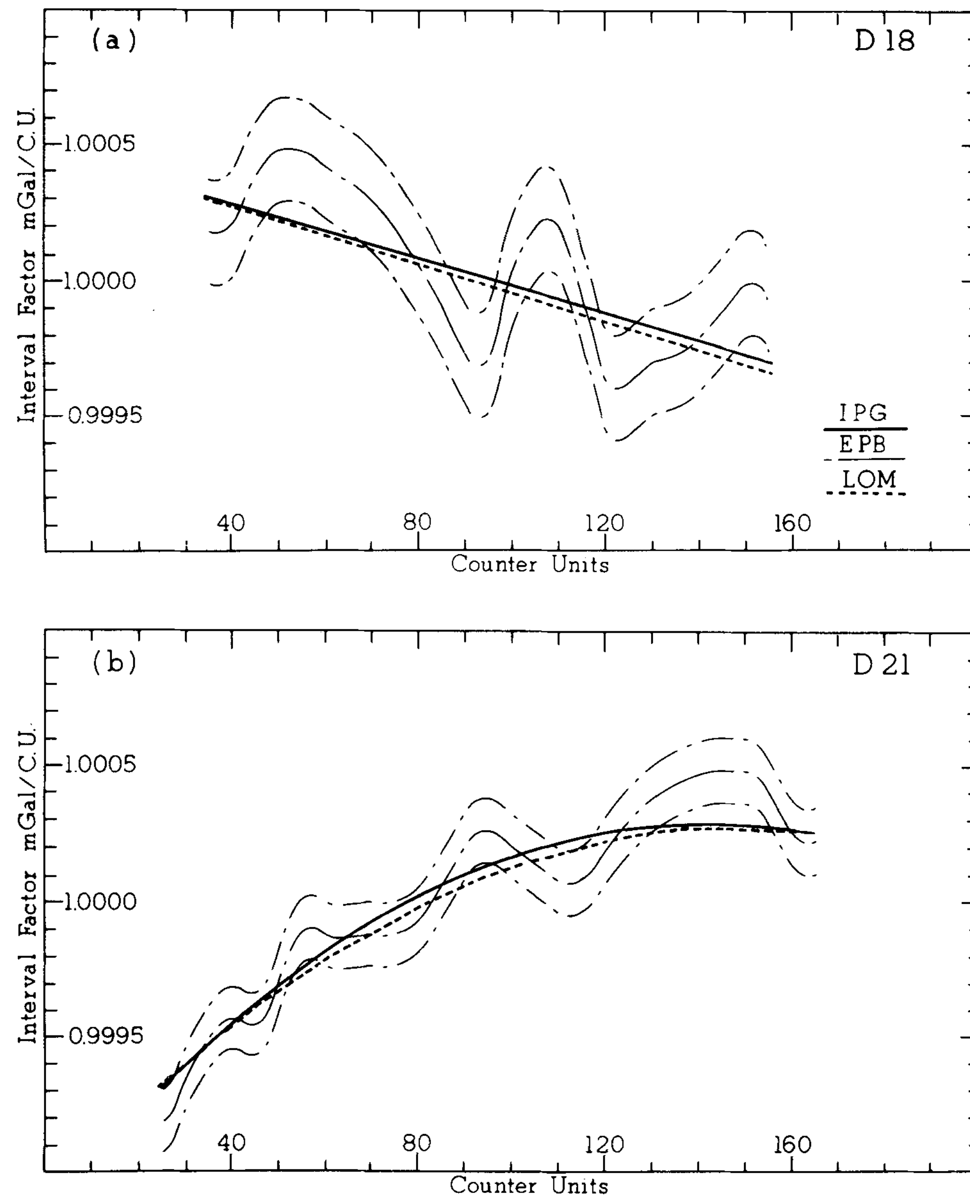


Figure 4. Interval factor curves for gravimeters D18 (a), D21 (b), D23 (c), D27 (d), assuming linear scale factors of 1.356 257, 1.120 181, 1.182 822 and 1.107 947, respectively. A 1σ error envelope for the EPB-calculated curves is denoted by the light dashed lines.

Readings taken at different settings did not produce significantly different calibration functions provided the data were sufficiently smoothed by a suitable curve fitting method. In other words, the significant changes due to reset found for some instruments during the initial curve fitting can be considered as short-wavelength, random instabilities that are better smoothed out by fitting a less flexible curve and accepting slightly larger errors.

The calibration functions for D6 and D27 were determined earlier in the laboratory by the Cloudcroft Jr. method (Lambert & Liard 1981). A comparison between the calibration

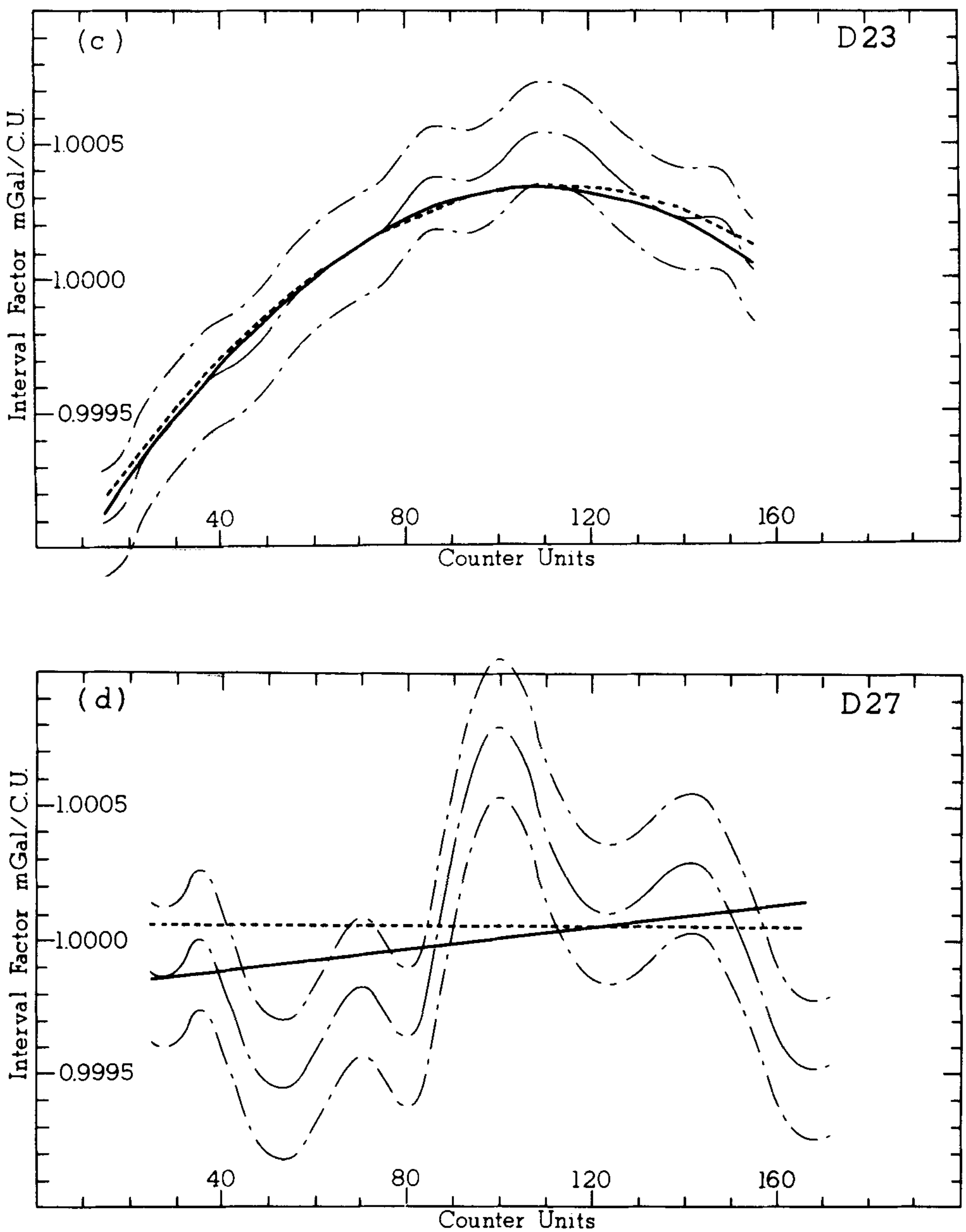
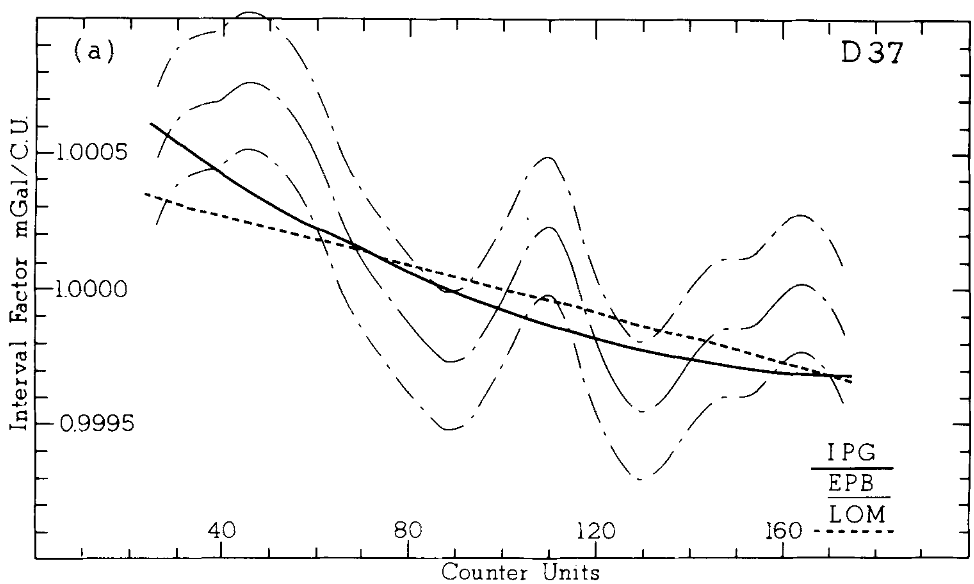


Figure 4—*continued*

functions derived during the present experiment with those determined by the Cloudcroft Jr. method shows a good agreement (Fig. 7). In this comparison the earlier Cloudcroft Jr. results have been modified slightly by correcting for the periodic errors computed by IPG during the D-meter campaign. Taking the experimental errors into account only one point (D6) determined by the laboratory method is significantly different from the campaign results at the 10 per cent probability level.



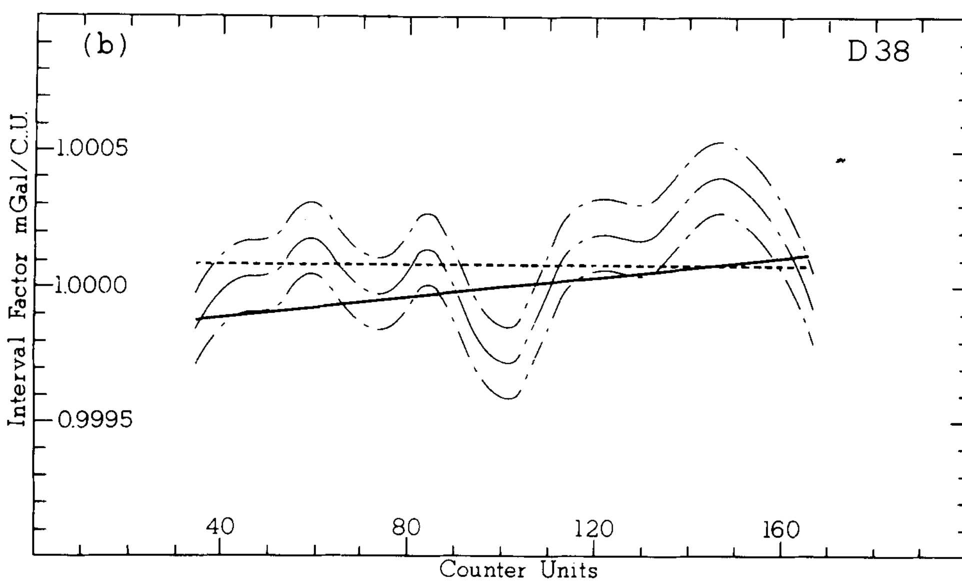


Figure 5. Interval factor curves for gravimeters D37 (a), D38 (b), D60 (c), D73 (d), assuming linear scale factors of 1.164 159, 1.246 578, 1.072 233 and 1.126 847, respectively. A 1σ error envelope for the EPB-calculated curves is denoted by the light dashed lines.

The application of periodic-error corrections (Table 5) to the data significantly improved the results. For example, EPB applied the IPG periodic-error corrections and noticed a reduced scatter of interval-factor values for many instruments. The flexibility of the curve necessary to fit the interval-factor values was significantly reduced for most instruments, whereas the standard deviation of fit remained the same. The improvement as a result of periodic error corrections was most evident for instruments D21, D23, D37 and D38.

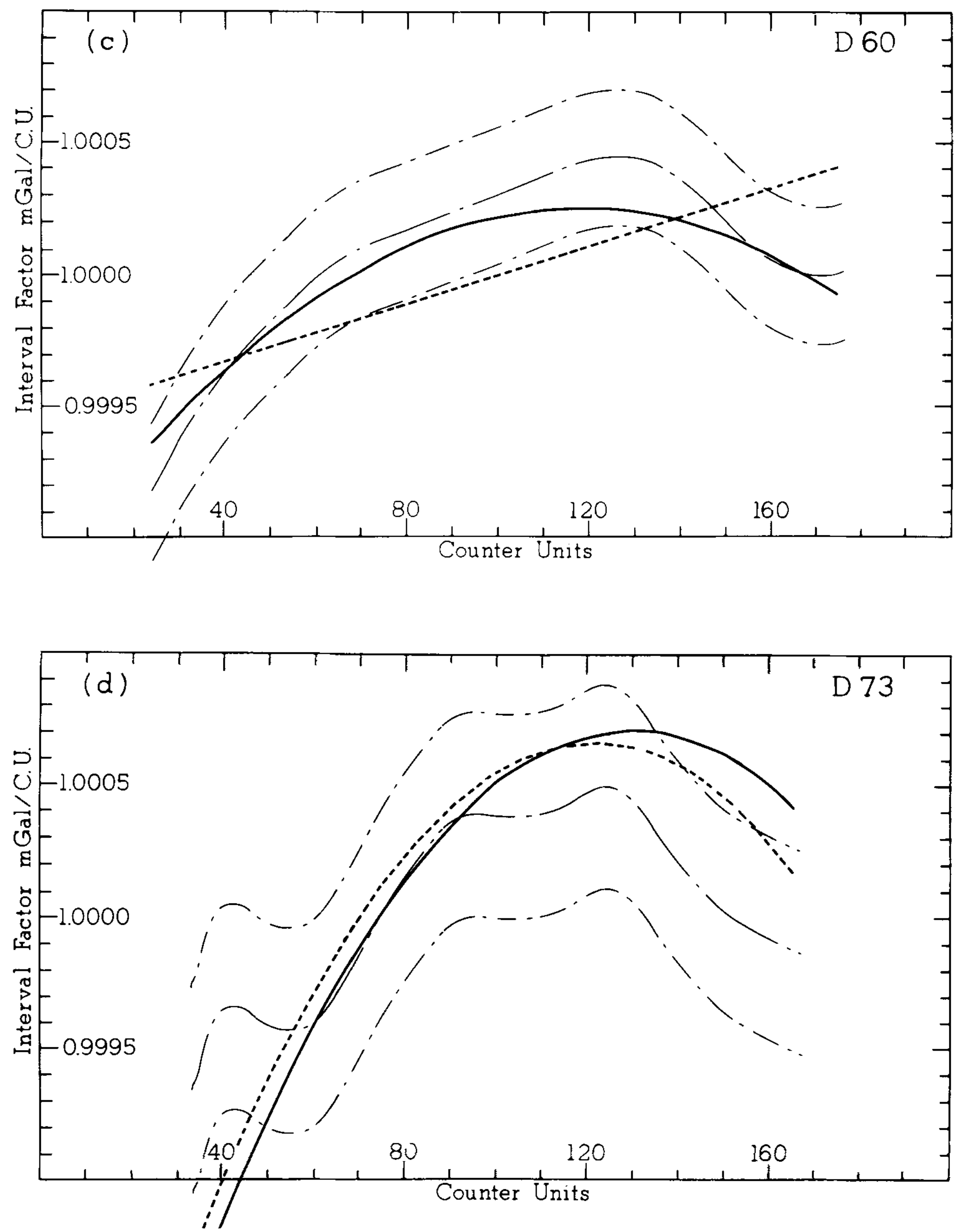


Figure 5–*continued*

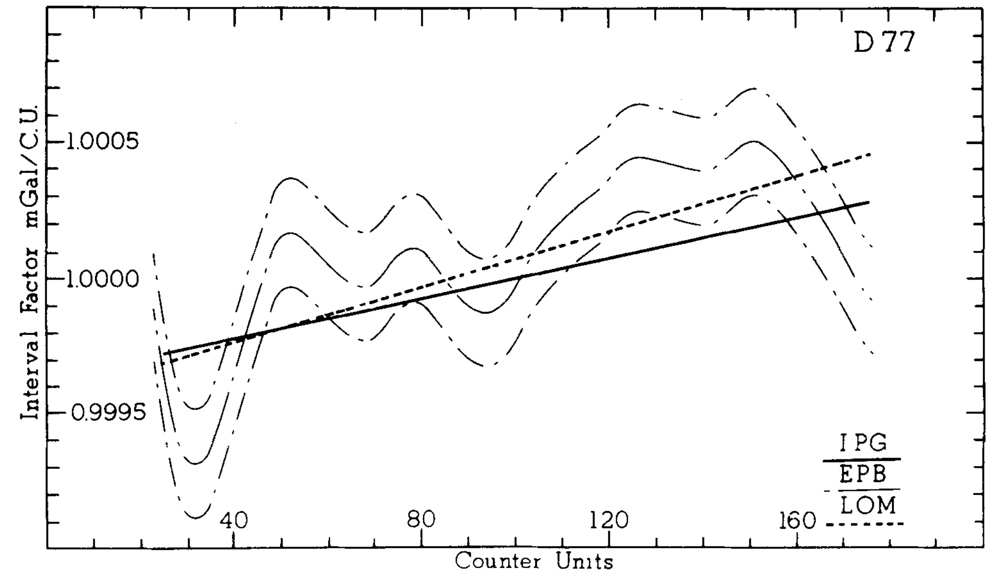


Figure 6. Interval factor curves for gravimeter D77 assuming a linear scale factor of 1.108 429, A 1σ error envelope for the EPB-calculated curve is denoted by the light dashed lines.

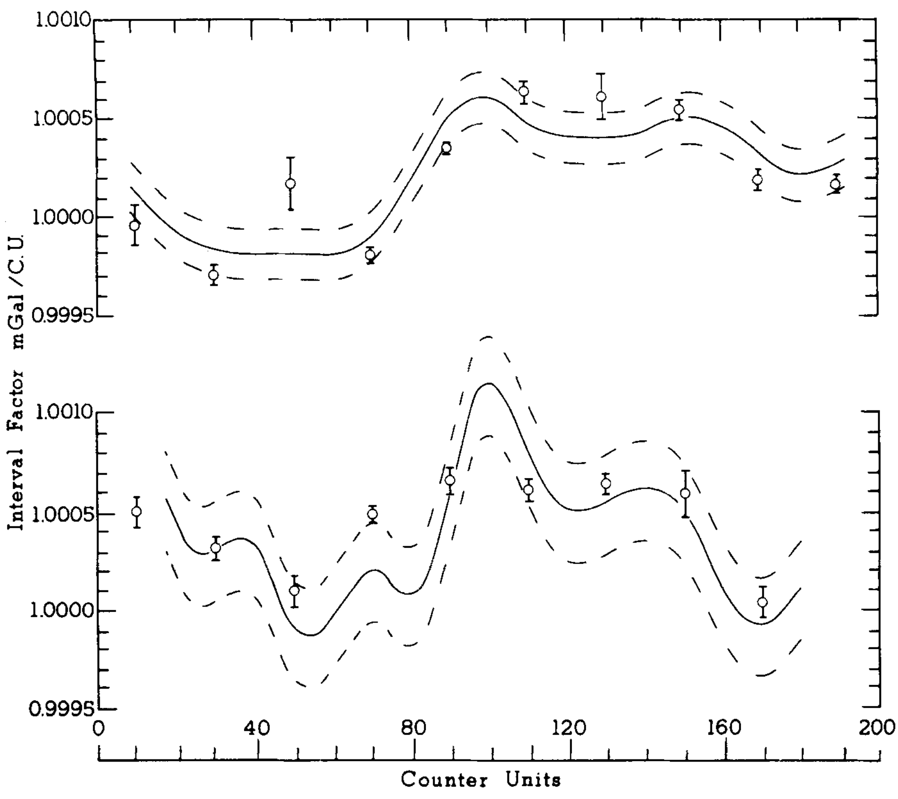


Figure 7. Comparison of interval-factor values derived by the Cloudcroft Jr. technique with curves derived from the D-meter campaign for D6 (upper panel) and D27 (lower panel). The Cloudcroft Jr. interval-factor values are only relative and have been adjusted to have the same mean value as the D-meter campaign curves. Vertical bars and dashed envelopes represent 1σ errors.

In classifying the performance of a gravimeter, precision must be distinguished from accuracy. The precision is a measure of the consistency of the observations of an instrument and can be determined by the free or unconstrained adjustment of the data. The accuracy is determined by comparing the results from one instrument with a set of reference values.

Some statements can be made about the performance of the individual D-meters from the mean standard errors of the station values obtained in a free adjustment of the campaign data (Table 3). Except for the group of instruments D8, D14, D60 and D73 which exhibited the lowest precision, the mean standard errors vary by less than 1–2 μGal for the different reset positions. No trends in precision with time or with the change from flat to hilly terrain could be detected. Comparisons by IPG show that the precision of some instruments (D18, D60, D77) deteriorate significantly going from indoors (staircase cal. line) to outdoors (Hannover–Harz line), whereas some (D6, D27, D37) had the same precision and others (D16, D21, D38) actually improved. Instruments transported in the manufacturers' cases without a special suspension system tended to give inferior precision in the field. D60 and D77 may also be more sensitive to shocks and vibrations because of their young age of about two and five months, respectively. Disregarding the optical reading method which is not used in high-precision work, the method of reading seems to have a minor effect on the precision. For example, D16, D18, D60 and D77 used the internal galvanometer; D6, D27 and D38 used an external analogue voltmeter (D38 used a 10 s RC filter); whereas D8, D14, D23 and D77 used external digital voltmeters with appropriate filters. D73 was a newly modified D-meter which appeared to suffer from problems with its prototype electrostatic nulling circuit; the results obtained during the campaign were not representative of the normal performance of this instrument.

It can be shown (Appendix C) that the accuracy of each of the 13 D-meters can be calculated from an estimate of the reading precision and the standard errors of the interval-factor curves. The accuracy of the measurement of gravity difference Δg from a set of observed gravity differences between the stations is given by

$$\sigma_{\Delta g} = \left[\sigma^2 + \frac{\Delta R}{10\ \text{c.u.}}\,(\sigma_c^2)\right]^{1/2}, \tag{5}$$

where σ is the standard error of the mean of the set of gravity differences in mGal, σ_c is the standard error of the calibration function of the gravimeter in mGal, and ΔR is the reading difference in c.u. For example, the accuracy of the measurement of an isolated 50 mGal gravity difference from six ties can be calculated as follows. An average D-meter has a mean standard deviation of unit weight of 8.0 μGal which translates into a standard error or precision (σ) (Table 3) of 3.3×10^{-3} mGal for the measurement of a gravity difference. An average D-meter has a calibration function error of 2×10^{-4} mGal c.u.$^{-1}$ (Figs 3–6) which translates into a standard error σ_c for each 10 c.u. interval of 2×10^{-3} mGal. Substituting these values of σ and σ_c into (5) and changing to μGal we have

$$\sigma = [3.3^2 + 5(2^2)]^{1/2}$$
$$= 5.5\ \mu\text{Gal}$$

The uncertainty resulting from errors in calibration surpass those associated with repeatability when the gravity difference exceeds about 26 mGal. Instrument D21 which was found to be the most accurate D-meter participating in the campaign would measure a 50 mGal gravity difference with an accuracy of 2.8 μGal. As anticipated high precision does not necessarily mean high accuracy. For example, D27 has a higher than average precision but a lower than average accuracy. Conversely, D14 has a poor precision but an average accuracy. A comparison between precision and accuracy was also made by comparing the root mean-square residuals for separate constrained and unconstrained adjustments for individual instruments on the Hannover–Harz calibration line. In a constrained adjustment where the gravity values of the stations were fixed to the reference values (Table 4), D8, D27 and D60 exhibited greater than average increases in root mean square residuals over the unconstrained case.

The application of equation (5) to determine the accuracy of station values in a network is not straightforward. The error contribution of the first term is reduced as the number of interconnections between stations is increased. The error contribution of the second term, however, can only be reduced by increasing the number of gravimeters in the survey. For a network that spans a range of 100 mGal the calibration-function error with respect to the network mean (maximum difference 50 mGal) can reach 4.5 μGal for an average D-meter. Combining two average D-meters in a network would reduce this component of the error to 3.2 μGal.

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Appendix A

Participants in the D-meter campaign	Instr.	Modifications	Method of transportation
1. International Latitude Observatory, Mizusawa, Japan (Dr Nakai)	D73*	Harrison–Sato feedback	IPG‡
2. California State University, Long Beach, USA (Professor Grannell)	D77	Electronic levels	IPG
3. Department of Scientific and Industrial Research, Wellington, New Zealand (Dr Woodward)	D37		IPG
4. Pacific Geoscience Centre, Sidney, Canada (Dr Dragert)	D27		IPG
5. Earth Physics Branch, Ottawa, Canada (Dr Lambert)	D6		IPG
6. Università Trieste, Italy (Dr Marson)	D18	–	Manufacturer's case
7. Università Roma, Italy (Professor Toro)	D60	–	Manufacturer's case
8. Eidgenössische Techn. Hochschule, Zürich, Switzerland (W. Fischer, A. Wiget)	D16 G317†	–	Manufacturer's case
9. Universität Hannover, FRG (R. Roder)	D14	–	Manufacturer's case
10. Niedersächsisches Landesverwaltungsamt, Hannover, FRG (K. Kummer)	D23	–	Open case, spring-suspension
11. Technische Universität Clausthal, FRG (observed by University of Hannover, R. Schnüll)	D8	–	Manufacturer's case
12. Inst. für Angewandte Geodäsie, Frankfurt, FRG (H. Beetz)	D21	Additional thermo-statized enclosure, electronic levels	Spring-suspension
13. Technische Hochschule Darmstadt, Darmstadt, FRG (Dr Becker)	D38	Inner G-meter type enclosure inside standard D-meter enclosure	IPG

* Instabilities of unknown origin reduced the performance of this instrument.

† Not included in this analysis.

‡ IPG = spring suspension with open carrying cases of the Institute of Physical Geodesy, Darmstadt.

Appendix B. Details of the observation scheme for the D-meter campaign

(1) Typical timetable of observations by an instrument on the Hannover–Harz calibration line.

Day	Reset-screw position	Observation sequence (– single measurement, ≡ triple measurement)
1	R1	11 ≡ 401 ≡ 411 ≡ 421 ≡ 431 ≡ 441
2	R1	441 – 11 – 481 – 441 – 11 – 441
3	R1	563 ≡ 551 ≡ 541 ≡ 531 ≡ 521 ≡ 571
4	R1	511 ≡ 521 ≡ 481 ≡ 571 ≡ 563
5	R1	481 ≡ 491 ≡ 501 ≡ 511
6	R1	441 ≡ 451 ≡ 463 ≡ 471 ≡ 481
7	. . . .	. Break. . . . .
8	R2	11 ≡ 401 ≡ 411 ≡ 421 ≡ 431 ≡ 441
9	R2	441 ≡ 451 ≡ 463 ≡ 471 ≡ 481
10	R3	511 ≡ 521 ≡ 481 ≡ 571 ≡ 563
11	R3	563 ≡ 551 ≡ 541 ≡ 531 ≡ 521 ≡ 571
12	R3	481 ≡ 491 ≡ 501 ≡ 511
13	R2	441 – 11 – 481 – 441 – 481 – 11 – 441

Calibration stations in order of decreasing gravity: 11, 401, 411, 421, 431, 441, 451, 461, 471, 481, 491, 501, 511, 521, 531, 541, 551, 563, 571

Approximate gravity differences between above calibration stations in mGal: 11, 9, 9, 12, 10, 9, 10, 17, 9, 13, 11, 13, 7, 13, 7, 14, 9, 8

(2) Number of observations per station and per instrument on the Hannover–Harz calibration line

	D06	D08	D14	D16	D18	D21	D23	D27	D37	D38	D60	D73	D77
11	9	9	10	8	8	8	10	8	10	8	8	8	8
401	6	6	6	7	7	7	6	6	6	6	7	6	6
411	6	6	6	7	6	6	6	6	6	6	6	6	6
421	8	7	7	6	7	6	7	10	8	10	7	10	8
431	10	7	7	9	9	7	7	7	10	7	10	7	10
441	15	10	10	17	14	13	11	13	15	13	14	13	15
451	6	6	6	6	6	6	6	7	6	7	6	7	6
461	8	6	6	6	7	6	6	11	8	11	7	11	8
471	7	7	7	8	8	7	7	6	7	6	9	6	7
481	20	17	17	20	17	17	17	17	20	17	17	17	21
491	7	6	6	7	6	6	6	6	7	6	6	6	7
501	11	6	6	7	8	6	6	12	11	12	8	12	11
511	6	8	8	10	8	7	8	8	6	8	8	8	6
521	13	13	13	13	13	13	13	13	13	13	13	12	13
531	6	6	6	7	6	6	6	10	6	10	6	9	6
541	10	6	6	7	8	6	6	12	10	12	8	12	10
551	6	6	6	7	6	7	6	9	6	9	6	8	6
563	6	8	8	10	8	7	8	7	6	6	8	7	6
571	12	10	10	14	11	10	10	10	12	10	11	10	12

(3) Typical timetable of observations by an instrument on the staircase calibration line in Darmstadt

Day Observation sequence

1 59–68–85–102–119–136–149–136–119–102–85–68–59–51–43–34–26–17–19–1–19–17–26–34–43–51–59

Reset by 5.63 + $2n(3.25)$ c.u., where $n = 1, 2 \ldots$

2 Repeat sequence of day 1

(4) Adjusted gravity values and number of observations per station and per instrument on the staircase-calibration line in Darmstadt

Station	Gravity value (mGal)	Number of observations D6	D16	D18	D27	D37	D60	D77	D21	D38
1	3.2943±0.0011	3	4	4	6	5	4	2	10	18
9	2.8910±0.0012	4	4	4	6	4	4	4	10	–
17	2.5480±0.0011	4	4	4	6	5	4	4	10	18
26	2.0983±0.0012	4	4	4	7	5	4	5	10	–
34	1.6979±0.0010	6	4	4	6	6	4	5	10	18
43	1.2864±0.0012	4	4	4	6	6	4	4	10	–
51	0.8587±0.0011	4	6	4	7	7	4	5	10	18
59	0.4811±0.0011	5	6	6	7	4	4	8	15	–
68	0.023	5	5	6	7	6	4	4	10	18
85	−0.8244±0.0010	5	5	4	8	6	7	4	10	18
102	−1.7249±0.0010	6	4	4	6	7	5	5	10	18
119	−2.6092±0.0010	4	4	4	8	6	4	5	10	18
136	−3.4710±0.0010	4	4	4	6	5	4	4	10	18
149	−4.1225±0.0010	4	4	4	8	4	3	2	10	18

Departing from the typical procedure D21 performed five series of measurements at different reset positions. D38 performed six series of measurements at different reset positions and with slightly different design.

Appendix C. Derivation of expression for D-meter accuracy.

The difference in gravity between two stations can be expressed as

$$\Delta g = \sum_{k}^{N} F_k \cdot \Delta R_k, \tag{1C}$$

where F_k is the mean value of the calibration function over the kth interval ΔR_k and

$$\sum_{k}^{N} \Delta R_k = \Delta R$$

the reading difference between the two station in c.u. By the law of propagation of error

$$\sigma_{\Delta g}^2 = \sum_{k}^{N} (F_k^2 \cdot \sigma_{\Delta R_k}^2 + \Delta R_k^2 \cdot \sigma_{F_k}^2) \tag{2C}$$

Taking into account that $F_k \simeq 1$ mGal per c.u. and

$$\sum_{k}^{N} \sigma_{\Delta R_k}^2 = \sigma^2,$$

the first term on the right-hand side of (2C) becomes equal to σ^2, the variance of the corrected reading difference in mGal. The second term on the right-hand side of (2C) reduces to

$$\sigma_{F_k}^2 \cdot \sum_{k}^{N} \Delta R_k^2,$$

since $\sigma_{F_k}^2$ is an estimate of the variance of the calibration function for a 10 c.u. interval (the spacing on the calibration line) and is taken to be constant across the range of the gravimeter. Given that ΔR_k = 10 c.u. the second term reduces further to

$$\sigma_{F_k}^2 \cdot (\Delta R/10 \text{ c.u.}) \cdot (10 \text{ c.u.})^2.$$

Substituting these simplifications into (2C) gives

$$\sigma_{\Delta g}^2 = \sigma^2 + (\Delta R/10 \text{ c.u.}) \cdot \sigma_{F_k}^2 \cdot (10 \text{ c.u.})^2 \tag{3C}$$

and finally

$$\sigma_{\Delta g} = [\sigma^2 + (\Delta R/10 \text{ c.u.}) \cdot \sigma_c^2]^{1/2} \tag{4C}$$

where $\sigma_c = \sigma_{F_k} \cdot 10$ c.u., the error in mGal associated with each 10 c.u. segment of the calibration function.