THE CAPACITY OF THE SCINTREX AUTOGRAV CG-3M NO. 4492 GRAVIMETER FOR "ABSOLUTE-SCALE" SURVEYS

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ABSTRACT

In autumn 2001, the *Institut für Erdmessung* (IfE), received the new Scintrex Autograv CG-3M spring gravimeter no. 4492 (SC-4492). Compared with LaCoste-Romberg gravimeters, the Scintrex instrument offers the advantage of a more simple calibration function. Due to the straightforward sensor design (no micrometer screws and gearboxes, no astatisation), a modelling of periodical calibration terms and of a higher order polynomial calibration function is not required. The costly calibration measurements can be reduced to some relative observations between two reliable absolute gravity stations. No complex calibration system should be necessary. A reliable evaluation of the SC-4492 was done with respect to the stability of the calibration, measurement accuracy and precision, drift behaviour, and gravity range dependency of the calibration factor. Measurements were performed on the Hannover vertical calibration line (200 $\mu m/s^2$ (20 mGal) range, 20-storied building, 10 $\mu m/s^2$ interval), on the Cuxhaven-Harz north-south line (3000 $\mu m/s^2$ range, 34 stations, 90 $\mu m/s^2$ interval) of the gravimeter calibration system Hannover, and in the absolute gravimetry net of the Fennoscandian land uplift area (6200 $\mu m/s^2$ range). A total gravity range of almost 0.015 m/s^2 has been covered. In addition, the gravimeter was employed in the determination of vertical gravity gradients and centring to safety points for absolute gravimetry, and the observation of the horizontal gradient field at the IfE absolute gravity reference station in Clausthal. This paper presents the results as obtained in regional, local and microgravimetric surveys. The achieved accuracies are in the order of ±10 to 100 nm/s^2 (±1 to 10 µGal). No instability of the calibration and no gravity range dependency could be proven within the order of $1 \cdot 10^{-4}$. Overall, the gravity meter SC-4492 meets fully the expectations of IfE.

Keywords: Relative gravimetry, Scintrex gravimeter, gravimeter calibration, accuracy, gravimeter drift

1. INTRODUCTION

Depending on the applications in gravimetry, the determination of the gravity acceleration (*gravity*) requires different instrumental techniques and observation methods to ensure the required accuracy level. Relative gravimetry contributes among others to the following geodetic tasks: support of absolute gravimetry (centring to safety points, gradient measurement), monitoring of changes in geodynamic research areas, densification of national gravity reference networks, providing dense point data to improve regional geoids. The accuracies striving for are in the order of ±0.01 to a few ±0.1 $\mu m/s^2$. For high-precision relative gravimetry, LaCoste-Romberg (LCR) gravimeters have been employed nearly exclusively over some decades. The details of LCR systems are well described in literature, cf. TORGE, 1989. Since more than 10 years, Scintrex offers a new type of gravimeter, the Autograv CG-3/3M, e.g. see HUGIL, 1988. Fig. 1 shows a LCR and a Scintrex meter. A main advantage of the CG-3 system is that periodic errors of measurement screw and transmission are not existing.

Fig. 1. - Scintrex Autograv CG-3M no. 4492 (right) and the LaCoste-Romberg model G no. 709 with carrying case (left).

Table 1 summarizes the magnitude of periodic errors for 21 LCR gravimeters as determined in the gravimeter calibration system Hannover. Neglecting these errors, an additional uncertainty (systematic error) of a few 0.1 $\mu m/s^2$ can be possible for gravity differences.

TABLE 1: MAXIMUM AND MEAN AMPLITUDE OF THE PERIODIC CALIBRATION TERMS AS DERIVED FOR 21 LACOSTE-ROMBERG MODELL G GRAVIMETERS IN THE GRAVIMETER CALIBRATION SYSTEM HANNOVER.

Periods	up to LCR-G457	1.00	7.88	35.47	70.94
[CU]	from LCR-G458	1.00	7.33	36.67	70.33
Max. Amplitude		81	152	215	180
Mean Ampl. in $[nm/s^2]$		25	52	59	80

Therefore, for high-precise measurements with LCR instruments, the complete calibration function, including a periodic part, has to be applied:

$$g = N_0 + \sum_{k=1}^{m} Y_k z^k + \sum_{l=1}^{n} A_l \cos(\omega_l z - \varphi_l), \qquad \textbf{(1)}$$

with N_0 = instrument level, Y_k = calibration coefficients of degree k, z = reading in counter units, A_l = amplitude, ω_l = Frequency, φ_l = phase of the periodic term of degree l (time-dependencies are neglected in (1)). Comparisons of the results for 3 LCR instruments from IfE, all 3 employed in the calibration systems Hannover and Wuhan/China (different gravity ranges), showed significant discrepancies for the polynomial and periodical calibration parmeters (XU ET AL., 1988). Therefore, it is advised to avoid the transfer of the calibration parameters of LCR meters to different gravity ranges (recommendation from the authors: for distances of more than 0.005 m/s^2 away from the calibration system). For this paper, the calibration (time stability and gravity range dependency) of the Scintrex Autograv CG-3M no. 4492 has mainly been the focus of attention. The investigations have been performed over a time period of about 2.5 years and cover a gravity range of nearly 0.015 m/s^2 (1.5 Gal). In addition, other publications can be recommended to achieve a more general overview about the quality of the Scintrex Autograv CG-3/3M system, e.g., HUGILL, 1988; JOUSSET, 1995; FALK , 1995; REHREN, 1997, EVERAERTS, 2002. With respect to instrumental precision, accuracy, and drift, this paper confirms the results of the references given above.

2. SENSOR CHARACTERISTICS OF THE SCINTREX AUTOGRAV CG-3M

Main features of the gravimeter system (Fig. 2) are as follows, cf. HUGILL, 1988; SCINTREX, 1998:

- non-astatised quartz spring system,
- capacitive displacement transducer with feedback system (0.2 nm resolution),
- auto-calibration to A/D converter,
- electronic tilt sensors (1 sec. resolution) with realtime correction,
- vacuum chamber for gravity sensing system,
- no micrometer srew, no gearbox, no mechanical feedthrough,
- gravity range more than 0.07 m/s^2, 10 nm/s^2 resolution.

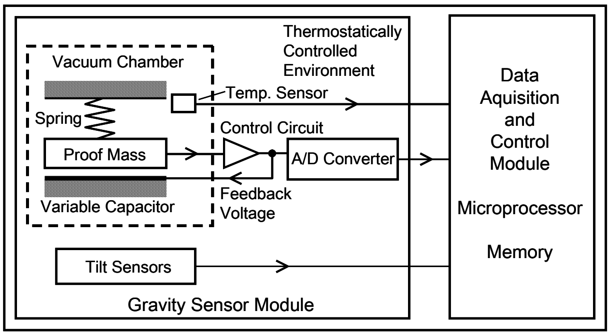

Fig. 2. - Scintrex Autograv CG-3 principle of operation, after HUGILL, 1988.

Besides the non-existence of periodic errors, an additional advantage of the linear system is that the sensitivity is independent of the inclination.

3. THE GRAVIMETER CALIBRATION SYSTEM HANNOVER

Most of the surveys with the SC-4492 were carried out in the gravimeter calibration system Hannover, see Fig. 3. This was established between 1976 and 1982 for the determination of calibration functions for LCR gravimeters with 0.01 $\mu m/s^2$ accuracy (KANNGIESER ET AL., 1983).

Fig. 3. - The station distribution of the gravimeter calibration system Hannover (Cuxhaven-Harz mountains, 3000 $\mu m/s^2$, 90 $\mu m/s^2$ interval), e.g. TORGE, 1989.

The system serves for the analysis of polynomial and periodic calibration terms, with the intent of improving the manufacturer's calibration tables which usually provide accuracies of 10^{-3} to 10^{-4} only. Over 13000 gravity differences measured with 47 LCR instruments and 12 absolute gravity determinations were included in the adjustment of the calibration system. The estimated mean standard deviations for the adjusted gravity differences are ±0.02 µm/s² for the Cuxhaven-Harz line (~90 µm/s² intervals) and ±0.01 µm/s² for the vertical calibration line Hannover (staircase of a 20-storied building, point intervals of 0.2, 2.0, and 10 µm/s²).

4. REGIONAL AND LOCAL SURVEYS WITH SC-4492

From November 2001 to May 2004, the SC-4492 has been employed in different projects in northern Germany and in Scandinavia (see Fig. 4). In most cases the instrument has not only been transported by hand but also by car. In general, the measurements were done using the step method. Each tie between neighbouring points was measured three times or more. Three registrations with a ReadTime (RT) of 60 s and a CycleTime (CT) of 80 s were carried out for each occupation. The seismic filter option of the online software was selected. The average of the second and third cycle was used for the postprocessing with the program system GRAV from WENZEL, 1993. Focussing on Table 2, the least squares adjustment provides accuracy estimates for the single gravity difference observations in the order of ±40 to ±100 nm/s². Measuring gravity ties with short transportation ways, points can be connected within an accuracy level of about ±10 nm/s². In Fig. 5 the discrepancies between the calibrations line reference values and the recent results from SC-4492 (datum defined by the two absolute gravity stations Hannover and Clausthal) are depicted. The points 461 to 571 are located in the Harz mountains and show discrepancies between -38 and +31 nm/s² (r.m.s. ±24 nm/s²). For the northern part of the calibration line, the differences are much larger (max. +65 nm/s², min. -114 nm/s², r.m.s. ±68 nm/s²). Besides measurement errors, the large discrepancies can also be caused by groundwater effects and/or real gravity changes during the last 20 years.

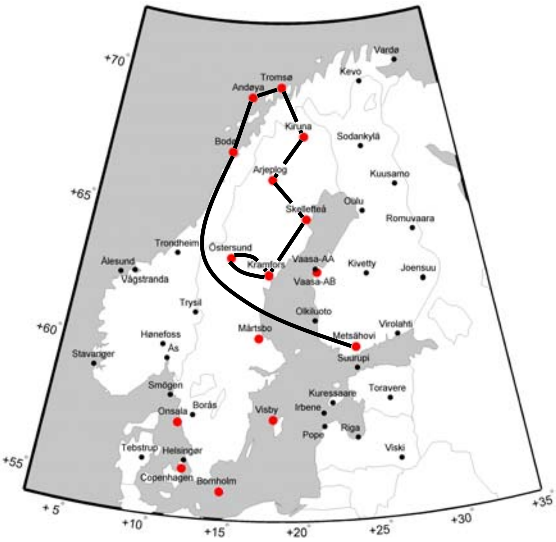

Fig. 4. - Absolute gravity station distribution in the Fennoscandian land uplift area. Lines are showing the ties measured by SC-4492 for calibration purposes.

Table 3 summarizes the calibration results obtained for SC-4492. Polynomial calibrations terms of higher degree were not found. The calibration factors E (improvement of the manufacturer calibration) were obtained with a precision between 2 to $8 \cdot 10^{-5}$, and are varying within a range of $3 \cdot 10^{-4}$. Calculating a mean factor and expressing the single deviations from the mean in gravity discrepancies (last column), disagreements not larger than 170 nm/s² were found.

TABLE 2: NETWORK AND ADJUSTMENT STATISTICS/RESULTS (RELATIVE ACCURACY, DRIFT, ETC.) FOR SCINTREX CG-3M NO. 4492, DERIVED IN DIFFERENT LOCAL AND REGIONAL NETWORKS.

Project	**Date**	**Max. Δg [µm/s²]**	**No. of points**	**No. of Δg meas.**	**Time span between obs. [min.]**	**Adj. linear drift [nm/s² per h]**	**Std.dev. of a single Δg meas. [nm/s²]**	**Std.dev. of station [nm/s²]**
Connection abs.station to calib.line in Hannover	12.11.2002 20.11.2002	14.0	3	20	~5 to 15	43	±60	±14
Excentre of abs.station in Onsala/Sweden	12.03.2004	0.5	2	19	~5 to 10	126	±50	±9
Profiling in Onsala	12.03.2004	1.7	4	22	~5 to 10	126	±50	±17
Calibration line Cuxhaven-Harz	05.11.2002 - 27.02.2003	3000	13	127	~10 to 60	133	±97	±50
Connection of two abs.points in Hannover	26.04.2004	8.0	2	15	~10 to 15	365	±36	±9
Conn. of abs.point to national net in Visby/Sweden	27.05.2004	48.0	2	6	~40 to 50	86	±63	±24

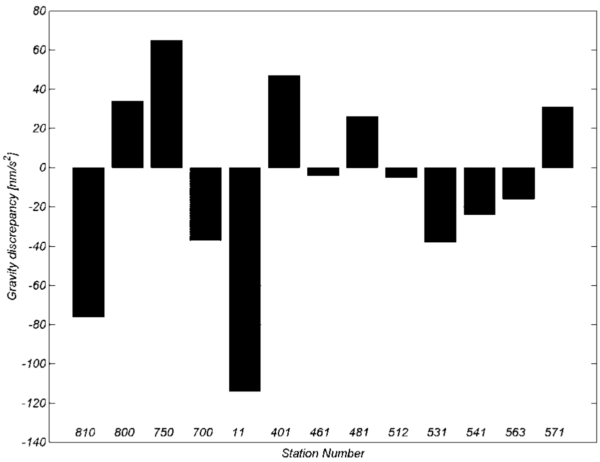

Fig. 5. - Differences between the results of the new survey of the North-South line of the Hannover calibration system with SC-4492 and the calibration line reference values.

But these values cannot be assigned to instabilities or gravity range dependencies of the calibration factor. The uncertainties in the reference gravity values, and, moreover, the subsurface water mass changes (ground water, soil moisture, crevasses and clefts in rock filled with water) can introduce errors of more than 100 nm/s^2. Therefore, a time dependent instability of the calibration in the order of $1 \cdot 10^{-4}$ cannot be excluded but is also not proven. In addition, the calibration results show no correlation with the different gravity ranges, which leads to the conclusion that no gravity range dependence exists over the total investigation range of 14700 µm/s².

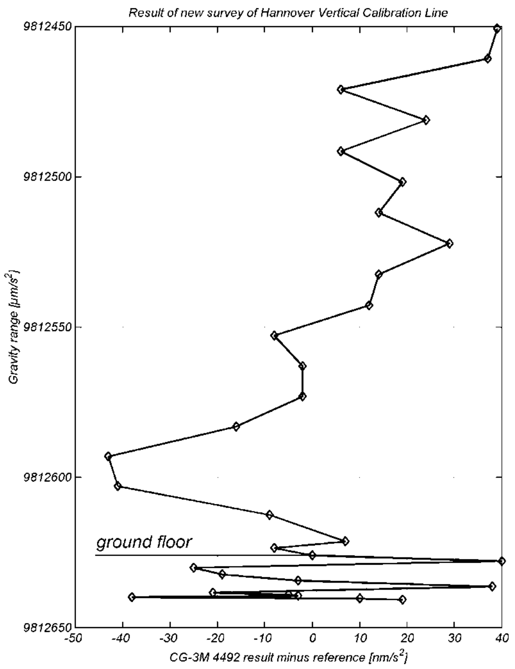

Fig. 6. - Differences between the reference values of the vertical calibration line and the new determined gravity values with SC-4492.

5. MICROGRAVIMETRIC MEASUREMENTS

Highest accuracy can be expected for measurements in a small network with points distributed

TABLE 3: CALIBRATION OF SCINTREX CG-3M NO. 4492 IN DIFFERENT GRAVITY RANGES OVER 2.5 YEARS (ADJUSTMENT RESULTS: CALIBRATION FACTOR, ACCURACY, DRIFT), TOTAL GRAVITY RANGE: 14680 µm/s².

Project	**Date**	**Gravity Range [m/s²]**	**Max. Δg [µm/s²]**	**No. of Δg measur.**	**Adj. linear cal.factor E**	**Adj. linear drift [nms^{-2}/h]**	**Std.dev. of a single Δg meas. [nm/s²]**	**Deviation ΔE from mean E [x10^{-6}]**	**ΔE → δg [nm/s²**
Calibration line Hannover-Cuxhaven	23.11.2001	9.81262-9.81380	1180	4	1.000854 ±0.000026	187	±135	80	+100
Connection of 2 abs. stations Hannover-Harz	04.07.2002	9.81263-9.81116	1470	4	1.000912 ±0.000034	248	±102	22	+40
Calibratione line Hannover-Harz	05.11.2002 - 22.01.2003	9.81262-9.81072	1900	104	1.001011 ±0.000025	180	±105	-77	-170
Connection of 2 abs. stat. Han.-Harz with intermediate points	14.11.2002 - 28.11.2002	9.81263-9.81116	1470	42	1.001031 ±0.000031	169	±54	-97	-140
Calibration line Hannover-Cuxhaven	23.01.2003 - 15.02.2003	9.81263-9.81380	1170	127	1.001062 ±0.000060	117	±99	-128	-170
Connection of 2 abs. stations Han.-Hamburg	27.02.2003	9.81263-9.81371	1080	13	1.000786 ±0.000020	196	±37	148	+160
Calibration line Harz mountains	21.04.2004	9.81165-9.81072	930	14	1.000872 ±0.000026	327	±81	62	+60
Fennoscandian land uplift area	02.06.2004 - 02.07.2004	9.81917-9.82540	6230	16	1.000945 ±0.000076	130	±247	-11	-70
Mean					1.000934 ±0.000033	194 (≡ 4.66 µms^{-2}/d)			

TABLE 4: NETWORK AND ADJUSTMENT STATISTICS/RESULTS (ACCURACY, DRIFT, ETC.): RE-MEASUREMENT OF 31 POINTS OF THE VERTICAL CALIBRATION LINE HANNOVER, DETERMINATION OF GRAVITY GRADIENTS WITH SCINTREX CG-3M NO. 4492.

Project (indoor observations)	**Date**	**Max. Δg [µm/s^2]**	**No. of points**	**No. of Δg meas.**	**Time span between obs. [min.]**	**Adj. linear drift [nm/s^2 per h]**	**Std.dev. of a single Δg meas. [nm/s^2]**	**Std.dev. of stations [nm/s^2]**
Vertical gravity calibration line Hannover	18.05.2002 - 6.08.2002	192	31	328	~7 to 10	251	±37	±12
Vertical gravity gradient at abs. station Hannover	05.12.2002	3.0	2	20	~5 to 6	74	±24	±5
Vertical gravity gradient at abs. station Clausthal/Harz	30.01.2003	2.7	2	20	~3	4	±42	±9
Horizontal gravity gradient at abs. station Clausthal	30.01.2003	0.2	9	47	~3	47	±46	±14
11 vertical grav. gradients in the Fennoscandia uplift area	Aug./Sept. 2003	3.8	11x2	11x10	~5 to 6			±17

TABLE 5: COMPARISON OF THE SC-4492 RESULTS WITH REFERENCE RESULTS (ALL DETERMINED WITH LCR GRAVIMETERS).

Project	**Comparative figures**	**Difference to SC-4492**
Vertical gravity calibration line Hannover	Calibration line reference values	±23 nm/s^2 (r.m.s.)
Vertical gravity gradient at abs. station Hannover	5 LCR SRW-feedback meters in 1993/94, mean: 3031 nms^{-2}/m	+18 nms^{-2}/m
Vertical gravity gradient at abs. station Clausthal/Harz	4 LCR SRW-feedback gravimeters in 1987, mean: 2660 nms^{-2}/m	+30 nms^{-2}/m
Vertical gravity gradient at abs. station Vaasa (AB)	Simult. observation with LCR-G709 SRW-feedback gravimeter in 2003: 3307 nms^{-2}/m	+28 nms^{-2}/m

in one room or in a single building (short time spans between measurements, meter transportation manually (shock prevention), no wind, stable temperature). In an extensive project, the vertical calibration line in Hannover has been surveyed with SC-4492 (31 points, 328 gravity difference observations), cf. Table 4 and 5. The standard deviation for a single gravity difference measurement is only ±37 nm/s^2. Fig. 6 reveals a systematic discrepancy between the calibration line reference values and the new determined figures. The differences for the points above ground floor show a height and gravity dependence which can be interpreted as a linear scale error of about $3 \cdot 10^{-4}$ (≡ 60 nm/s^2). After these investigations with SC-4492, it can not be excluded that the vertical calibration line is deteriorated by a small scale error. Additional investigations with another CG-3M are needed to clarify this issue. One reason for the discrepancies of points below ground floor may be due to the different gravimeter setups. The LCR meter has normally an average sensor height of about 6 cm above floor level. The CG-3M system with its tripod measures the gravity at a height of about 27 cm. The points are all in corners very close to the walls, only 20 cm away. Unknown non-linear gravity changes along the vertical have to be assumed which disturb the comparison of the different gravimeter systems. The rms discrepancy between the recent SC-4492 results and the reference values is ±23 nm/s^2.

The determination of vertical gravity gradients is important, because the combination of instruments with different reference heights strongly needs a highly precise centring of the measured gravity values to a common reference. Vertical gradients were observed at the two absolute gravity stations of IfE, Hannover and Clausthal, and at stations of the Fennoscandian uplift

Fig. 7. - Simultaneous measurement of the vertical gravity gradient with LCR G709 with integrated SRW-feedback system, and with Scintrex CG-3M no. 4492. In a standard procedure, the difference is measured 10 times with each instrument.

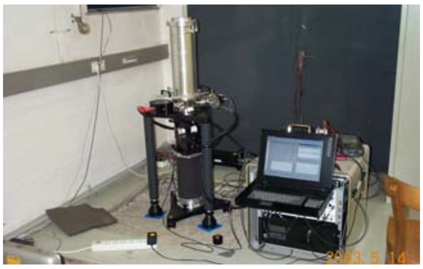

Fig. 8. - The FG5-220 occupying the absolute gravity point at station Clausthal.

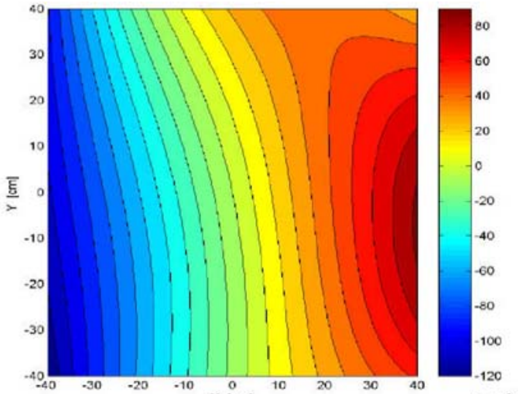

Fig. 9. - Contour plot of the horizontal gradient field above the pier in Clausthal with 10 nm/s² interval.

area, see Table 4 and 5. With the help of a tripod of 1 m height, the gravity difference is measured to determine the gradient (Fig. 7). Because of the reference height differences of the LCR and the CG-3M systems (about 21 cm), the results from the two kinds of meters can differ by some 10 nm/s². Four of the LCR meters of IfE are equipped with the SRW-feedbacks (SCHNÜLL ET AL.; 1984), which eliminates the problems with periodic errors and gravity dependencies. Fig. 8 shows the absolute gravity meter setup on the pier in the basement of station Clausthal. A mesh of 9 points with a spacing of 40 cm has been surveyed with SC-4492 to determine the horizontal gravity field above the pier surface. The result (Fig. 9) seems to be reasonable. With distance to the wall (left side in Fig. 8 and 9) gravity increases by about 25 nm/s² per 10 cm.

The obtained accuracies for all microgravimetric surveys are in the order of ±10 to ±20 nm/s². In Tab. 5, three vertical gradients are compared with LCR results. In all cases the obtained results from SC-4492 are smaller than the LCR results which are reasonable for these stations considering the different sensor heights above the massive concrete piers.

6. INSTRUMENTAL DRIFT

After TORGE, 1989, the gravimeter drift can be decomposed in two parts: stationary drift mainly due to spring aging, and the transportation drift (shocks etc.). Fig. 10 depicts the changing daily drift factors of SC-4492 in stationary operation (no transportation) over 7 days. A long term drift (composition of stationary and transportation drift) of the meter is shown in Fig. 11. On 8 different days within a time span of 100 days, the first reading in the morning on a common starting point has been used to derive this long term behaviour. Both figures depict a nearly linear behaviour. Table 6 summarizes the adjusted linear drift factors from daily field surveys obtained on 14 different days. It becomes

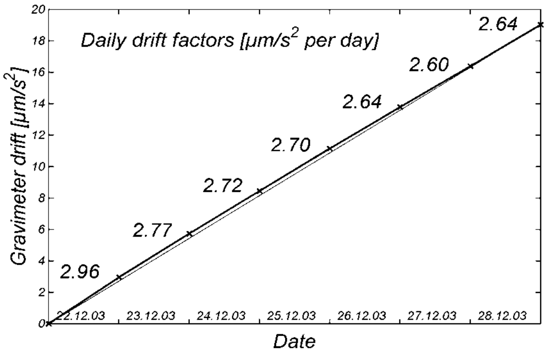

Fig. 10. - Stationary drift of SC-4492 over 7 days (no transportation, stable environment).

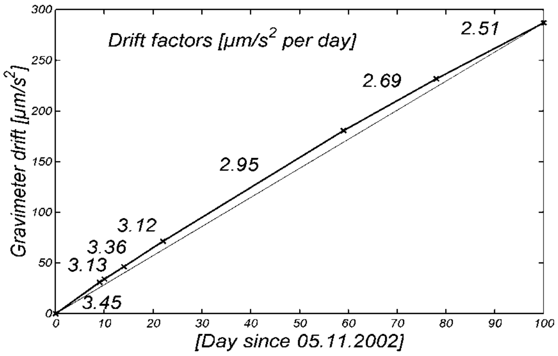

Fig. 11. - Long term drift (composition of stationary and transport drift) of SC-4492.

TABLE 6: ADJUSTED LINEAR DAILY DRIFT FACTORS FROM DAILY FIELD SURVEYS WITH SC-4492.

Date	No. of points	No. of Δg obs.	Measuring time [h]	Drift [µms^{-2}/d]
05.11.02	11	14	8	4.36
14.11.02	5	12	9	3.61
15.11.02	7	19	6	5.32
20.11.02	2	10	2	4.33
28.11.02	3	10	6	3.83
05.12.02	2	20	2	1.77
04.01.03	2	9	5	3.09
21.01.03	4	6	4	3.78
22.01.03	2	4	2	5.92
23.01.03	4	5	6	0.69
05.02.03	3	6	6.5	0.78
12.02.03	4	9	6.5	-0.49
15.02.03	2	10	3	4.12
27.02.03	2	3	6.5	4.69
			Mean	3.27
			Scatter	±1.89

clear that the drift behaviour of the SC-4492 during the field surveys is significantly not linear. The drift can vary enormously. Therefore, for precise geodetic measurements the non-linear drift during a survey has to be taken into account by choosing the step measuring method with each connection observed at least 3 times and by considering drift in the postprocessing procedure.

7. SUMMARY

The investigation of the Scintrex Autograv CG-3M no. 4492 yielded the following results:

- Over 2.5 years of surveys, the calibration was stable at least in the order of $1 \cdot 10^{-4}$. No instability could be proven.
- Within a total range of almost 0.015 m/s², no gravity range dependence has been found.
- For gravity ties with short distances (local and microgravimetric nets), the connection can be determined with an accuracy of ±10 nm/s². Observation and calibration uncertainties are considered.
- The drift behaviour is strongly non-linear during the field work which can not be covered by a pre-programmed drift factor in the online software.

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Invited paper.