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Evaluation of the Scintrex CG-3 gravity meter

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Geophysics Division
Geological Survey of Canada

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Foreword

Evaluation of the Scintrex CG-3 gravity meter: a note of explanation

The main body of the report was written in 1991 when later instrument modifications had not been implemented. The manufacturer, Scintrex, had received an early version of the report by December, 1991, and had encouraged us to send the device back to the company for repairs and upgrades.

The instrument reported on here underwent a certain evolution as this report was being prepared. Consequently, comments have been added to the original draft to acknowledge the improvements made by the company in response to some of the criticisms in the original draft. We hope that our investigations on instrument performance have expedited the discovery and repair of certain "bugs" in the instrument.

I think the instrument has been improved as a result of our investigations of its characteristics and I hope that we can maintain an interest in looking for ways to improve gravimetry.

Jacques Liard March 8th, 1993

SUMMARY

We carried out a series of tests on the Scintrex CG-3 gravity meter. We found that the gravity scale factor was relatively stable for the period of the tests and that the drift correction decreased steadily by half as predicted by the manufacturer. Limited transportion tests also demonstrated the "ruggedness" of the instrument to transport vibrations. In some regards, the automation features of the instrument make it very easy to operate even though it has a few drawbacks as a field device.

Problems encountered with the instrument were easily fixed by the manufacturer during the early part of the tests and after the first version of this report. We have identified some field conditions where the instrument would perform poorly and Scintrex has rectified these shortcomings by modifying the way some functions are implemented.

RÉSUMÉ

Nous avons effectué une série de tests sur le gravimètre CG-3 fabriqué par la compagnie Scintrex. Le facteur de conversion gravimétrique s'est avéré relativement constant pour la période des tests et le facteur de dérive a graduellement diminué de moitié tel que prévu par le manufacturier. Nos quelques tests de transport ont démontré que l'instrument est résistant aux vibrations de la route. À certains égards, l'appareil est très facile à utiliser à cause de son automatisation bien qu'il possède quelques lacunes comme instrument de terrain.

Au début de la période de tests et après que la première version de ce présent rapport fut rédigée, la compagnie a effectué certaines modifications à l'appareil lorsque des problèmes se sont présentés. Nous avons aussi identifié des conditions de terrain où l'appareil pourrait fonctionner de façon moins qu'optimale ce qui a porté la compagnie à modifier la méthodologie de certaines des fonctions de l'instrument.

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INTRODUCTION

Scintrex (Concord, Ontario) has recently developed a new gravity meter model CG-3 which is based on a fused quartz elastic system and which takes advantage of electronic nulling and computer control to perform gravity measurements. At the Geological Survey of Canada, we have carried out a series of tests on CG-3, designated X054, to evaluate its performance under a variety of conditions and its repeatability over the test period.

Tests were designed to address the calibration stability over a period of a few months, to check for any susceptibility to transport conditions, to monitor its long term drift, and to identify any potential effects due to external temperatures and pressures. Initially, instrument tests were conducted using settings recommended in the manufacturer's operating manual.

PREAMBLE

The instrument was tested in the field as well as in the laboratory. Field work consisted mostly of calibration trips south of Ottawa, transportion tests and one set of helicopter flights. A number of tests were simulated in the laboratory using an environmental test chamber which can vary atmospheric pressure and temperature. Some instrument functions were tested in static regime where readings were taken in "cycling" mode over periods of days on the same stable site. The data was continuously sent to a computer through the instrument's RS232 connection to allow for data storage beyond the built-in capacity of X054.

This report summarizes the behavior of the gravity meter in terms of experimental results without going into detailed theoretical explanations. The principles of operation of the instrument are presented in order to understand later references to different functions. Results of field and laboratory testing then follow.

PRINCIPLES OF OPERATION

In concise terms, the gravity meter maintains the sensing beam at its null position through electronic feedback and uses the nulling voltage as the observable which is scaled in milligals. The nulling voltage is sampled every second and an average is computed from a number of samples (called the duration or "**DUR**") which is set by the user prior to the measurement. At specific intervals (called calibration after or "**CAL AFTER**"), again set by the user, the internal voltmeter is calibrated against a known voltage reference. All observations (samples uncorrected or **Su**) are compensated for random voltage drift between any two internal voltage calibrations.

$$Su = GCAL1\ (Sf / Sc) + GCAL2\ (Sf / Sc)^2 \qquad [1]$$

where **GCAL1** and **GCAL2** are scale factors stored under instrument constants, **Sf**, is the sampled feedback voltage and **Sc** is the sampled voltage from the reference. The feedback voltages **Sf** are scaled with the previous voltage calibration **Sc** and the first readings are scaled with a calibration done prior to the start of the samples. Each sample **Su** is corrected for internal residual temperature compensation, **Tt**, for instrument drift, **Dc**, and for tilt effects **Ts** if selected in continuous mode (see later).

$$S = Su - Tt - Dc + Ts + GREF. \qquad [2]$$

We have set "**GREF**" (an arbitrary gravity offset value) mentioned in the manual to zero so it is not used in this equation.

The draft manual provided with the instrument is not very clear as to what function or what formal equation is used to compute the mean and standard deviation. The following descriptions are based on inference after many readings of the text and many tests with different functions.

Statistics are calculated from these internal observations so that the user obtains a gravity reading with an associated error value. In simplified form,

$$Ru = \sum_{i=1}^{n} S_i \;/\; DUR. \qquad [3]$$

$$SD = \left[\left(\sum_{i=1}^{n} S_i^2 - \left(\sum_{i=1}^{n} S_i\right)^2 / DUR\right) / (DUR-1)\right]^{1/2} \qquad [4]$$

$$ERR = SD \;/\; (DUR)^{1/2}. \qquad [5]$$

We can see that as the value of **DUR** increases, the **ERR** value will decrease since the standard deviation will tend to become stable after about 30 samples. If the instrument noise is truly random, large sample sizes will guarantee a small scatter between any two readings. This longer reading period has to be weighed against field requirements where time might be of the essence.

Some observations can be rejected while the instrument is taking a reading by setting the **AUTO REJ** function ON. Any sample that exceeds four (4) standard deviations is then rejected. The instrument computer starts calculating the standard deviation after the fifth sample. Any rejected sample is not used or stored to calculate the mean **Ru**.

Another function is available to the user which will let the gravity meter sample long enough to reduce the error down to a specified acceptable level. This function called **ERR<LIM**, when enabled, will have the instrument stop sampling when the error level reaches a lower limit even though the number of samples **DUR** are not all taken. The lower limit is set by the user prior to the readings.

INTERNAL CORRECTIONS

Compensation for internal residual temperature **Tt**, inside the sensor container, is defined

$$Tt = TEMPCO * T \qquad [6]$$

where **TEMPCO** is a correction factor in mGal/ mK and **T**, the residual temperature in millikelvins. Typically, the coefficient for the fused quartz spring is of the order of -130mGal/ K. The residual temperature must be kept within ±2 mK using the zero-offset (trim potentiometer) on top of the instrument. The procedure for this adjustment as explained in the manual is straightforward.

Since fused quartz systems drift with time, a drift correction calculated by the user prior to a survey is applied to each sample **Su**. The correction function is

$$Dc = DRIFT *(t - ts) \qquad [7]$$

where **t** is the time of the **Su** observation and **ts**, a reference starting time set by the user prior to the survey. The **DRIFT** factor units are in mGal/day.

Errors in tilt can be continuously corrected for by setting the **CONT.TILT CORR.** function. In this mode, each sample is corrected for tilt errors with

$$Ts = 980600.(1 - Cos(x)Cos(y)) \qquad [8]$$

where **x** and **y** are angles of tilt off vertical in both instrument horizontal directions.

The tilt sensors have a sensitivity of 1 arc second and they should be monitored and checked every few months (according to the manual). The true vertical will tend to drift with time and the sensors themselves should be calibrated at the same time. The procedure for these adjustments as explained in the manual are fairly straightforward.

If the continuous tilt correction is disabled, a tilt correction is calculated and applied at the end of the sampling period. The intent here is to let the tilt sensors stabilize to their proper positions during the measurement for greater accuracy.

Another correction to each reading, **Ru**, is available in the software, namely a tidal correction based on the Longman formula. However, for these evaluation tests this function was disabled since the software had a flaw in calculating this correction.

In order to calculate the tide correction, this function used as clock time the beginning and not the middle of the sampling period (J. Liard, 1990), thus adding a small error to the data. If the sampling period is one minute long, the error is trivial but for special cases where a sampling period exceeds 2 minutes, a larger error can be introduced into the data. The timing error for a 2 minute sampling period would be about 1 minute depending on the **CAL AFTER** setting. The peak-to-peak error due to the use of the wrong clock time can be as high as 1.0 μGal per minute of error for latitudes around 45. The tidal tests reported on here were done in response to Dr. Hugill's (from Scintrex) concern about fairly large residuals evident in the data when a **DUR**=600 was used.

More recent tests with the instrument (1992-10-13) have shown that the tidal correction is now applied for the mid-point of the reading. The instrument had been returned to Scintrex by mid-spring 1992 for software upgrade/modification. The tidal correction now agrees within a microgal with our own Longman subroutine.

FIELD TESTS

1. Calibration

Several sets of observations were made on a small 96 mGal range south of Ottawa. Absolute gravity stations have been established at each end of the range (Ottawa and Gananoque) and the line is comprised of four main gravity differences (Table 1.). The absolute gravity values given in Table 1 are nominal values. Recent re-observations (1992) confirmed that the 1990 absolute gravity determinations were 0.014 mGal too high in Ottawa and Gananoque as a result of technical difficulties. The gravity differences along the calibration line are not affected by these problems.

For the purpose of the calibrations, instrumental parameters were fixed at what we considered to be more than optimum settings. For each gravity reading, a **DUR** of 240 and a **CAL AFTER** value of 15 were chosen and the **CONT.TILT CORR.** function was enabled. The **AUTO REJ** function and the tidal correction routines were disabled. A long duration assured us that only a small error would be associated with each reading and that, in principle, we would obtain minimal scatter between survey readings.

In addition to the observations made by the JILA-2 absolute gravity meter (GSC), LaCoste & Romberg model D and G gravity meters were used to establish the intermediate gravity differences. In particular, gravity meter D-6 was used on all surveys except the last one. The analysis of the observations was done using the gravity network adjustment system (GRAVSYS) developed by the GSC.

Table 1.
Ottawa-Gananoque Calibration Line

Station	Gravity (mGal)	δg (mGal)	Name
980185	980607.070		OTTAWA (ABS)
		44.602	
908180	980562.468		KEMPTVILLE
		11.989	
908280	980550.479		PRESCOTT
		19.562	
908380	980530.917		BROCKVILLE
		20.644	
908480	980510.273		GANANOQUE
		-0.458	
981390	980510.731		GANANOQUE (ABS)

Table 2.
Ottawa-Gananoque Calibration Line
Scale factor results (all instruments)

Inst	Day Number	Adjusted Scale	Error X1E-6	Instrument Residual** Mean	Instrument Residual** S.D.
D006	79	1.001150	0F*	.0014	.0045
D006	100	1.001150	0F	.0003	.0111
D006	107	1.001150	0F	.0007	.0063
D006	123	1.001150	0F	.0013	.0055
D006	135	1.001150	0F	.0014	.0053
G291	100	1.000631	337	.0015	.0260
G932	100	1.000799	392	.0012	.0301
G932	123	1.000804	524	.0054	.0399
X054	79	1.001516	724	-.0098	.0523
X054	100	1.000929	244	-.0050	.0167
X054	107	1.001024	180	-.0021	.0150
X054	123	1.001060	128	-.0027	.0080
X054	135	1.001092	151	-.0043	.0097
X054	149	1.001070	223	-.0084	.0134

* "F" = fixed scale factor
** "Instrument Residual" with respect to the least squares solutions

Between the 20th of March and the 29th of May, 1991, six (6) calibration trips were made with the instrument. A calibration trip consists of one return trip down the 5-station Ottawa-Gananoque line. During the first three surveys, a suspension-box system was used to transport the instrument when in transit between sites. For the remainder of the surveys, the instrument was secured on the rear seat of the transport vehicle used (a GM mini-van). Careful handling procedures were followed when carrying the instrument to and from the vehicle. Sufficient time (> 1 minute) was given to allow the instrument levels to settle before starting the sampling at each station.

Internal battery voltage was monitored at each station and a spent battery was replaced by a fully charged battery unit when needed (the instrument sends a warning beep) between sites. This occurred mostly near the end of the day and especially on colder days (one survey usually lasts 6 hours). Data was recorded in GSC field books as well as in the internal memory system. A print-out of each survey was done at the end of the day for quality control.

Since the objective of the test was to monitor scale stability as well as repeatability, only the scale values are presented in tables 2, 4 and 5. Each table shows the results of different analytical techniques.

The first analysis (Table 2) takes all observations from all the instruments, and except for instrument D6, scale factors are adjusted to the gravity network. As mentioned before, Ottawa and Gananoque are also "tied" or fixed by the absolute gravity meter which according to latest publications has an accuracy of about 0.007 mGal (Boulanger et al., 1989). In terms of precision, the absolute gravity meter is repeatable to within 3 μGal which translates over the calibration line to about 3 parts in 10^5.

Test results indicate that the scale factor for X054 has remained constant to within a few parts in 10^5 for the duration of the tests. Only the survey on day 79 shows an anomalous scale and it can be argued that because of its large error, the change is not statistically significant. The standard deviation of the residuals is fairly large compared to later surveys and this explains the large discrepancy. An anomalous reading at Kemptville (908180) created two .080 mGal residuals in the adjustment for this period and because these residuals did not exceed our 3 standard deviation rejection criterion, they were kept as part of the observations. The cause of the anomalous reading was not determined.

The analysis was repeated with only instrument X054 but this time with the end points of the calibration range fixed to slightly different gravity values. Because this instrument takes measurements at a different height with respect to the other instruments, the gravity differences or ties will be slightly offset due to the local vertical gravity gradient. For instance, the gradient at station 981390 is 0.2669 mGal/m as compared to 0.3161 mGal/m for station 980185.

Since instrument D6 is read at 5 cm above the ground while X054 is at 26 cm, the gravity difference between 908480 and 981390 will not be equal for both instruments if the gradient for 908480 is assumed to be 0.3086 mGal/m (normal). The error due to the gradient for 981390 will be about +0.009 mGal if the true gradient is not taken into account at 981390. The gravity tie between 981390 and 908480 for D6 is 0.458 ±0.0048 mGal and 0.473 ±0.0133 mGal for X054, the discrepancy being nearly equal to the error mentioned before. For this reason, the reference values for the ends of the network were modified slightly in order to minimize such effects (Table 3).

Table 3.
Ottawa-Gananoque Calibration Line for X054 only

Station	Gravity (mGal)	δg (mGal)	Name
980185	980607.004		OTTAWA (ABS)
		44.597	
908180	980562.407		KEMPTVILLE
		11.990	
908280	980550.417		PRESCOTT
		19.567	
908380	980530.850		BROCKVILLE
		20.644	
908480	980510.202		GANANOQUE
		-0.473	
981390	980510.675		GANANOQUE (ABS)

Table 4.
Ottawa-Gananoque Calibration Line
Scale results (grouped analysis)

Inst	Day Number	Adjusted Scale	Error X1E-6	Inst. Residual Mean	Inst. Residual S.D.
X054	79	1.001516	724	-.0098	.0523
X054	100	1.000929	244	-.0050	.0162
X054	107	1.001024	180	-.0021	.0118
X054	123	1.001060	128	-.0027	.0069
X054	135	1.001092	151	-.0043	.0084
X054	149	1.001070	223	-.0084	.0126

Table 5.
Ottawa-Gananoque Calibration Line
Scale factor results (individual analysis)

Inst	Day Number	Adjusted Scale	Error X1E-6	Instrument Mean	Residual S.D.
X054	79	1.000923	732	-.0098	.0364
X054	100	1.001069	184	-.0050	.0079
X054	107	1.001033	216	-.0021	.0116
X054	123	1.001049	139	-.0027	.0066
X054	135	1.001085	185	-.0043	.0084
X054	149	1.001054	257	-.0084	.0098

The combined results for the scale factors are listed in Table 4. The values are nearly identical to those found in Table 2, except for some improvements in the standard deviations of the residuals. The slight change of gravity references might explain the improvements but they do not seem to matter very much in the calculation of the scale factors.

The results are based on a common adjustment where observations are weighted by the inverse of the variance of each survey group. For instance, all the gravity ties from survey 79 will have a weight of 365.6 (S.D.= 0.0523) while survey 123 will have a weight of 21004.0 (S.D. = 0.0069), a ratio of 57.5 to 1! Such a procedure might unfairly weight a particular set of ties.

For this reason, each survey was analyzed separately with the same conditions, namely with the end points of the network fixed to pre-determined values. In this way, individual surveys would not be biased by other surveys in the scale factor analysis. Table 5 clearly shows that such a procedure does improve dramatically the comparison between surveys. Survey 79 does not differ from the other surveys by a large amount anymore and error levels are also reduced for all surveys.

We can conclude that the scale factor did not change over the testing period to well within 10^{-4} on the 96 mGal range of the network. It should be noted, however, that the overall scale factor is off by $+10^{-3}$ from the scale factor provided by the manufacturer. We were later informed that the original calibration of the instrument had been done with a tilt-table without an additional adjustment using the manufacturer's calibration range, north of Toronto.

2. Transportion tests

Four series of transportion tests were performed to evaluate the effects of vibrations due to transportation. Seven sites were chosen so that different observation conditions were encountered and repeatability could be evaluated. For example, one site was located at a busy intersection to test the rejection functions (**AUTO REJ**) of the instrument and the error limit feature (**ERR<LIM**). These transportion tests used short durations (**DUR** = 60, or 120) corresponding to regular survey requirements and no isolation device was used except for securing the instrument on the back seat of the survey vehicle. The analytical technique applied to the data was the method used on a traverse for gravity anomalies. A linear drift correction is applied to all readings based on observations done at the beginning and the end of each survey. Tidal corrections are also applied. No statistical analysis is done.

On the first traverse, instrumental parameters recommended in the operator's manual were used. These parameters were:

DUR = 60,
CAL AFTER of 4,
AUTO REJ function enabled,
ERR<LIM function enabled at 0.005 mGal,

and **CONT.TILT CORR.** was enabled since some stations were not as stable as primary gravity stations. In the second traverse, the same settings were used except for the **ERR<LIM** function which was disabled. Since laboratory tests (see later) had shown that **CAL AFTER** should be set to about 13, and that a longer duration should reduce the scatter, for the third traverse the settings were adjusted to:

DUR = 120,
CAL AFTER = 13,
AUTO REJ function enabled,
CONT.TILT CORR. enabled,
ERR<LIM function disabled.

For the first three traverses, the instrument was secured on the back seat of a small truck (Suburban) and for the fourth traverse, it was set on the vehicle floor between the seats and the parameters were identical to those of the third traverse.

The traverses started from the Ottawa absolute gravity station (980185 not shown in the Tables) and ended back at the same location after observing each station twice except for the seventh and last station at the end of the line. Instrument drift which was linearly corrected for in the reduction processing, was easily monitored under such conditions. The results in Tables 6 and 7 are presented as though the traverse were a single line and not doubled up on itself. This makes inter-traverse comparison easier to show. Only the last 6 digits of the reduced observed gravity are displayed in Table 6 ("980" has been stripped). Table 7 presents the differences in observed gravity between surveys on each traverse.

Table 6
Summary of transportion tests
Units: mGal

#	Test 1*	Test 2	Test 3	Test 4
1	610.756	610.746	610.758	610.757
2	609.962	609.950	609.968	609.964
3	599.418	599.415	599.423	599.422
4	587.801	587.802	587.806	587.814
5	598.758	598.750	598.762	598.746
6	598.494	598.499	598.501	598.501
7	612.059	612.058	612.060	612.061
6	598.503	598.507	598.493	598.505
5	598.751	598.735	598.756	598.748
4	587.803	587.806	587.801	587.803
3	599.423	599.420	599.418	599.422
2	609.959	609.966	609.964	609.960
1	610.746	610.755	610.750	610.751

* Test 1: CA 4 DUR 60 ERR<LIM @ 0.005 / AUT-REJ / On Seat
Test 2: CA 4 DUR 60 - -- - AUT-REJ / On Seat
Test 3: CA13 DUR120 - -- - AUT-REJ / On Seat
Test 4: CA13 DUR120 - -- - AUT-REJ / On Floor

We can conclude that no pattern exists to differentiate one traverse from another. The noise level is well within normal survey requirements as well as within the manufacturer's specifications. It would seem that the instrument settings described in the manual are adequate for traverse work although we should caution the reader that tests detailed later in this report would tend to suggest that certain settings should be avoided. The limited number of test surveys may not have encountered enough conditions to definitely determine which settings are optimal for traverse work.

The one function that we felt to be very usefulness is the **AUTO REJ** function. As mentioned earlier, one site (#2) is located at a busy intersection. On some of the trips along the traverse, up to 10 samples were sometimes rejected in one reading. This value is much larger than what we would expect from a four standard deviation rejection limit on **DUR** = 60. Clearly, large ground vibrations are rejected in the data sampling, thus improving the chance of getting a good reading.

Table 7
Gravity differences between transportion tests
Units: mGal

#	(1)-(2)	(2)-(3)	(3)-(4)	(4)-(1)
1	-0.010	0.012	-0.001	-0.001
2	-0.012	0.018	-0.004	-0.002
3	-0.003	0.008	-0.001	-0.004
4	0.001	0.004	0.008	-0.013
5	-0.008	0.012	-0.016	0.012
6	0.005	0.002	0.000	-0.007
7	-0.001	0.002	0.001	-0.002
6	0.004	-0.014	0.012	-0.002
5	-0.016	0.021	-0.008	0.003
4	0.003	-0.005	0.002	0.000
3	-0.003	-0.002	0.004	0.001
2	0.007	-0.002	-0.004	-0.001
1	0.009	-0.005	0.001	-0.005
Mean	-0.0018	0.0039	-0.0005	-0.0016
S.D.	0.0077	0.0100	0.0070	0.0057

Transport vibrations did not seem to degrade data quality when compared to the calibration surveys where an isolation system was used. A small survey test in a helicopter was done following the transportion tests which confirms this observation. The instrument was flown for two hours with repeated landings and readings at the same site. During the first hour, the instrument was left on the floor of the helicopter without any vibration protection. During the second hour, it was put on the back seat with a seat-belt holding it in place. Since the gravity difference between readings was essentially zero, only the standard deviation of the ties was used in the analysis. With four ties (tide corrected) in each test, the standard deviation for the first test was 0.0068 mGal and it was 0.0032 mGal for the second test. Clearly helicopter vibrations in normal flight mode did not disturb the instrument for normal survey requirements.

3. Instrument drift

The accuracy of the instrument drift correction factor was monitored over the testing period by taking continuous readings at a laboratory site for a few days at regular intervals and by analyzing the gravity residuals. Residual drift from these readings was used to calculate a new daily drift correction factor. Figure 1 shows the steady decline of the drift correction factor since December, 1990. This decline was predicted by the manufacturer as the normal relaxation of the quartz spring in a new instrument. It should be mentioned that the drift rate follows a smooth decline even though the instrument had been sent back to the manufacturer for hardware/software modifications in early February, 1991. It is encouraging to note that the instrument scale factor has remained constant over the March to June period of this drift curve.

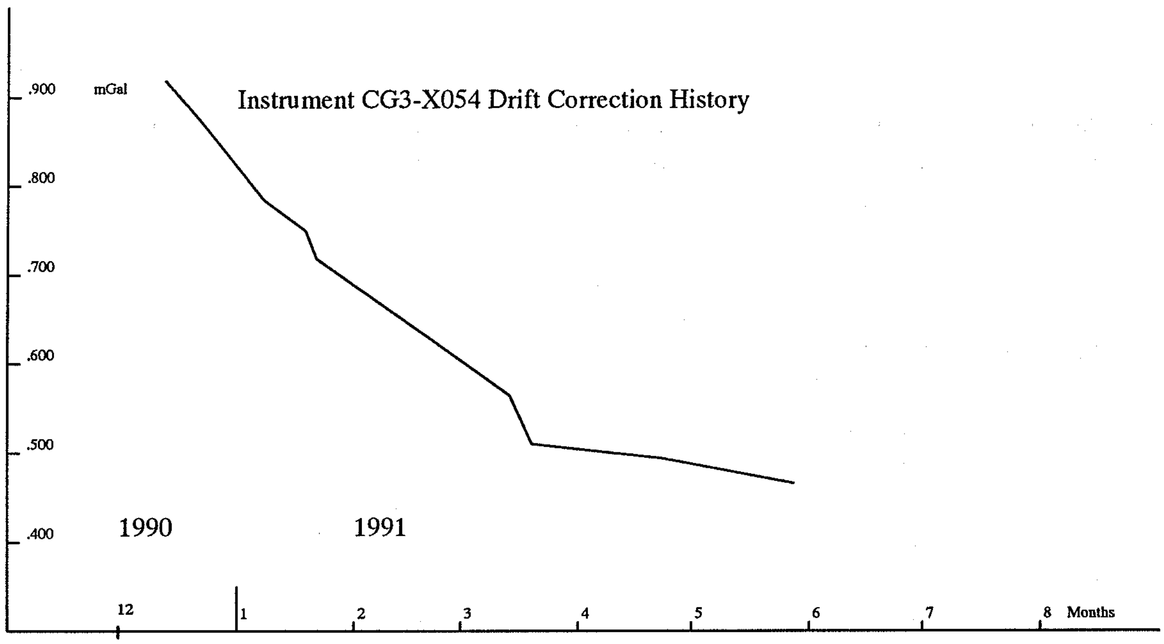

Figure 1

If the drift rate tapers off to a daily correction of about 0.4 mGal/day, this will mean a yearly drift of 146 mGal or 1460 mGal in 10 years. This will cause the instrument to exceed its 7000 mGal operating range for surveys in the high Arctic. At the time of this report, a predicted value for Alert, NWT is about 6617 mGal on this instrument (Ottawa = 4099 mGal by June, 1991) and with a drift of 1460 mGal in 10 years, the reading will then be 8077 mGal ! The instrument will have to be sent to Scintrex for re-adjustment within 10 years. However, the effective range of our X054 instrument according to the manufacturer, is closer to 8200 mGal, which makes this problem less important if the drift rate keeps decreasing (0.35 mGal/d as of 1992/12/10).

LABORATORY TESTS

1. Atmospheric pressure

A sealed chamber capable of testing gravity meters (from field instruments to tide meters) was used to simulate pressure and temperature conditions most likely to be encountered on routine gravity surveys by the CG-3 instrument.

For the atmospheric pressure tests, a range of 800 to 1100 mbar was used to simulate altitudes of 1950 m to -700 m. Although the latter altitude will not be reached, the Dead Sea being at -400 m, a high pressure front at that particular location might come close to the 1100 mbar value. The 1950 m altitude is easily attainable in the Canadian Rockies.

Since no communication cable (RS232) was available from within the testing chamber, test data was stored in the gravity meter. With an appropriate cycling interval, the 390 reading storage capacity could hold more than 24 hours of testing results. The instrument settings were for this occasion

DUR = 120,
CYCLING ON at 300 (5 minutes),
CAL AFTER = 15,
AUTO REJ disabled,
CONT.TILT CORR. enabled,
ERR<LIM function disabled,

and the pressure inside the sealed chamber varied from 1100 to 800 mbar twice in 8 hours, thus simulating a traverse in mountainous regions either by road or by helicopter. The temperature of the chamber was kept at about 23° C. Figure 2 shows that the readings are inversely proportional to the outside pressure. Based on this test, the response of the instrument is

$$R = Ro - 0.000152 * (P - 1013.25) \text{ mGal} \qquad [10]$$

where Ro would be the reading at sea level, and P the atmospheric pressure in millibars.

Figure 3 indicates also that there seems to be some hysteresis in the response of the instrument to outside pressure ("oval look" to the trace). In the field, this would result in a lagging effect in the readings when the instrument goes back down after a trip up a mountain. We estimate this lag to be about 0.010 mGal for the range in our test.

For applications such as traverse work, where density determination is not that well known, a "small" pressure problem can be ignored. However, for gravity control network surveys where the "expected error level" is around 0.02-0.03 mGal, this effect is not negligible. Furthermore, if the manufacturer is to develop an enhanced version of this instrument (good to 1 μGal), this pressure effect will have to be minimized.

The manufacturer has since then (October, 1992) identified a hardware problem which produces this pressure effect. It will soon be rectified.

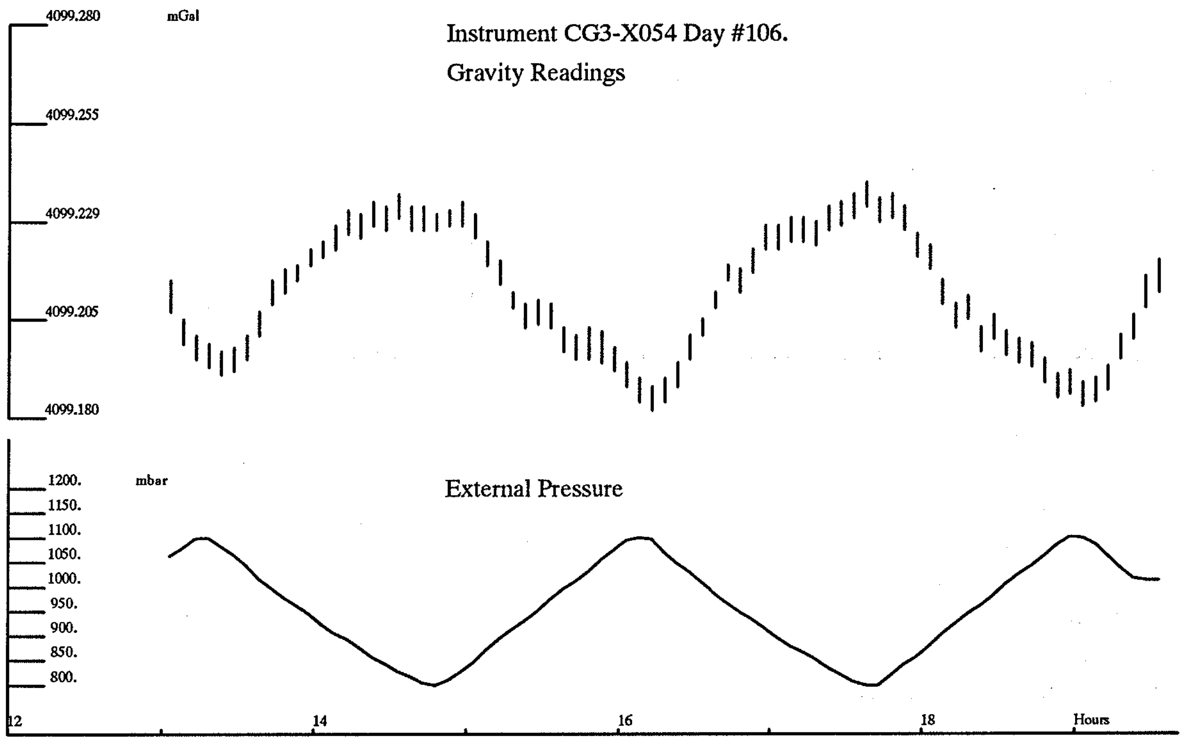

Figure 2

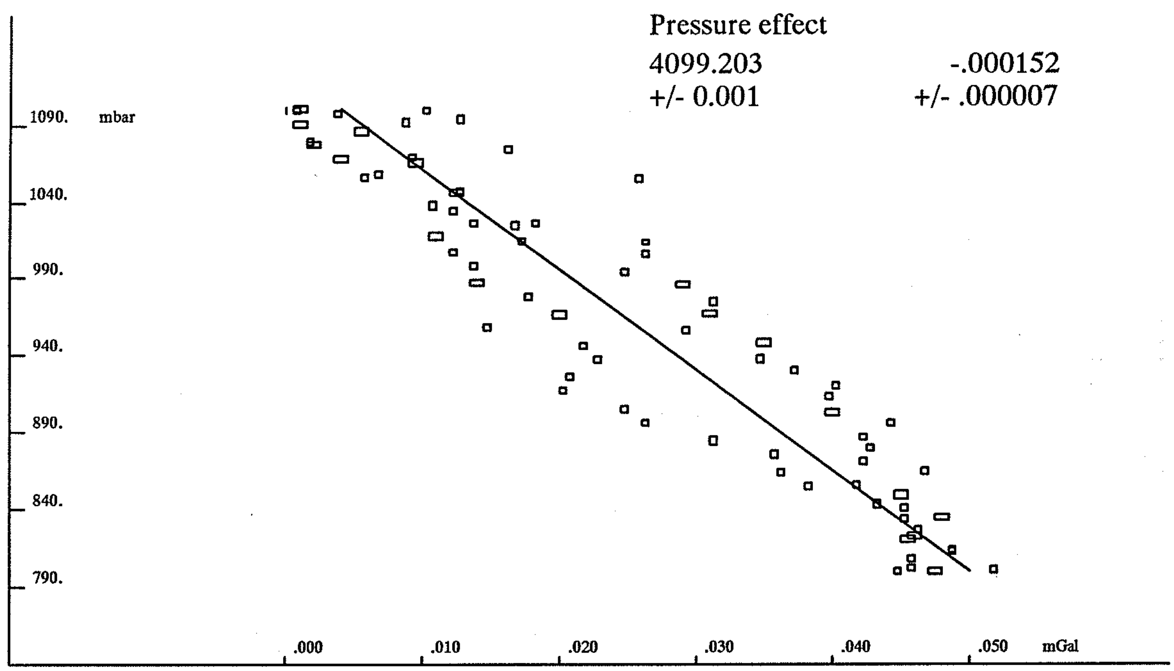

Figure 3

2. External temperature

Readings were taken inside and outside the testing chamber to generate a large temperature contrast. The outside temperature was around 20°C and the chamber temperature was kept at -9°C. The technique was to put the instrument in cycling mode and have it read at each location for a certain length of time, in order to let the chamber stabilize after briefly opening it for instrument insertion. The gravity difference of about 0.045 milligals between locations was removed so that the effects could be better displayed.

The most important parameter to display for these tests is the internal residual temperature since it indicates how well the instrument remains stable under such external stresses. The sequence of readings was O-C-O-C-O-C-O, where "O" is the site outside the chamber and "C" is inside the chamber. We can see in Figure 4 that the internal temperature is drifting slightly upward during the reading test. Furthermore, the temperature residual seems to increase during the readings inside the chamber, identified by the small hills in the temperature curve. However, the gravity readings are stable enough to meet the manufacturer's specifications.

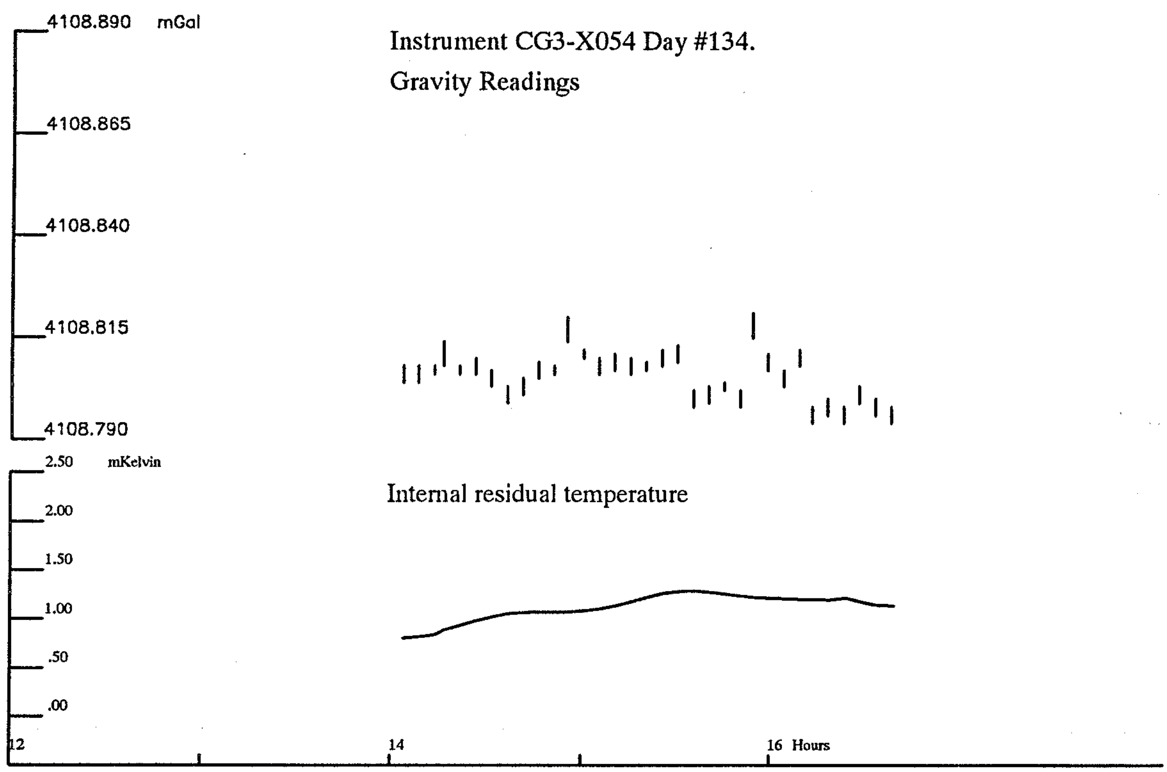

Figure 4

Another test consisted of leaving the instrument inside the chamber and varying the temperature between -5°C and +25°C while the instrument read continuously. Since the chamber was not designed for rapid temperature changes, this test lasted more than 24 hours and the instrument was kept on its charger for stable and continuous power. Figure 5 shows the readings as well as the temperature within the chamber and we conclude that although the readings change slightly, no significant effect is indicated by the data. However, the internal residual temperature is affected by the external temperature change (Figure 6.) and this brings up the next subject of our tests.

3. Internal temperature compensation

In principle, each gravity reading is corrected for internal residual temperature (equation 6) where **TEMPCO** for instrument X054 is equal to -0.1325 mGal/ mK according to the manufacturer. This correction is automatically applied for each reading and cannot be disabled.

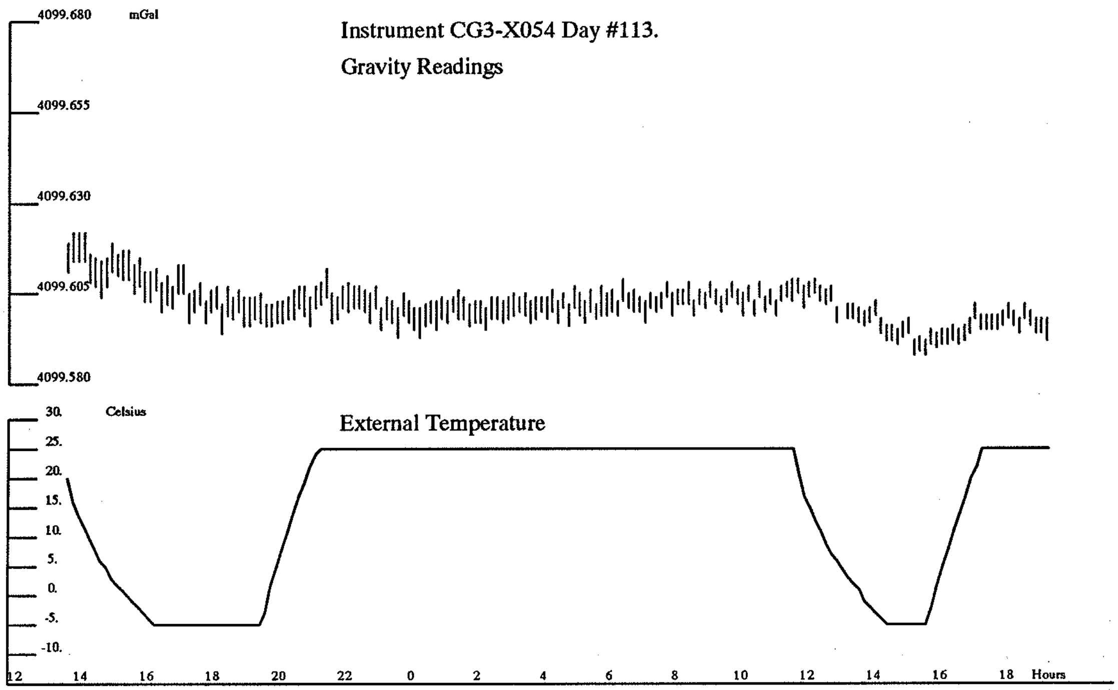

Figure 5

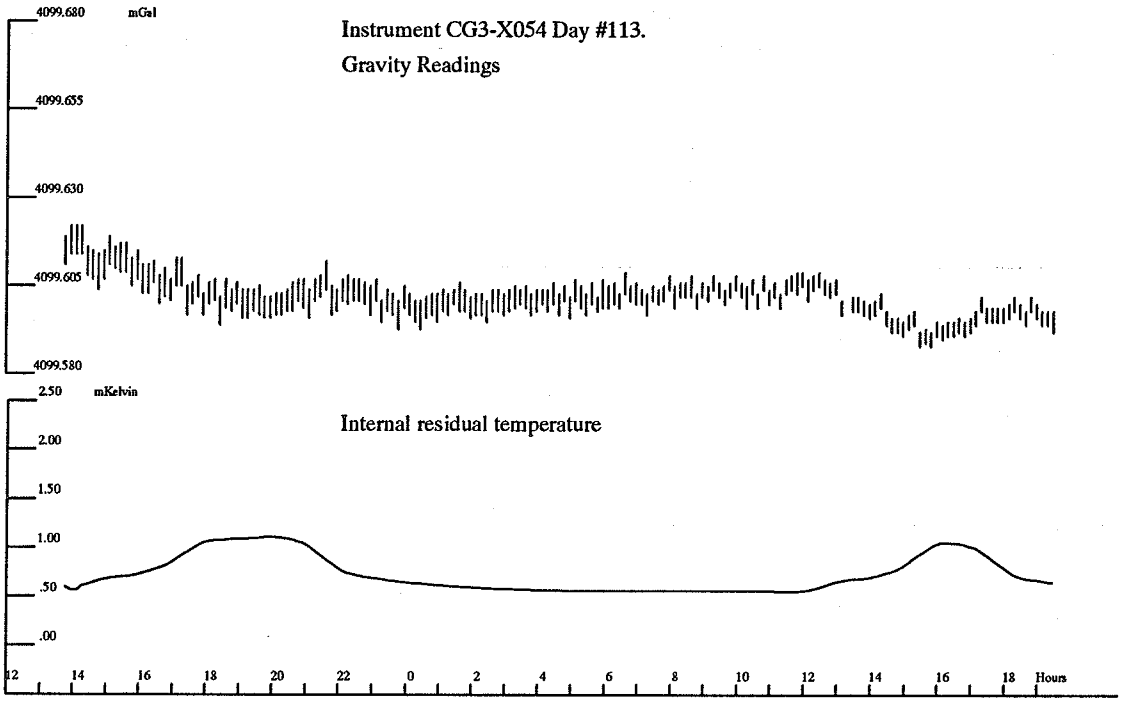

Figure 6

What was not mentioned in section 2 above, is that Figure 6 was drawn with an additional correction and if we remove this correction, we can see that there is a large "external temperature effect" (Figure 7) in the gravity residuals. As it turns out, since the begining of our testing period, we have found that we had to systematically correct every reading with an additional factor which is a function of the internal residual temperature:

$$R'_i = R_i + 0.1364*(T_i - T_1) \qquad [11]$$

where $\mathbf{R_i}$ is the ith reading, and $\mathbf{T_i}$ its corresponding temperature and $\mathbf{T_1}$, the temperature of the first reading. Since the instrument already has a temperature compensation function (equation 6), the total **TEMPCO** correction contribution would then be

$$S' = S + 0.2689 * T + C \qquad [12]$$

which contradicts what the instrument manual says about the approximate value of this correction, namely about -0.130 mGal/ mK. All laboratory tests had to be corrected for internal residual temperatures with the additional factor of 0.1364 mGal/ mK.

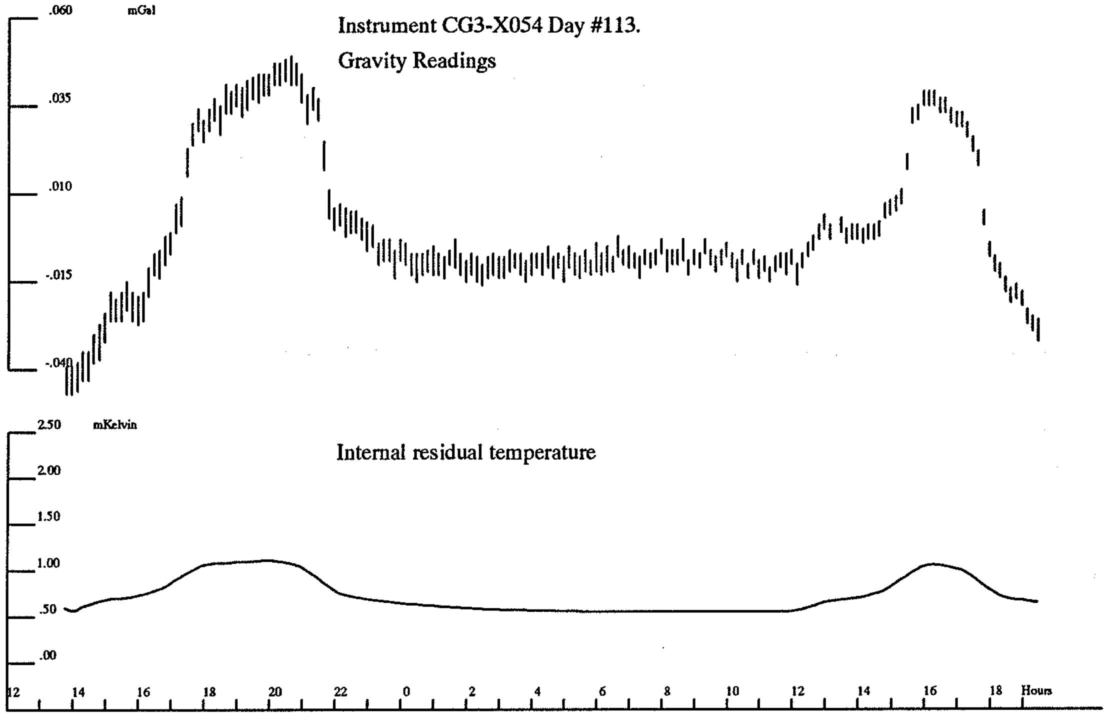

Figure 7

Another explanation could be that the **TEMPCO** correction is NOT applied in the software and that we have simply re-calibrated this correction factor which is close to the -0.130 mGal/ mK mentioned in the manual. Scintrex suggested sending the instrument back for rectification. It was sent back around April, 1992, and the problem was identified as a software bug: under certain conditions the **TEMPCO** correction was not applied to the readings. The problem was fixed.

4. Battery duration

The internal residual temperature will change gradually during a normal survey when the instrument is on its 12 V battery. The battery voltage drops as it maintains the internal temperature at 60°C and keeps the instrument nulled during the readings. For instance, at 25°C ambient temperature, the instrument current consumption will jump (for a second or two) to 2.2 A every 20 s, and will also jump to 0.5 A (for a second or two also) every 18.75 s, indicating the two stage heating system as mentioned in the manual. The background current consumption is about 0.19 A for all other functions.

When the battery voltage drops from 12 V to below a certain voltage threshold, the instrument sends a warning beep to indicate that a newly charged battery is needed. We found that the warnings start at about 11.9V, especially when the instrument is taking a reading (the manual mentions a level of 10.5V as the warning threshold). Later, it was found that the warning beeps were set at too high a level and that the batteries actually lasted longer than previously thought. The instrument still functions at a lower voltage but as the voltage drops, the internal residual temperature will eventually exceed the ±2 mK limits and the TEMPCO correction factor might no longer apply.

We found that when the outside temperature is at 25°C, the battery appeared to last nearly 8 hours, indicated by the warning beeps. Also tests showed repeatedly that at -10°C, the battery appeared to last only 2 hours.

In order to determine whether the instrument or the battery was faulty, we were able to repeat two tests with a battery provided by Scintrex between the 4th and the 8th of December, 1992. The first test was done at an ambient temperature of +10° C (1992-12-04) and the second test, at about +23° C (1992-12-08). Similar to Scintrex's technique, a chart recorder was used to monitor the battery voltage as well as room temperature. We waited only a few hours (4:40) for the warning beeps to occur during the first test. These occured every time the voltage dropped to 12V, which was every 96 s at the beginning, and every 60 s later on.

During the second test, the warning beeps started 7 hours later, and again they occured whenever the voltage dropped to 12V. Four (4) hours after the first beeps, the voltage was fluctuating between 11.2V and 11.7V and the instrument was beeping every 15 s. Since the same battery had maintained an acceptable voltage for 11 hours according to Scintrex, these tests showed that the threshold setting for the warning beeps was set too high.

5. Horizontal transport

We have already given details on survey transport where the instrument performs well even in rough road conditions. However, there is a special case when the device has to be carried on its side between sites such as in commercial aircraft. On such occasions, it is not always possible to keep the instrument upright.

We tested this condition by setting the instrument on its side for different lengths of time and by taking readings immediately after. Figures 8 and 9 indicate that the recovery of the readings seems to be proportional to the time the instrument has been on its side. In the first case (Figure 8), the instrument was left on its side for 1/2 hour while in the second case, for 3 hours. Furthermore, in the second case, readings were taken prior to the test as a base line. As Figure 9 shows, there are even signs of an offset in the data after the test.

Evidently, laying the instrument on its side should be avoided or else the observer will have to wait a fairly long time before taking a reading when arriving at a gravity station after a long flight. We estimate that an observer would have to wait 30 minutes before using the instrument after setting it sideways for 10 minutes, and the longer the instrument is on its side, the longer the waiting period would have to be.

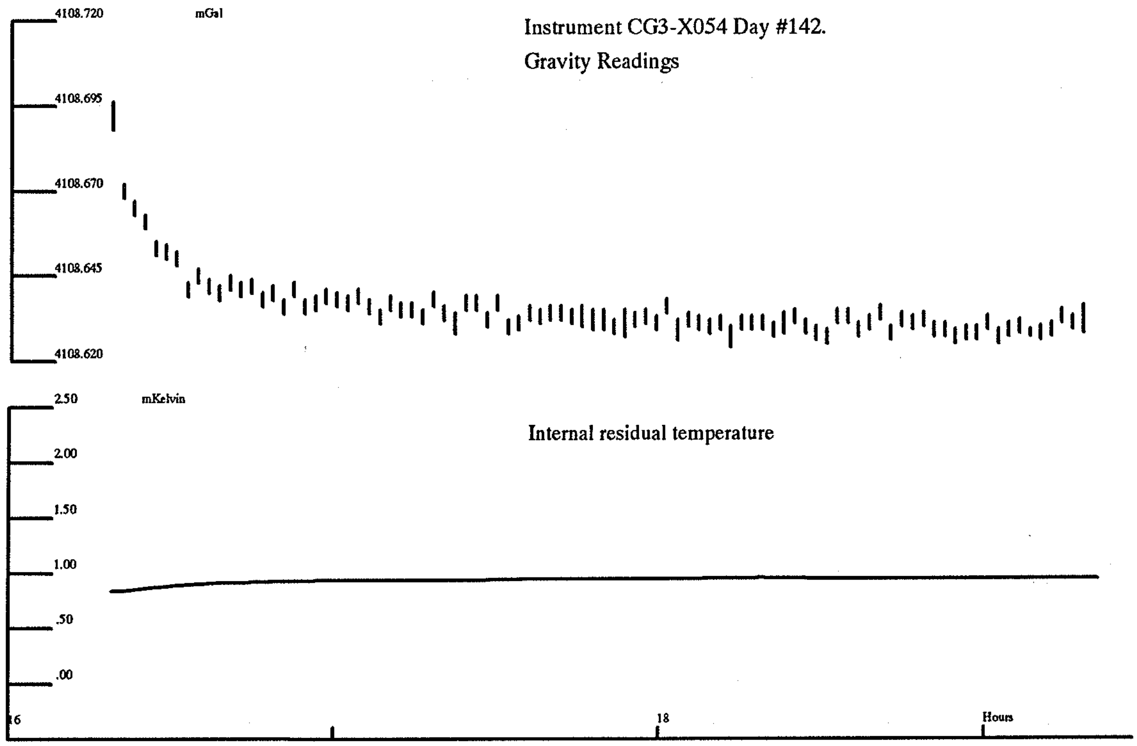

Figure 8

6. Tilt accuracy

The tilt correction is a feature or function that we found to be very useful and accurate within reasonable limits. This function applies a correction either in continuous mode to each sample or at the end of each gravity reading. Any small deviation from vertical is compensated for within the limits set down in the manual. We found that if the instrument is leveled to within a few tens of arc seconds off vertical, the leveling error will not be noticeable. For instance, with a leveling error of 130" this function will over-compensate by only 0.005 mGal which indicates that the scale factors of the leveling correction function are out by only +2.5% !

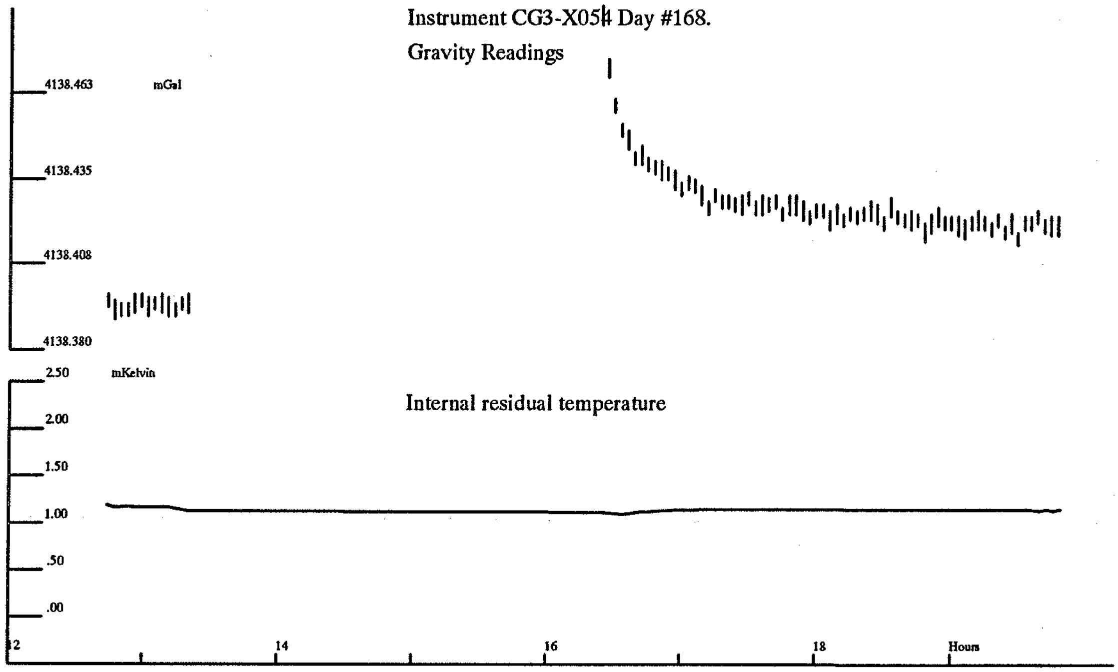

Figure 9

Readings were taken in both X and Y leveling directions to the extremes of the range sensors in order to check the response of the system in continuous mode. With the X and Y directions combined into one signal according to equation 8, we can see (Figure 10) that this compensating function starts to fail appreciably past the 200" range and that the center of the curve is not at 0" but some 50" to one side, which implies that the "true" vertical of the instrument needs to be adjusted slightly. This is to be expected since regular maintenance is required on the sensors as well as on the scale factors as mentioned in the manual.

We feel furthermore, that if this function is useful on unstable ground, it should be even better on stable ground. We cannot assume that on stable ground the instrument will not tilt slightly (settling of tripod etc...) at the beginning of the readings.

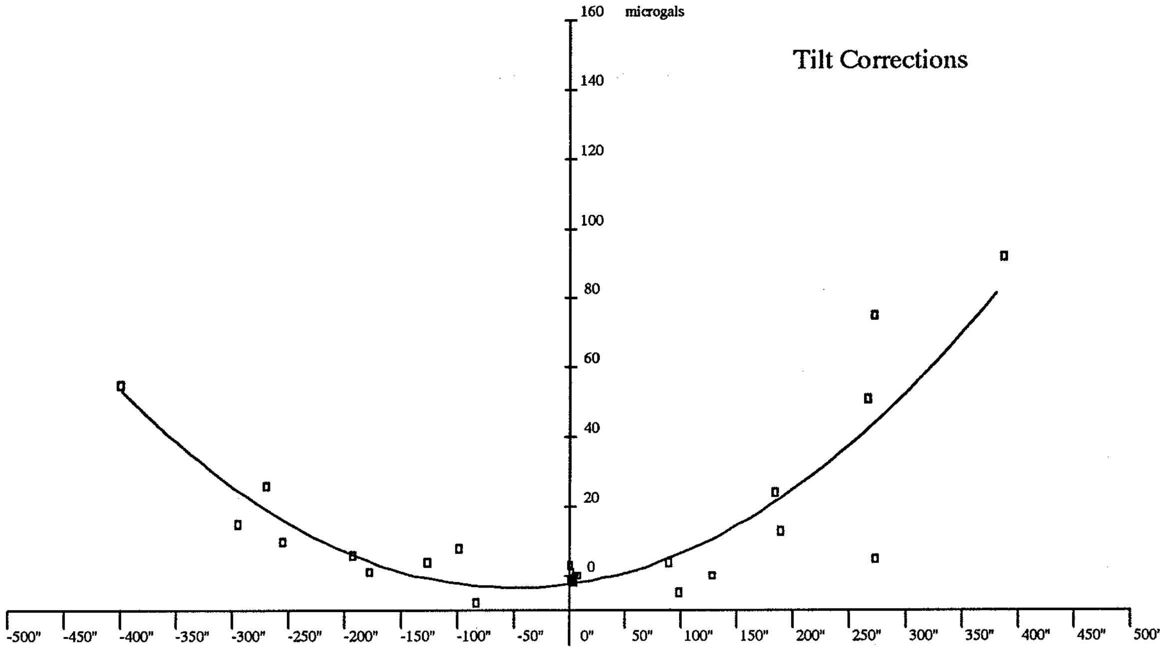

Figure 10

7. Function tests

The manual recommends that the instrument internal parameters be set to specific functions, such as

CAL AFTER = 4,
AUTO REJ ON
ERR<LIM set at 0.005 mGal
DUR = 60 or 120.

CAL AFTER

It turns out that parameters such as the **CAL AFTER** setting are dependent on the noise environment (micro-seismic noise) which is not easy to measure without additional equipment (low period seismometer). When the noise level is low, any setting between 3 and 25 for **CAL AFTER** will suffice (Figure 11), but the optimal setting will be around **CAL AFTER**=13 when the noise level is higher. The scatter between readings will increase with the micro-seismic noise level which depends on the seasons and on stormy conditions offshore. Fewer points were plotted for the higher noise level since this type of experiment is very time consuming and such large noise levels do not occur often during the warmer months of the year.

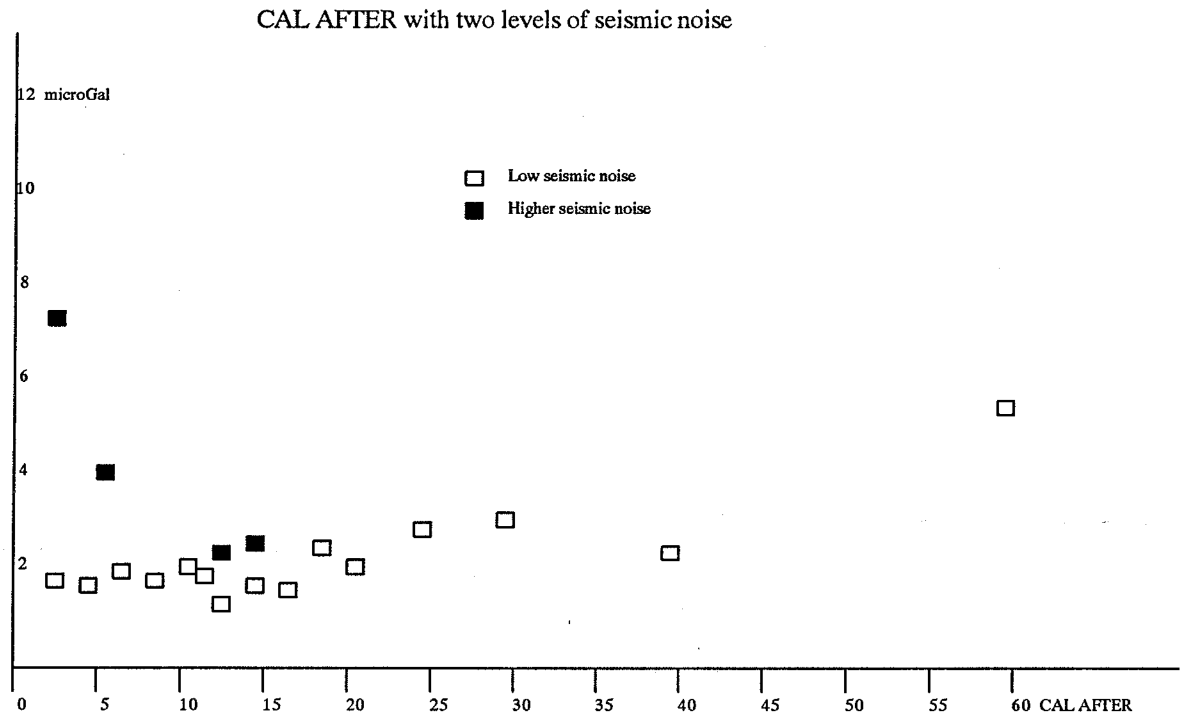

Figure 11

The micro-seismic periods range from less than 4 s to more than 8 s, with peaks at around 6 s and if the **CAL AFTER** parameter is set within these periods, this will introduce a bias in the scatter depending on the noise level. In effect, the instrument loses one second sample every time it does a voltage calibration and if this happens to occur at a seismic band period, the reading might be biased because of sampling at vibration peaks. A simulation of ground noise with the appropriate periods with arbitrary amplitudes was used to test different **CAL AFTER** settings (Figure 12) and we can partially reproduce the higher scatter observed at lower settings. The simulation was based on measured ground noise with the LaCoste & Romberg D-28 instrument from which we were able to obtain a good seismic spectrum. It may be that the Scintrex instrument is more sensitive to lower periods which would explain the higher standard deviations at **CAL AFTER=3** for instance which is not reproduced in our simulation.

It would seem that unless a survey crew has a seismometer handy to monitor ground noise, a default setting for **CAL AFTER** of around 13 would be a safe choice for all types of conditions. It is interesting to note that as the **CAL AFTER** setting increases past 20, the scatter gets worse, indicating that the voltmeter calibration works properly. In addition, the minimum standard error attainable is slightly less than 0.002 milligal with the best **CAL AFTER** setting.

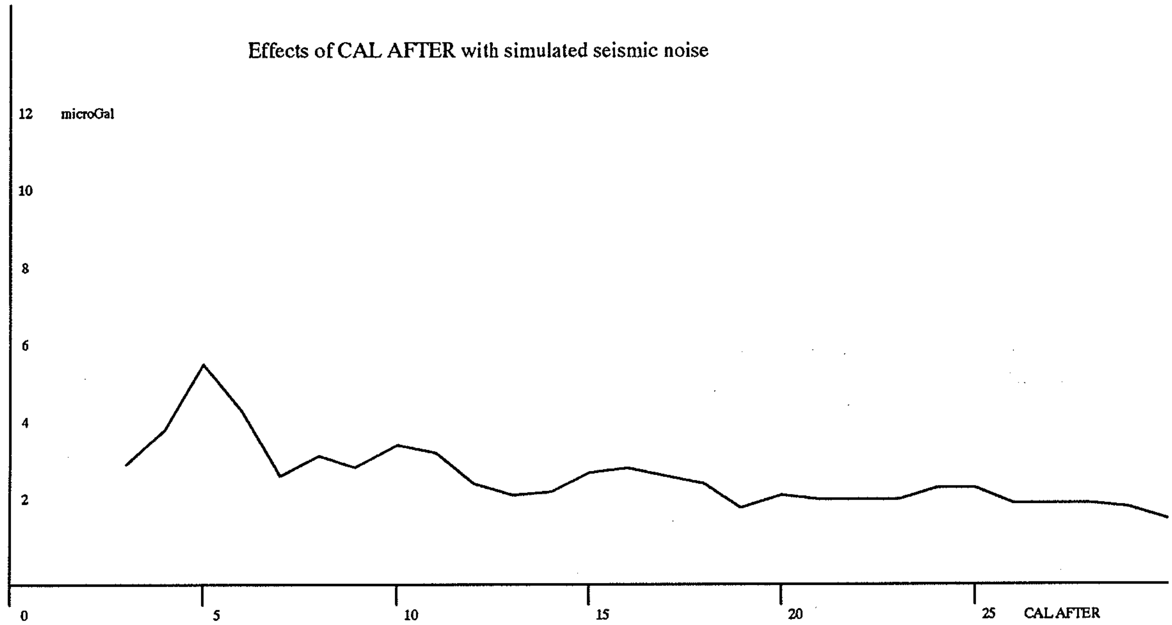

Figure 12

AUTO REJ

This function was used only on the transportion tests and it performed as intended. However, the method used to reject data, as mentioned above, is based on calculating continuously the standard deviation after the fifth sample. This rejection technique might fail if, during the start of the sampling, the ground noise level is very low for the first 5 samples, and then gets larger. Fortunately, we have not observed such conditions and on the occasions where a large amount of samples were rejected, traffic noise was found to be the cause.

ERR<LIM

The **ERR<LIM** function used in the field was also tested for longer periods in the laboratory. As with the function **AUTO REJ** above, it starts functioning only after the fifth sample since it has to calculate the standard error (equation 5) which needs a minimum of 5 samples. In principle, the instrument will stop sampling once the standard error is equal to or lower than the set limit even before the end of the set duration.

For our laboratory tests, we set

CAL AFTER = 15,
CYCLING at 600 (10 minutes)
AUTO REJ OFF
ERR<LIM set at 0.005 mGal
DUR = 240.

The error limit of 0.005 mGal was the recommended setting in the manual. About 16 hours of test samples are displayed with the effective duration of each reading (Figure 13). Approximately 50 samples were needed for most readings with a few readings exceeding 120 samples and one the full duration of 240. This last point occurred during a small remote earthquake.

We noticed that many readings have a duration of only 5, the minimum set of samples for calculating the standard error. Furthermore, there are indications that the readings that deviate the most from all the observations are those that have the smallest duration. Residuals displayed with respect to duration (Figure 14), show the greatest scatter occurring at a duration of 5. As described above, it is easy to see that the seismic noise will bias this function since its minimum sample size for calculating the standard error falls within the seismic band. Other tests where a smaller limit (<0.005 mGal) was used did not correct this effect since the seismic noise will also be smaller at times and during these quiet episodes, a limit of even 0.001 mGal will be reached in five samples. Clearly, the minimum sample size for calculating the standard deviation is too small, and should be modified to about 15 as seen in the **CAL AFTER** section.

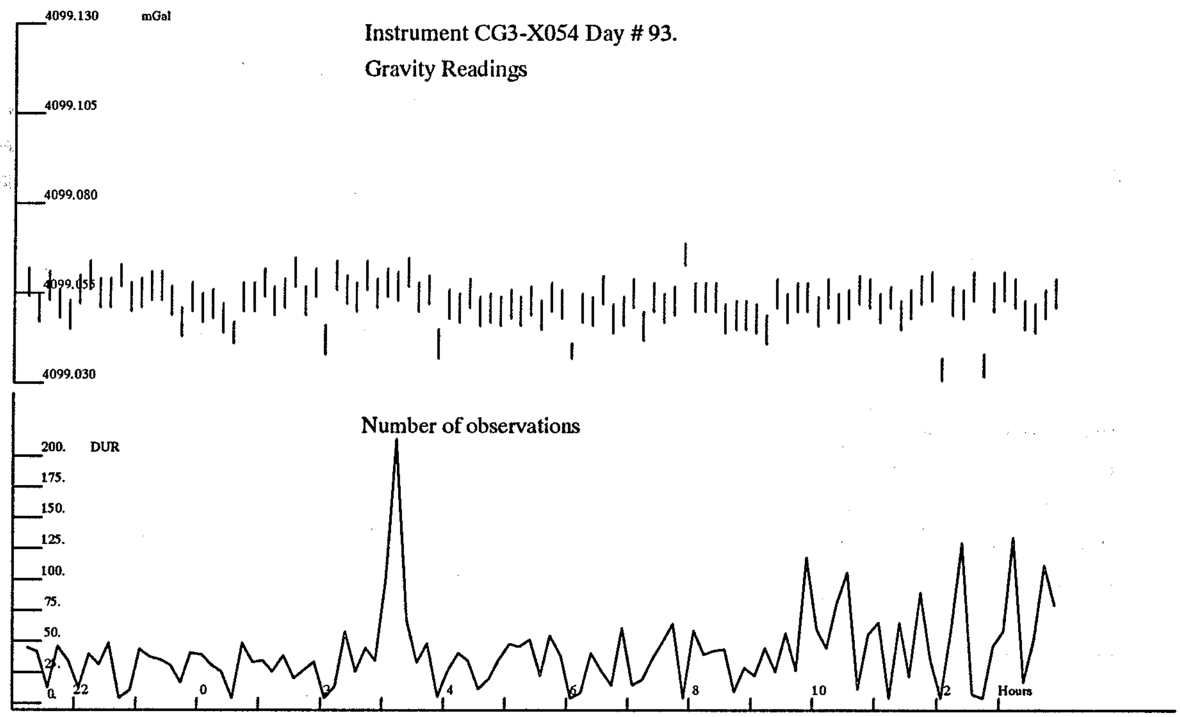

Figure 13

Our suggestion was implemented in the software when the instrument was sent to Scintrex in April, 1992. The minimum sample size before calculating the standard deviation has been increased to 15.

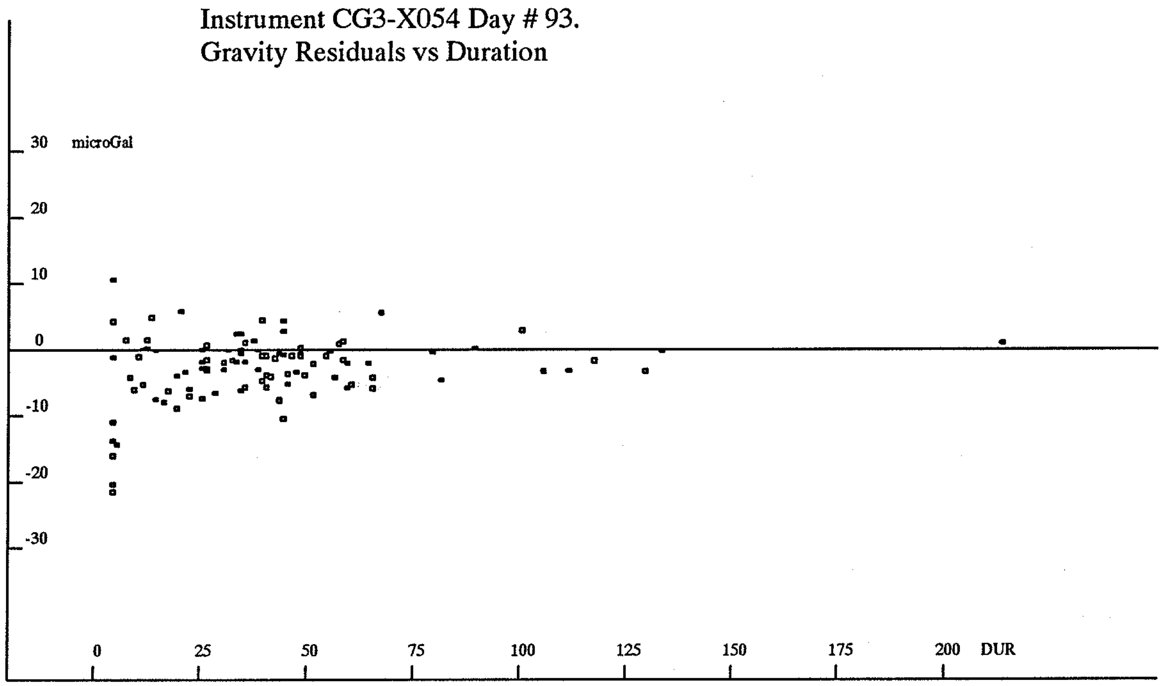

Figure 14

DURATION

The recommended duration of 120 could be reduced to 60 as seen above in the **ERR<LIM** tests where 50 samples were usually sufficient to achieve an error level below 0.005 mGal. For most applications, the increase from 60 to 120 will not reduce by half the standard errors of the readings.

8. Unexplained results

During the early stages of our tests, we repeatedly took readings on a continuous basis for drift monitoring. On one occasion, after a three hour test in the cold, we let the instrument stabilize as it was taking continuous readings for a few days. During this cold test, the internal residual temperature exceeded the 2 mK limit and the instrument took one hour to recover. The gravity residuals after the test (Figure 15) show that when the instrument had come to a stable internal residual temperature for many hours, the instrument fluctuated for no apparent reason. The level of seismicity was normal for the season and the laboratory environment was kept stable. Such an event may be an indication of scale instability early on when the instrument is new. It may partially explain the abnormal reading taken at the Kemptville station during the first calibration (day #79) which did jump for no apparent reason. These are the two events for which we have no clear explanation and until we understand such behavior, we have to be aware that they might happen again.

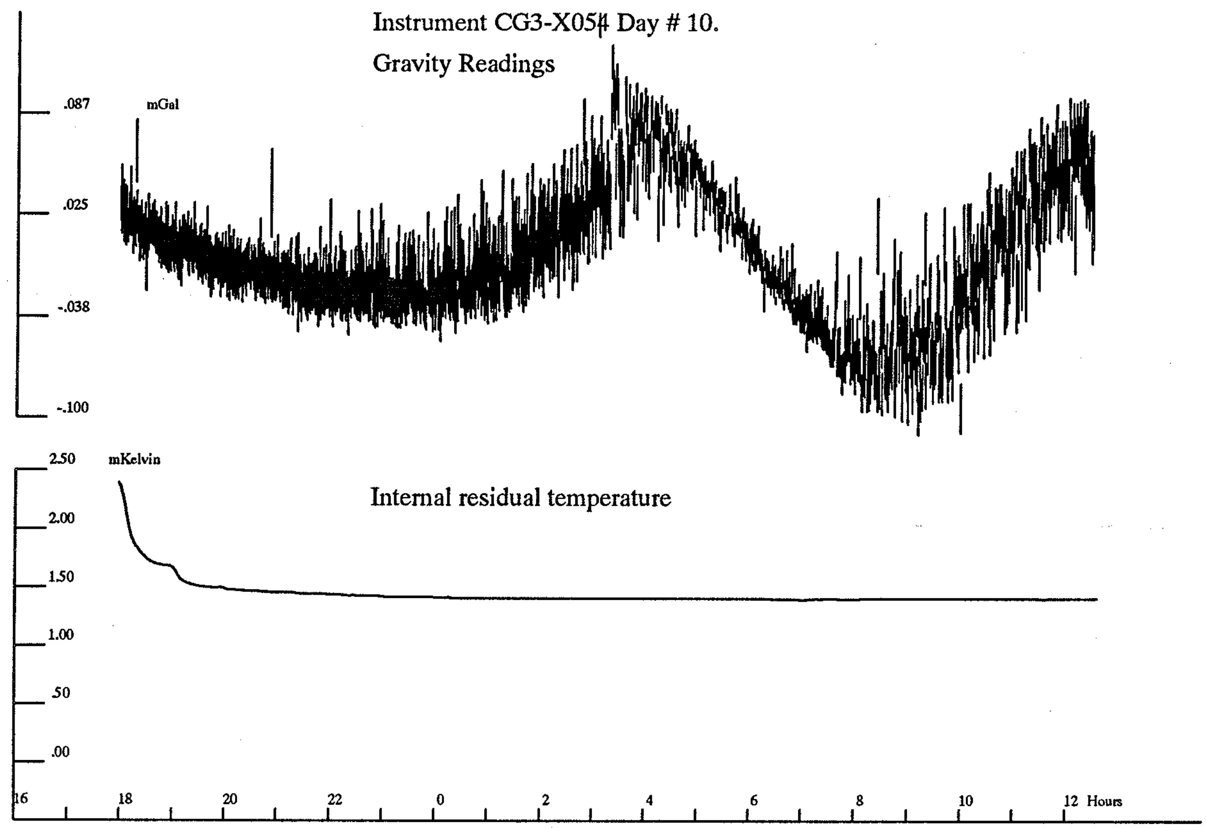

Figure 15

GENERAL REMARKS AND RECOMMENDATIONS

1. Use of instrument

The instrument has been designed to be self contained except for the leveling tripod and external batteries in cold conditions. The battery is inside the instrument and the device itself is its own carrying case. Based on our tests, the internal shock mounting works quite well in protecting the meter from external vibrations. However, as a field unit it has some drawbacks.

The main problem that we have identified is the principle of separating the leveling screws from the instrument and using an intricate tripod to do this function. The self-contained design loses its purpose since an essential piece of equipment must be carried around separately, sometimes under awkward conditions. Furthermore, the receptacles underneath the instrument for resting on the ends of the tripod are difficult to align since there are no clear markings and these surfaces are not on the same level. The instrument sometimes falls into place with a hard shock because of this design. Other types of instruments also use separate tripods but only as rough installation surfaces since the leveling is done within the units themselves. During the April, 1992 upgrade, indicator arrows have been put on either side of the meter to help the field operator line up the tripod legs with it.

Leveling the instrument has been another problem mentioned by the field crew. Because the levelling function is done electronically, no mechanical indicator is available to help the observer in bringing the meter close to the operating range of the electronic levels. The operating range of 300" of arc is quite small for an instrument that can be many degrees off level. Furthermore, the needles in the leveling dials are hard to see when off level so that an operator can start leveling the wrong way and not stop until it becomes obvious that the instrument is far off level.

The digital display was found to be unreadable under bright sunlight. This may be due to the extra recess that this display is located in and would be difficult to remedy.

Software:

The design of the software is a puzzling feature of this instrument. Once some parameters are set, the instrument can be started easily with only a **minimum of training.** However, the stored information, the operating menu, the organization of the data and the sequencing of the observations seem to be poorly designed for gravimetry. The station numbering system for instance will not use other characters besides numbers (alpha-numeric characters for instance). We have avoided using most of the menu system except for the instrument set-up. Some suggestions for improvement are listed here which deal with "bugs" found in the manuals, software and hardware. These proposed changes are not presented in order of importance.

The observations should not be automatically sorted by station numbers when being output to a printer or to a serial port. Whenever a non-sequential set of station numbers is used, it creates an editing headache which can be avoided.

The station numbering system would need to be re-designed in order to contain more characters. We use a six character code at the GSC and we know that people at the US-NGS use a lettering system with even more characters. Clearly this would be a good marketing option.

The use of tidal corrections is difficult to use over large distances. Each gravity station will have significantly different coordinates making tidal corrections inaccurate without changing the coordinates. Inserting new coordinates at each site is time consuming. It would be more efficient to store beforehand a set of gravity stations (numbers with coordinates) which could be called when needed. If these values could be introduced through the RS-232 cable, the process would be very fast and accurate. For the moment, we have avoided using this tide function because of these problems. Data is processed and tide corrected after a survey back at the main office.

There is a problem with the "GMT difference" feature. We found that this value can only be modified when in tidal correction mode. If the tide correction is disabled, the user cannot change this specific field in the menu. Furthermore, files sent out by the instrument and saved for later use, have the line "GMT Difference..." which may lead to confusion for people who process the data (other than the surveyers). At the GSC, we have systematically set the time of the instrument to GMT before going out in the field, thus minimizing any problems since too often have we encountered errors in reading times simply because operators in the field were uncertain as to the right GMT difference to apply.

When the instrument outputs data to a printer or computer, the **CYCLING** mode lacks a useful feature found only in the **DUMP** mode, namely day-breaks. These breaks indicate whenever the date changes (00:00 hours etc...). A possible solution would be to output (in cycling mode only) the full date with each data line with the "yymmdd" format for minimum memory use.

When using the station number incrementing feature (increments each station value automatically), the users have been confused by the method readings are stored. We feel that the incrementation should only occur at the begining of a new reading, not at the end of one. Observers have repeatedly called up **DATA** to get the reading, time and station number for writing in their notebook and the station number was never the right one. For the moment, field measurements are written down for the sake of redundancy since we have been aware of one case of total data loss from the instrument's memory (wrong keys were pushed). Furthermore, when using the **DATA** key, field personnel have found that the readings should be ordered next to the observation time in the menu. They found it annoying to have to push the arrow keys a few times to get from the reading to the time.

Instrument constants should not be readily available in the menu of the **AUTOGRAV SETUP**. We think these values should be accessible only in the **INITIALIZE** portion of the menu. These fields are not usually changed during a survey. For instance, these values could be accessed along with the "**LOCK AUX**" for better data safety. We also find that an observer could in fact change the serial number of the instrument in this menu. This data field should not be in the menu at all.

Data in the output files now contain the standard **deviations** of the readings instead of the standard **errors**. This change (spring 1992) occured during the recent repairs. This is not consistent with the **ERR<LIM** function which uses standard **error** values. We prefer the standard error format.

2. Data storage and output

As mentioned above, instrument X054 can store a maximum of 390 readings. This data can be transferred through a communication line (RS232) with the **DUMP** function. The output file contains a header record for every day followed by the respective readings.

Another useful feature is to continuously send out the data as it is being acquired in **CYCLING** mode. However, we found a software bug by which all signs are stripped from the data when used in that manner. The X and Y tilts as well as the internal residual temperatures lose their signs whereas in **DUMP** mode, all the signs are transferred properly. Further analysis on data received using this feature might prove impossible with the loss of the signs.

A bug was found in the CG-3 software which "stripped" the signs of the data when in cycling mode. It has been fixed when the instrument was sent back to the manufacturer in the spring of 1992.

3. Maintenance

The manual indicates that the sensors for internal temperature and X-Y tilts need periodic checks and adjustment to maintain accuracy. In addition, the drift factor has to be verified on a routine basis. For the internal temperature sensor, there is a set of offset screws under the lid on top of the instrument that need adjusting when the residual temperature reaches $>\pm 2$ mK. Since taking delivery of instrument X054 in December, 1990, we have had to adjust this sensor twice; once in January, 1991, and again at the end of our tests in June, 1991. This is consistent with the normal upkeep of the instrument mentioned in the manual.

As indicated previously under laboratory tests, the tilt sensors are not aligned exactly with the vertical and the scale factors have an error of about 2%. The manual recommends that tilt sensors be checked every other month and our experience with the meter confirmed this recommendation even though the vertical offset was not significantly large at the time.

Drift correction determination takes a minimum of one or two days of readings for accurate calculation. It turns out that the long term drift rate cannot be accurately determined from one or two readings at a base station. We have seen the instrument drift unevenly over short periods of time (sometimes over one day). We feel that continuous monitoring over one day is a better method to get this long term drift rate.

We have had one total shut-down (July 1991) of the instrument since acquiring it in late 1990. The drift rate after this event reversed its down-going trend (toward a smaller drift rate) and was in fact larger than before. Based on this one experience, we cannot trust previously determined drift rates if there is a full power shut-down.

All these maintenance requirements imply that a minimum of two days are needed prior to a survey if the instrument is to perform reasonably well in the field. Furthermore, if the instrument happens to be cold (off heat), another 48 hours are needed before any of these tests can be done. Evidently, any survey with this instrument needs a fair amount of lead time for checks and adjustments to ensure proper operation.

Finally, we have found that the battery compartment has been a problem with repeated use. It becomes difficult to close because the battery must be inserted in a particular way due to short cabling and to excess adhesive tape binding the power cable to the battery. Some improvements here would certainly help.

CONCLUSIONS

The series of tests outside the laboratory such as the calibration trips and the transportion tests have shown that **the instrument performs quite well** under a variety of field conditions and that **the scale factor is relatively stable.** The scatter in the scale for the different surveys is about 6.10^{-5} which is equivalent to 0.006 mGal on the full range of our calibration line south of Ottawa. The instrument's **ruggedness and automated features** makes it a useful device in the field since it may not require special vibration isolation during transit and it is usually faster than other gravity meters to read when set down at a site. However, the following suggested improvements could enhance its acceptability in the geophysical survey community.

Ergonomically, the instrument needs further improvements. We suggest the following changes. Leveling control knobs should be part of the instrument and not in a separate platform to improve ease of leveling. The leveling displays should be complemented with a coarse level (bubble) indicator so that the user can assess quickly how off-level the instrument is when setting it on the ground. The LCD display should be improved to accommodate for brighter conditions (in direct sunlight for example) and the leveling displays should have a stronger contrast for better viewing.

Reduction in power consumption to extend the duration of a single battery charge for most field conditions should be investigated. The competition still has longer field time on a single battery charge.

The software could be simplified. Most often used functions such as instrument set-up and data output could be put in a separate menu. The calculation of tidal corrections would be improved if an easy and efficient way was used to input station coordinates as well as gravity station numbers.

The statistical part of the software has received needed improvement such as a longer sampling period prior to standard deviation calculation. Because of the way the system has been re-designed, one function (**ERR<LIM**) has been restored to its full effectiveness and another (**CAL AFTER**), more immune to seismic noise. The minimum number of samples for these functions has been increased from 5 to 15 samples. Furthermore, we suggest for surveys where high accuracy is needed, that a minimum sample size for a reading be set to **DUR** = 60. Field surveys would not suffer from such a requirement and it would increase the chance of a successful survey.

Our CG-3 intrument has undergone continuous improvements by Scintrex these last two years in response to our suggestions. These improvements have been advantageous to both the GSC and Scintrex.

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