SCINTREX

The New Scintrex CG-3 Autograv Gravity Meter

Description and Test Results

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Introduction

Commercially available gravity meters for use on land in the post World War II period have been dominated by two designs: the Worden type of quartz instrument, and the Lacoste and Romberg, with a metal sensor. Both of these were developed to operate without the use of electronics. They rely on the zero length spring concept developed by Lacoste (1934) to obtain high mechanical sensitivity to gravity changes (astatisation) and to reduce the effect of seismic noise.

Although the accuracy of these instruments is adequate for their intended applications, they have several deficiencies both from an operational and a manufacturing viewpoint.

In normal field use with both instrument types, the operator is required to null the sensor beam manually by rotating a micrometer screw and then record the reading manually. There are several possible sources of error in this process and a high level of operator skill and experience is required. Entering the data into a computer for processing is time consuming and is a further source of potential error.

The manufacturing difficulties are significant. Achieving astatisation requires a finely balanced mechanism. Mechanical feedback systems require more precision mechanisms. They also incorporate mechanical feedthroughs into the chamber containing the sensing element, leading to pressure sensitivity problems. Solutions to these further increase the complexity of the system.

As well, the adjustments required to effect mechanical temperature compensation in quartz instruments demands an extremely high level of craftsmanship. In the Lacoste and Romberg instruments the problem is reduced by using low temperature coefficient alloys. These however are sensitive to magnetic field variations, making it necessary to shield the sensor.

Against this background, Scintrex started the development four years ago of a new gravity meter, the CG-3. The goals of the project were to overcome the operational deficiencies of existing instruments, and to produce a design that was mechanically simple enough to be manufactured on a routine production basis, on the assumption that the electronic advances of the thirty to forty years since the initial development of the Worden and Lacoste instruments could be utilized to achieve these goals.

The more specific technological base for the development was the recent introduction of the Scintrex IGS general purpose field portable data acquisition/control system; and current developments in the application of capacitive displacement transducers and electrostatic feedback to gravity meters (Hugill 1984).

An instrument conforming to these requirements has successfully been developed, and is presently in the final testing stages. This paper describes the CG-3 gravity meter and its performance in laboratory and field tests.

Sensor Design

The sensing element of the CG-3 gravity meter (figure 1) is based on a fused quartz elastic system. The gravitational force on the proof mass is balanced by a spring and a relatively small electrostatic restoring force. The position of the mass, which is sensed by a capacitive displacement transducer, is altered by a change in gravity. An automatic feedback circuit applies DC voltage to the capacitor plates producing an electrostatic force on the mass, which brings it back to a null position. The feedback voltage, which is a measure of the relative value of gravity at the reading site, is converted to a digital signal and then transmitted to the instrument's data acquisition system for processing, display and storage.

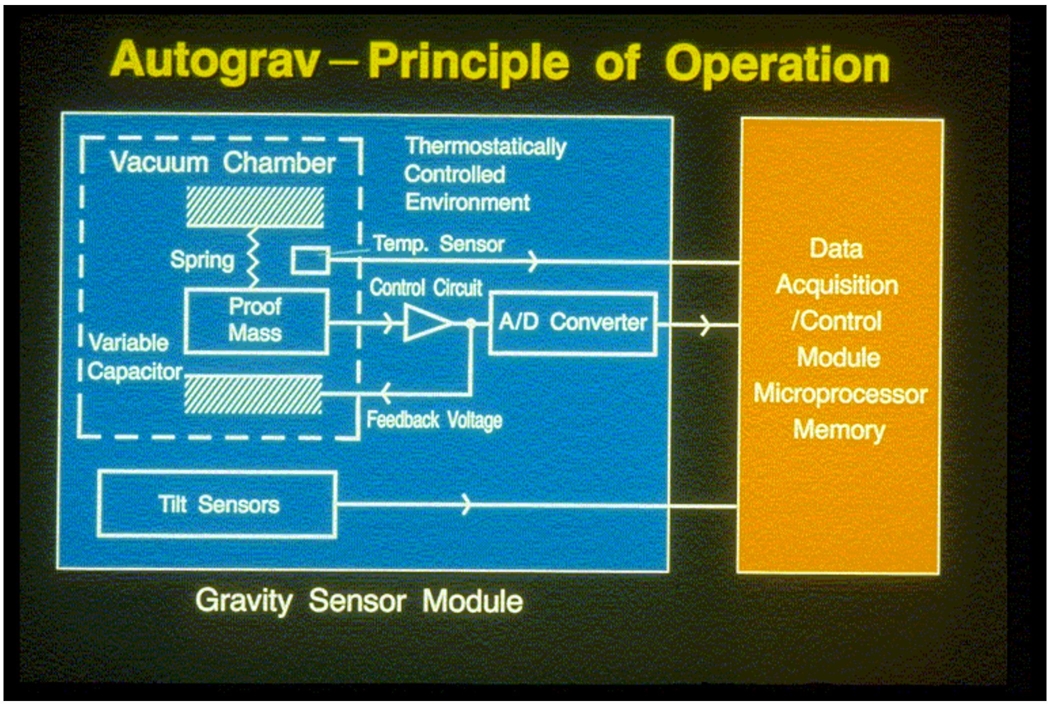

Figure 1 CG-3 Principle of Operation

The inherent strength and excellent elastic properties of fused quartz together with limit stops around the proof mass permit the instrument to be operated without clamping. Further protection is provided by a durable shock mount system attaching the sensor to the housing.

The parameters of the gravity sensor and its electronic circuits are chosen so that the feedback voltage covers a range of over 7000 mGals without resetting. The use of a low-noise electronic design together with a highly accurate auto-calibrating analog to digital converter results in a resolution of 0.01 mGal, equipping the gravity meter for both detailed field investigations and large scale regional or geodetic surveys.

The instruments' tilt sensors are also electronic, with a resolution of I arc second. The outputs from the sensors are displayed on high resolution meters on the instrument's front panel and also transmitted to the data acquisition system where they are displayed and stored. If the instrument is operated on an unstable base, realtime corrections for tilt errors are automatically made over
a range of <u>+200</u> arc seconds.

Protection from ambient temperature changes is provided by locating the quartz elastic system, the analog to digital converter, sensitive electronic components and the tilt sensors inside a high-stability, two stage, thermostatically controlled environment. There is no mechanical temperature compensation. External temperature changes are reduced by a factor of 105 and small residual effects are corrected in software using the output of a sensor located in close thermal contact with the main spring. The operating range of the thermostat in the standard instrument is –40°C to +45°C. However, as there is no critical operating point for the sensor, the upper operating temperature can be set at a higher or lower value.

The entire gravity sensing mechanism is enclosed in a vacuum chamber. As there are no mechanical feedthroughs, excellent isolation from variations in atmospheric pressure is obtained. This extremely stable operating environment for the quartz elastic system allows the long-term drift of the sensor to be accurately predicted, and realtime software correction reduces it to less than 0.02 mGals/day.

The sensor design is mechanically very simple for several reasons. The fine balancing required to obtain astatisation is not needed, as the displacement transducer has sufficient resolution (0.2nm) to detect the beam position of a non-astatised system, and electronic filtering reduces the effect of seismic noise. The mechanisms, micrometer screws, gearboxes and mechanical feedthroughs associated with mechanical feedback systems have been replaced by a voltage applied to the same plates, which form the displacement transducer. The temperature control is also accurate enough for the sensor to operate without mechanical compensation.

Packaging

The housing has been integrated with the carrying case (Fig. 2), so that one unit contains the sensor, supported by shock-proof mounts, the data acquisition/control module, and the battery. This design reduces handling and therefore the danger of associated accidents of various kinds, such as upsetting the instrument with the cable connecting the sensor to the battery. The dimensions are specifically designed to fit under an airline seat. The base of the gravity meter case incorporates a kinematic mounting system which indexes onto the tripod, further increasing instrument stability.

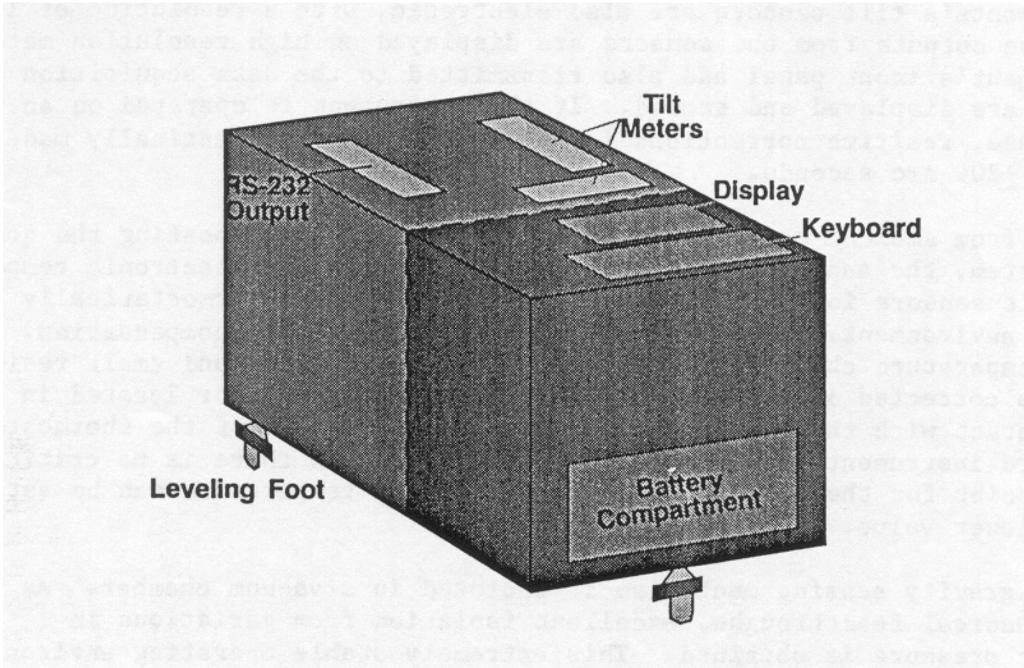

Figure 2. Integrated Housing

The unit is fully weather-proof. The total weight of the instrument including the battery is 12kg.

The housing's modular concept enables the control console to be removed for maintenance or alternative use. With the standard CG-3 Autograv the control console is dedicated to the gravity meter. With the IGS-2/CG4 version of the instrument a Scintrex IGS-2 System Control Console is used. This version has identical performance to the CG-3 with respect to gravity measurements but offers additional flexibility. The addition of a proton magnetometer sensor allows gravity and magnetic measurements to be made simultaneously. When the console is removed, it can be used to perform magnetic, VLF, IP or other measurements when equipped with the appropriate sensors.

The battery is charged through an external connector without being- taken out of the case. This connector is also used with an external power source such as a battery belt for cold weather operation. The standard 5.7Ah lead-acid battery has a life of approximately 12 hrs at 25°C. Battery voltage can be monitored on the instrument display; an alarm sounds when the battery is within 30 minutes of being discharged.

Control Console and Software

The control console includes a 14-key dual function keyboard, a 32-character LCD display, the microprocessor and the solid state memory. It processes and applies corrections to the signals from the sensor, stores data and for-mats it for outputting, and performs instrument control functions. A menu format with prompts is used to operate the instrument.

The gravity meter has two modes of operation: a field mode and a cycling mode. In field mode, readings are initiated by the operator. In cycling mode, a series of readings are made automatically with a preset cycle time between each reading. The software function is essentially the same in both modes.

Prior to the commencement of each reading, a software-controlled procedure calibrates the A/D converter, using a high-stability internal voltage reference. When the calibration is completed, the A/D converter samples the gravity sensor output every second. The individual samples are averaged to filter out seismic noise. The standard deviation of the mean of the samples is displayed in realtime. Corrections for tilts, sensor temperature and long-term drift are made every second during the reading. A statistical rejection criterion is used to discard any noise spikes. A tide correction is applied at the end of the reading. (These last two functions can be disabled from the keyboard.)

When a measurement is completed the gravity reading is stored in the memory along with nine other variables. These are: station number, standard deviation of the mean; tilts (X and Y); sensor temperature; tide correction; reading duration; number of rejected samples; time of start of reading. All current and stored data can be viewed on the LCD display, using the scroll feature on the keyboard.

As well, additional information can be entered at the time of measurement for recording in memory. Eight blocks of data, each containing up to a five-digit signed number, can be stored with each reading.

The standard memory stores up to 420 readings and can be expanded to a maximum of 1260 readings. The memory is protected for several days in the event of battery failure.

Other information is also generated and is accessible through the display, including time, date, battery voltage and available memory space.

The instrument is equipped with an RS232 interface. This enables data from the memory to be accessed through a connector on the instrument front panel. Output of selected portions or of the entire contents of the memory can be obtained in the form of a data listing or as a plot, which can be printed out directly on to a line printer, transferred to a portable computer or tape recorder or transmitted over a telephone line to a modem.

Header information consisting of survey parameters and instrument constants is shown at the top of each data listing (fig. 3). Each gravity reading is located by station number and time. The record of the other variables facilitates data quality control. For example, the record of tilts indicates if the instrument has been properly levelled; sensor temperature shows if the thermostat is functioning correctly; the standard deviation of the mean (ERR) and the number of rejections indicate the noise level at the measurement site.

SCINTREX V1.6 CG-3 GRAVIMETER / Cycling Mode R1.0

Cycle Time: 58 Ser No: 2.

Line: 1. Grid: 1. Job: 0. Date: 88/02/08 Operator: 1.

Drift Correction Start Time: 09:30:11 On-Line Tilt Corrected = "*"

Date: 88/02/03

Gravity Reference: 0.5 Tilt y sensitivity: 178.6

Gravity constant #1: 5485.938 Tilt x sensitivity: 175.4

Gravity constant #2: -7.76229 Temperature constant: -0.183

Drift constant: 0.2 Deg.Latitude: 43.67

GMT Difference: 5. Deg.Longtitude: 79.61

Station	Grav.	ER.	Tilt x	Tilt y	Temp.	Tide	Dur	# Rej	Time
10.	4232.30	0.002	2.	-4.	-1.69	0.037	36	0	17:15:10
10.	4232.30	0.003	2.	-4.	-1.68	0.037	36	0	17:16:10
10.	4232.30	0.003	2.	-4.	-1.69	0.037	36	0	17:17:10
10.	4232.30	0.003	2.	-4.	-1.68	0.037	36	0	17:18:10
10.	4232.30	0.003	2.	-4.	-1.68	0.037	36	0	17:19:10
10.	4232.30	0.003	2.	-4.	-1.69	0.036	36	0	17:20:10
10.	4232.29	0.003	2.	-4.	-1.68	0.036	36	0	17:21:10
10.	4232.30	0.003	2.	-4.	-1.69	0.036	36	0	17:22:10
10.	4232.29	0.003	2.	-4.	-1.68	0.036	36	0	17:23:10
10.	4232.30	0.003	2.	-4.	-1.68	0.036	36	0	17:24:10
10.	4232.29	0.003	2.	-4.	-1.68	0.036	36	0	17:25:10
10.	4232.29	0.003	2.	-4.	-1.68	0.035	36	0	17:26:10
10.	4232.29	0.003	2.	-4.	-1.68	0.035	36	0	17:27:10

Figure 3. Atypical gravity meter listing Units are mGal for gravity, ERR and tide: arc seconds for tilts: mK for temperature. Duration is in seconds.

An example of data output as a plot is shown on Fig. 4. Up to two variables can be plotted either as a function of station number along a survey line in field mode; or as function of time in cycling mode. The plot scale and offset bias are adjustable for each variable plotted.

```
---------------------------------------------------------------------------------
SCINTREX V1.6        CG-3  GRAVIMETER / Cycling Mode  R1.0
Cycle Time:     1798                                             Ser No:
Line: 80759.W  Grid:  -14408    Job:            Date: 88/01/30  Operator:

Drift Correction Start  Time: 00:20:05          On-Line Tilt Corrected = "*"
                        Date: 87/01/01
Gravity Reference:              0.              Tilt y sensitivity:        178.6
Gravity constant #1:      5485.938              Tilt x sensitivity:        175.4
Gravity constant #2:      -7.76229              Temperature constant:      -0.09
Drift constant:               0.47              Deg.Longtitude:             43.8
GMT Difference:                5.0              Deg.Latitude:               79.8
---------------------------------------------------------------------------------
x Grav.
Bias:     4592.8 F = 1.        Bias +   .2xF      .4xF      .6xF      .8xF     1xF
o Tide
Bias:       -0.5 F = 1.        Bias +   .2xF      .4xF      .6xF      .8xF     1xF
```

Station	Grav.	Tide
3348S	4593.034	0.110
3348S	4593.043	0.096
3348S	4593.032	0.079
3348S	4593.048	0.060
3348S	4593.037	0.040
3348S	4593.029	0.019
3348S	4593.041	-0.001
3348S	4593.035	-0.020
3348S	4593.036	-0.037
3348S	4593.039	-0.052
3348S	4593.042	-0.064
3348S	4593.038	-0.073
3348S	4593.038	-0.079
3348S	4593.035	-0.082
3348S	4593.037	-0.082
3348S	4593.041	-0.080
3348S	4593.031	-0.077
3348S	4593.040	-0.072
3348S	4593.039	-0.068
3348S	4593.037	-0.063
3348S	4593.039	-0.059
3348S	4593.037	-0.056
3348S	4593.043	-0.055
3348S	4593.037	-0.055
3348S	4593.035	-0.057
3348S	4593.052	-0.059
3348S	4593.045	-0.063
3348S	4593.032	-0.066
3348S	4593.039	-0.070
3348S	4593.036	-0.073
3348S	4593.029	-0.074
3348S	4593.040	-0.073
3348S	4593.040	-0.069
3348S	4593.032	-0.062
3348S	4593.038	-0.052
3348S	4593.038	-0.039
3348S	4593.027	-0.024
3348S	4593.038	-0.005
3348S	4593.037	0.014
3348S	4593.036	0.035
3348S	4593.022	0.056
3348S	4593.036	0.076
3348S	4593.030	0.095
3348S	4593.043	0.111
3348S	4593.043	0.124
3348S	4593.031	0.132
3348S	4593.040	0.135
3348S	4593.043	0.134

Figure 4. Data Output as a plot. Corrected gravity and tide correction are plotted as a function of time.

In cycling mode the corrected gravity value is converted to a voltage which is available on the RS232 connector. This enables the gravity signal to be continuously monitored on a chart recorder. Output scale is controlled by the software and the system is autobiasing so that no adjustment is required to bring the recorder into range.

Examples of analog records are shown in Figs. 5-8.

Operating Procedure

When the instrument is placed on the tripod, the start key is pushed once. This initiates the A/D converter calibration procedure and displays the tilt sensor outputs in digital form. When levelling is completed, the start key is pushed again. The instrument pauses for two seconds. (This allows any disturbance to dissipate.) The reading then commences. During the reading, the operator can observe gravity, standard deviation of the mean, and reading duration, which are displayed simultaneously and updated every second. (As the gravity reading is a continuous average of one-second samples, it will converge as the reading progresses, and the standard deviation of the mean will also decrease.) The reading is stopped automatically according to the chosen preset time, or manually by pressing the stop key when the reading has stabilized sufficiently. (The time required for convergence depends on seismic noise. In a quiet location, a 20-second reading is sufficient.)

Pressing the record key stores the reading when the measurement is completed.
If the operator does not want to record a reading, pressing the start key again will reset the instrument for another reading. Alternatively, more than one reading made with the same coordinates at different times can be stored.

If the auto station increment feature has been selected, the next station number is entered automatically when the record key is pressed. Otherwise the instrument prompts for the next station number, which is entered from the keyboard. The instrument is now ready to be moved to another location.

Ancillary information, such as tripod height or instrument elevation, must be entered before the record key is pressed.

Results of Laboratory Tests

Results of laboratory tests to determine instrument sensitivity to changes in temperature, pressure and magnetic field are presented below.

Figure 5 shows the results of high and low temperature tests performed on an instrument specified to operate up to 50°C. In the high temperature test the instrument was set up in cycling mode and a portable oven lowered over it and left there for over 2 hours. The analog output of the gravity meter and the air temperature close to the instrument were recorded continuously throughout the test. Readings are stable until the temperature reaches 55°C. When the oven is removed the temperature drops rapidly from 47°C to 24°C. There is a delayed increase of approximately 0.02 mGal in reaction to this step.

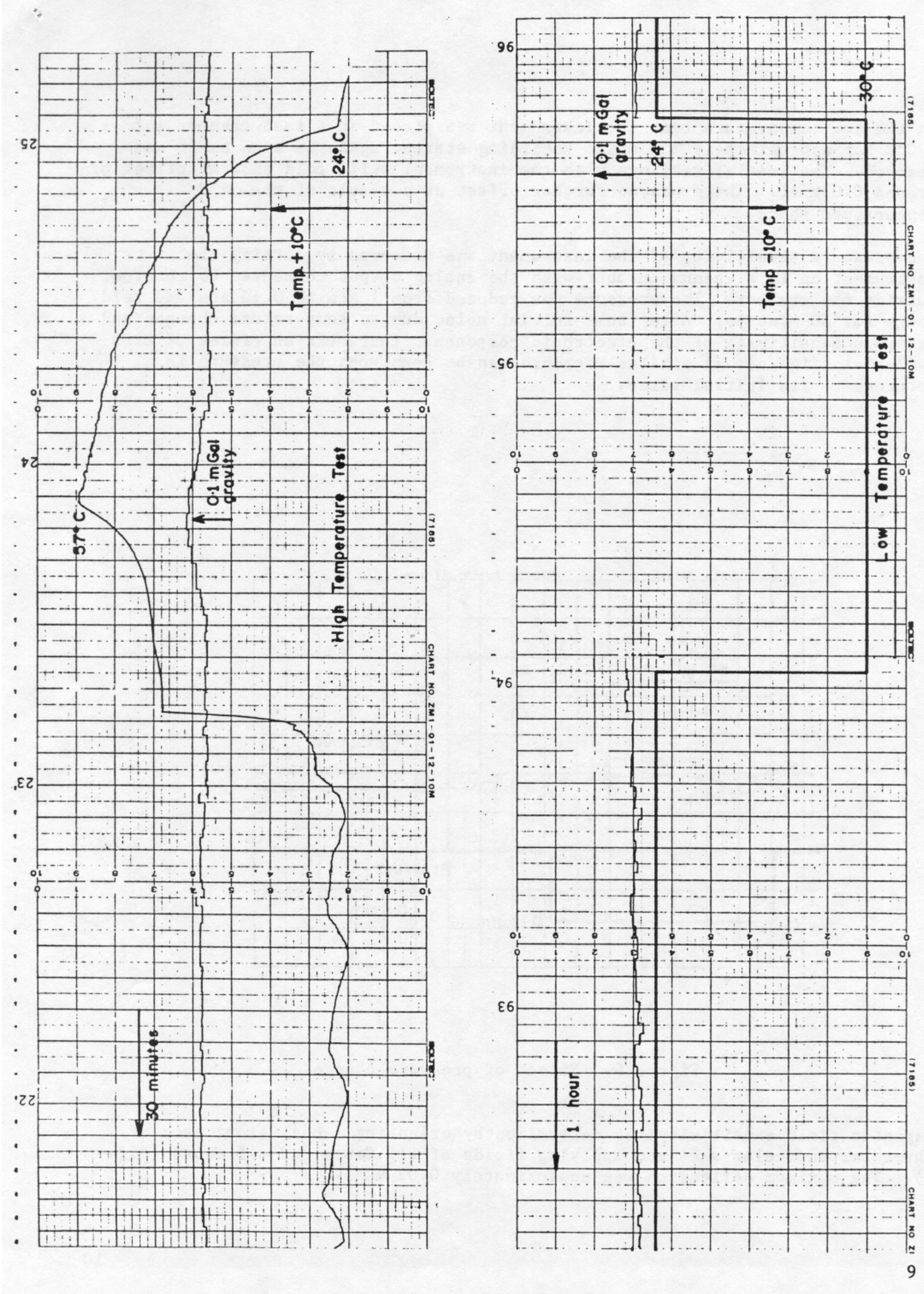

Figure 5. Results of high and low temperature tests. Gravity signal comes directly from the analog output of the instrument.

In the low temperature test the instrument was placed in a test chamber set at –30°C for approximately 4 hours. Recording started again as soon as it was removed. The initial readings with the instrument still cold show an offset of around 0.03mGal. There was no further offset as a result of the 54°C temperature shock.

The pressure sensitivity of the instrument was measured by setting the instrument up in a vacuum chamber with the analog output connected to recorder outside the chamber. The pressure was reduced from 1 atm to 0.15 atm and held there for 50 minutes. After some initial noise due to temperature changes and pressure sensitivity of the electronic components there was an offset of 0.02 - 0.03 mGal (fig. 6). A similar response can be seen when the pressure is returned to its initial value.

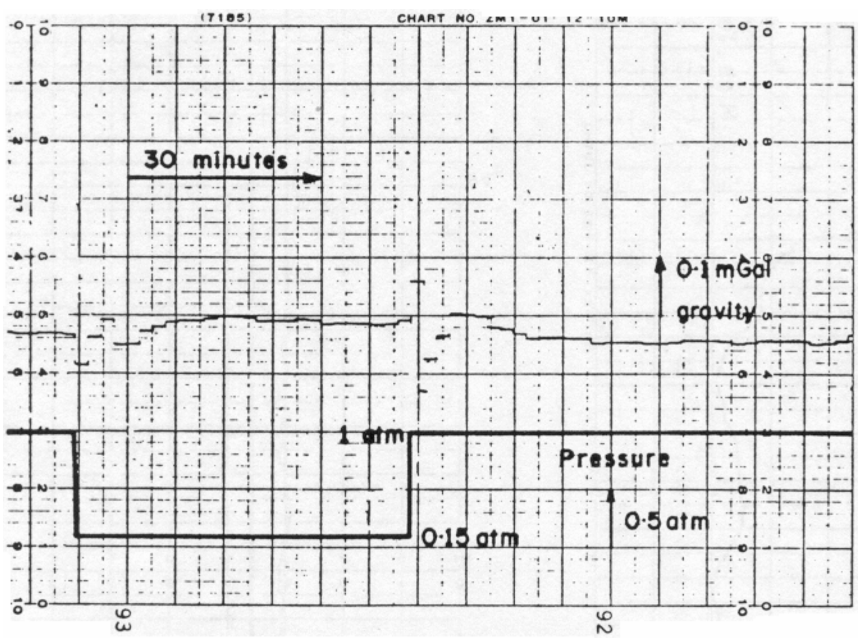

Figure 6. Effect of Pressure Change

Magnetic field sensitivity was determined by orienting a coil along each of three perpendicular axes and applying fields of +15 Gauss and -15 Gauss (Fig. 7). The maximum deflection was approximately 0.02 mGal.

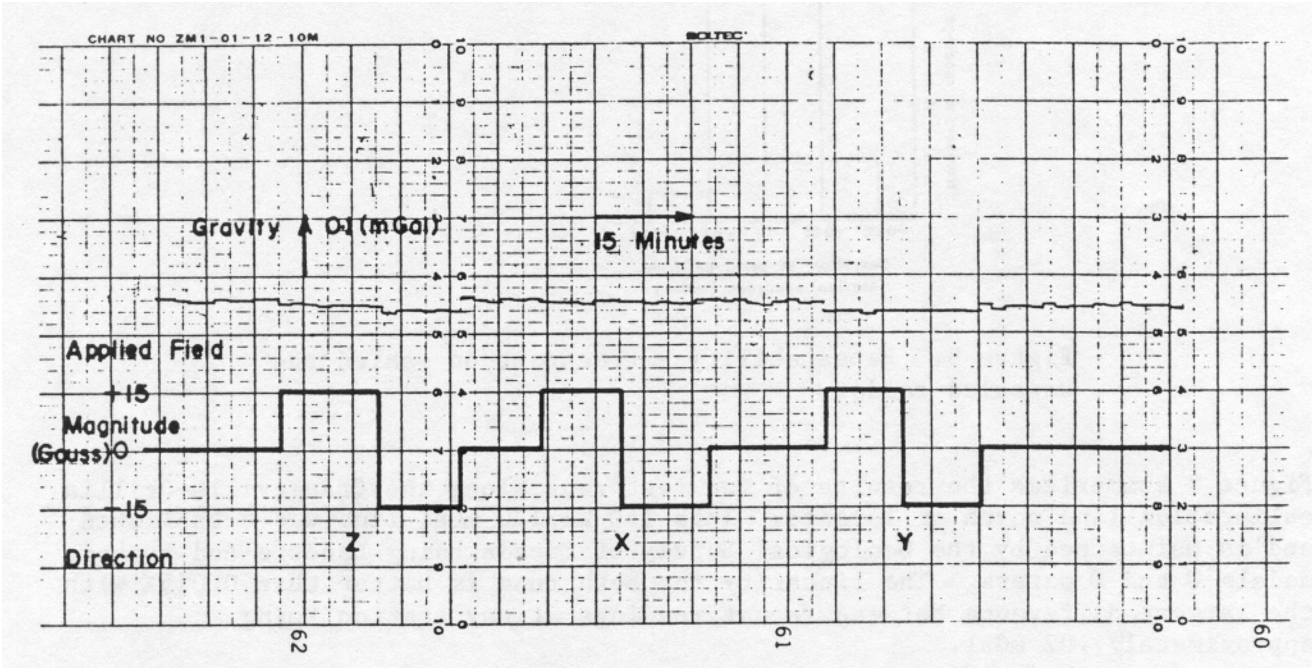

Figure 7. Magnetic Field Sensitivity

In summary: the temperature sensitivity of the instrument is less than 0.001 mGal/°C, pressure sensitivity is 0.03 mGal/atm and maximum magnetic field sensitivity 0.00013 mGal/Gauss.

Results of Field Tests

In this section the results of representative field tests are presented. Repeatability, linearity and the effect of transport on long term drift rate are discussed.

Results of a field test performed on a test site located 65 km from the Scintrex plant are shown in figure 8. Two loops of approximately 20 km were made around the test range with the instrument being transported by car over badly corrugated unsealed roads. The largest deviation of a reading from the station mean was less than 0.02 mGal and the standard deviation of the difference between individual readings and station means is 0.007 mGal.

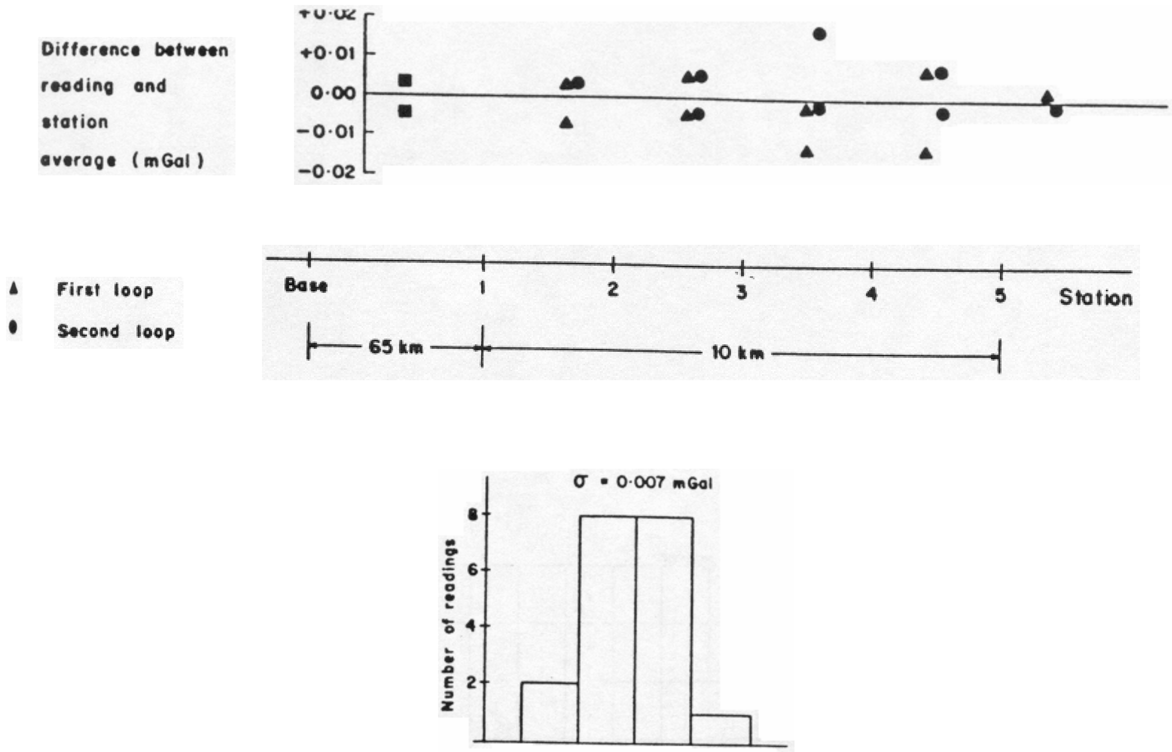

Figure 8. Repeatability – transport on sealed and usealed roads

Figure 9 summarizes the results of two test runs along the Orangeville-Orillia calibration line north of Toronto. This 140 km/120 mGal line was established and is maintained by the Geological Survey of Canada using Lacoste and Romberg models G and D meters. The linearity for both runs is better than 0.015% with the largest difference between repeat readings at any station being approximately .02 mGal.

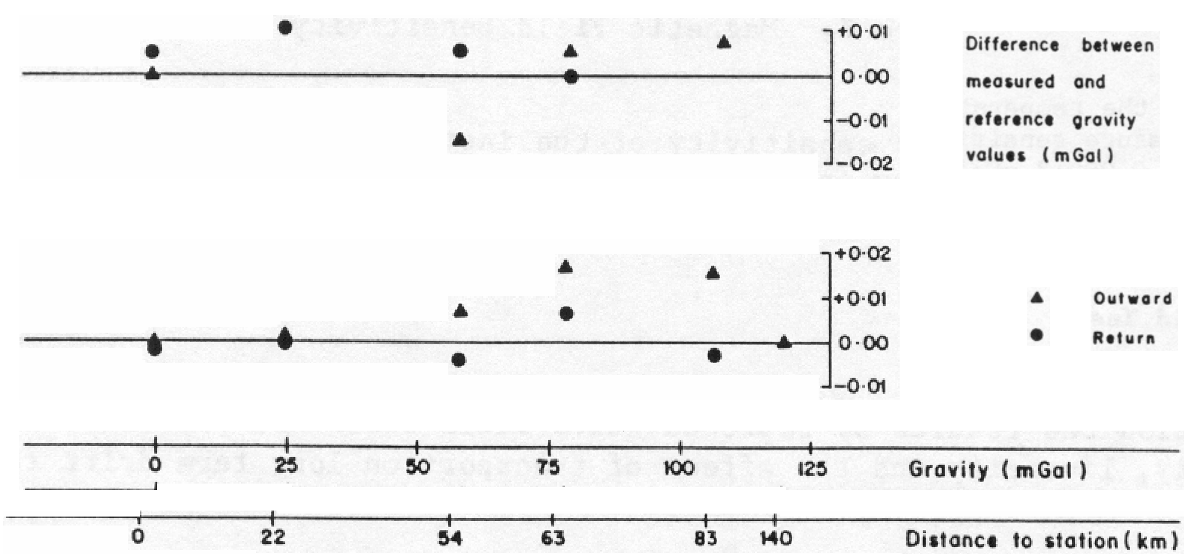

Figure 9. Test runs on the Orangeville-Orillia Calibration Line

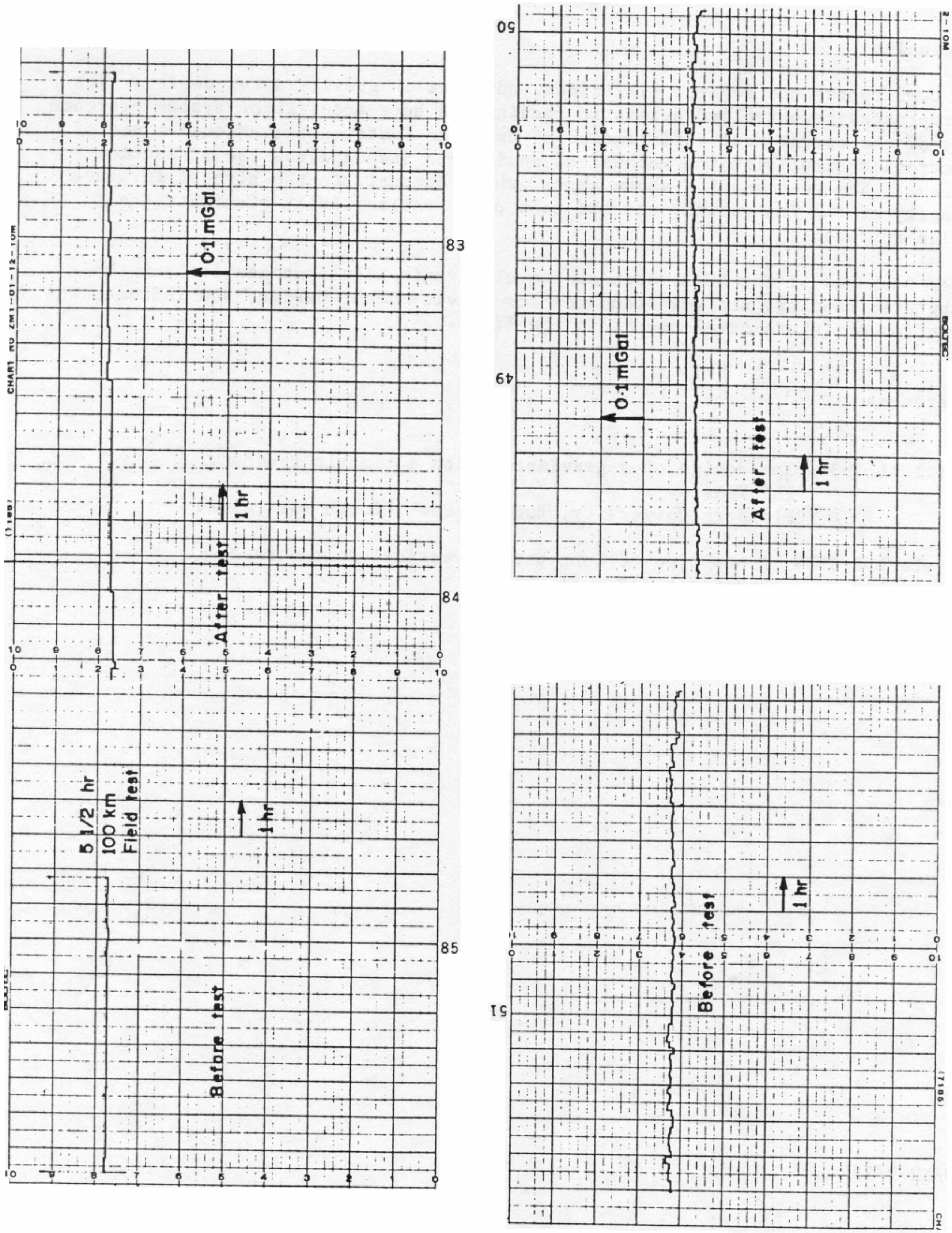

Figure 10. Effect of transport on drift rate

Conclusion

The CG-3 represents several significant advances in gravity meter design. Its microprocessor-controlled automatic reading and data acquisition system overcome many of the operational deficiencies of existing instruments; extensive use of electronics simplifies the mechanical design and standardizes the production process. The test results shown above, which demonstrate the high performance capacity of the instrument, and the ease of operation, fully vindicate the design approach.

Other features of the CG-3, such as the electronic tilt compensation and the integrated housing, set new standards for gravity meter design, and indicate the direction of future developments in the field.

References

Hugill, A.L., 1984, "The design of a gravimeter with automatic readout". Ph.D. Thesis, Flinders University, Bedford Park, South Australia.

LaCoste, L.J.B., 1934, "A new type of long period vertical seismograph", Physics, 5, pp. 178-181.