A GUIDE TO HIGH PRECISION LAND GRAVIMETER SURVEYS

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FOREWARD

The purpose of this treatise is to bridge the gap between monographs on geophysical methods and the Operator Manuals provided by manufacturers of gravimeters. Included herein, you will find the various factors, both instrumental and external, which may affect your gravity data, recommendations on how to minimize the possible errors from these factors, and how to apply appropriate corrections for them.

Some guidelines have also been provided for the processing, presentation and interpretation of your corrected gravity data.

Of necessity, I have included enough theoretical background on the physics and mathematics of the gravitational field of the Earth, for you to understand the why? and the how? of the matter.

Since this is intended as a guide to achieving better gravity data, I have, for both convenience and emphasis, summarized all the pertinent recommendations in the first section. You will find them again, in their proper context, in the individual sections that follow.

An extensive suite of case histories is included, illustrating the application of gravimeter surveys to many types of objectives.

Whereas, I have endeavoured to touch on all the significant aspects of land gravity surveying, there may be, from your perspective, some omissions or uncertainties. If so, please draw these to my attention, for remedial action in the next printing.

For those readers who wish to learn more about any specific aspect of land gravimetry, an extensive list of references has been provided.

SUMMARY OF RECOMMENDATIONS

Object	Recommendation	Reference in Text Section
Gravimeter Check List	1. Calibrate your gravimeter periodically.	*Calibration* on page 27 and *Gravimeter Calibration on a Calibration Range* on page 117
	2. Adjust your levels periodically for alignment.	*Levelling* on page 25
	3. For software controlled gravimeters, set up local time, tidal correction factors (latitude, longitude and UTC differences), long-term drift correction, temperature correction, and calibration factor.	*Calibration* on page 27 and *Long and Short Term Drifts* on page 29
	4. On restoring power after power-down, ensure that your gravimeter has stabilized before measuring.	*Power-Down* on page 22
Station Location	1. Avoid areas of high seismic noise.	*Seismic Noise* on page 30
	2. Avoid areas of unstable ground.	*Selection of Station Location* on page 32
	3. Avoid areas of sharp local topographic relief.	*Selection of Station Location* on page 32
Measuring	1. For microgravity surveys, ensure that elastic relaxation effect has dissipated.	*Elastic Relaxation* on page 24
	2. Level your meter to within 10" of arc.	*Levelling* on page 25
	3. Measure your station elevation to the required precision.	*Station Elevation* on page 33
	4. Measure your instrument reference level relative to the station elevation mark.	*Station Elevation* on page 33

Object	Recommendation	Reference in Text Section
Measuring (continued)	**5.** If necessary, create a wind-break to reduce wind noise effects.	*Wind-Induced Vibration* on page 32
	6. For microgravity surveys measure the barometric pressure at the time (and preferably the place) of the gravimeter measurement.	*Atmospheric Pressure* on page 34
	7. If near the margins of sea, lake or river, note the local water level at the time of gravity measurement.	*Changes in Groundwater and Surface Water Levels — C_{GW}* on page 41
	8. Measure relative elevation of nearby points for near-zone terrain correction.	*Terrain Effects — C_{TE}* on page 46
Field Procedures	**1.** Establish the station pattern and location, with the required precision.	*Survey Layout* on page 51, *Positional Accuracy* on page 54, and Step **2.** on page 55
	2. Select a suitable set of base stations and measure their gravity values with repeat loops.	Step **3.** on page 56, and Step **4.** on page 56
	3. Complete the survey by measuring at all survey stations, occupying a base station at the beginning and end of each day (or more frequently, if necessary).	Step **7.** on page 56
Data Processing	**1.** Make the necessary corrections to your observed gravity data.	*Corrections to Observed Gravity Values* on page 35
	1.1. Earth tidal correction - C_T	*Earth Tides Corrections — C_T* on page 35
	1.2. Instrumental drift - C_D	*Instrumental Drift — C_D* on page 37
	1.3. Atmospheric pressure changes - C_P	*Atmospheric Pressure Changes — C_P* on page 40

Object	Recommendation	Reference in Text Section
Data Processing (continued)	1.4. Groundwater and Surface Water level changes - C_{GW}	*Changes in Groundwater and Surface Water Levels — C_{GW}* on page 41
	1.5. Variation with latitude - C_L	*Variation with Latitude — C_L* on page 43
	1.6. Variation with elevation - C_E	*Variation with Elevation — C_E* on page 44
	1.7. Terrain Effects - C_{TE}	*Terrain Effects — C_{TE}* on page 46
	2. Grid the regional gravity values with a suitable grid interval.	*Data Presentation* on page 59
	3. Apply computational procedures, where required,to remove regional gradients, calculate spacial derivatives and continuation up/down, etc.	*Data Presentation* on page 59
Data Presentation	1. Present final corrected and processed gravity data in desired forms for interpretation.	*Data Presentation* on page 59
Interpretation	1. Use foreward solutions based on simple two-dimensional, geological models to obtain best fit to final gravity anomalies.	*Two Dimensional Models* on page 69
	2. Where applicable, apply direct interpretation for total mass determination and apparent density mapping.	*Determination of Excess Mass* on page 66 and *Apparent Density Maps* on page 68

INTRODUCTION

One of the basic forces of nature is the attraction between all masses. This attraction is called the force of gravity.

According to the Newtonian law of gravity, the gravitational force between any two point masses is given by (see Figure 1 on page 2)

$$\mathbf{F} = \frac{\mathbf{G M_1 M_2}}{\mathbf{r^2}} \qquad \mathbf{(1)}$$

where **G** (universal gravitational constant) = $6.673 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$
$\mathbf{M_1}$ and $\mathbf{M_2}$ are the two masses in kg, and
r is the distance between the point masses, in metres.

This force acts in the direction joining the two masses.

The resulting acceleration **a** of mass $\mathbf{M_1}$, is given by

$$\frac{\mathbf{F}}{\mathbf{M_1}} = \mathbf{a} = \frac{\mathbf{G M_2}}{\mathbf{r^2}} \text{ in } m/s^2 \qquad \mathbf{(2)}$$

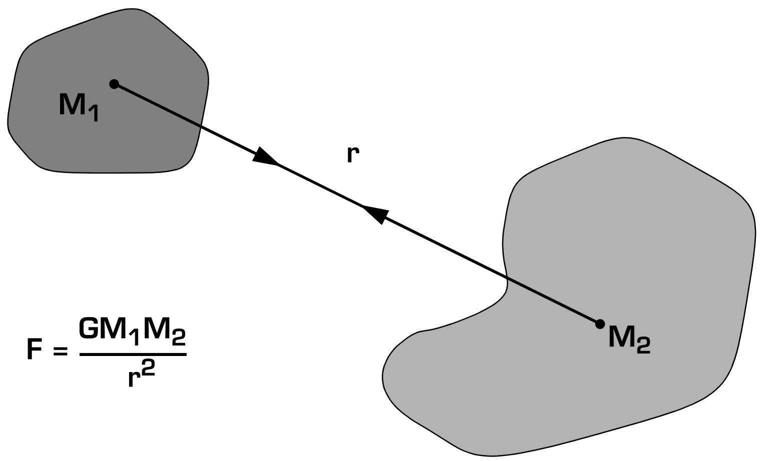
The mass **M** (kg) of an object is related to its volume **V** by a constant **d**, where **d** is the *density* of the object in kg/m^3, or

$$\mathbf{M} = \mathbf{dV} \qquad \mathbf{(3)}$$

If an object is not of uniform density, the gravitational acceleration it exerts on another mass is given (vectorially) by

$$\vec{\mathbf{a}} = \mathbf{G}\int \frac{\mathbf{d} \cdot \vec{\mathbf{r}}}{\mathbf{r^3}}\mathbf{dv} \qquad \mathbf{(4)}$$

integrated over the volume **V** of the object.



$$F = \frac{GM_1M_2}{r^2}$$

Figure 1 Newton's Law of Universal Gravitational Attraction

Thus, the gravitational attraction of a body of non-homogeneous density will vary from point to point, in response to the distribution of density within the body. For this reason, measurements of the variation, with location, of the gravitational attraction of the Earth can provide valuable information about its subsurface geology. This is the basis for the science and practice of gravimetric measurements.

THE EARTH'S GRAVITATIONAL FIELD, AND ITS VARIATIONS

The gravitational attraction of a sphere with central symmetry (i.e. made up of concentric layers, each of homogeneous density) at a point external to the sphere, is mathematically the same as though the entire mass of the sphere were concentrated at its centre (as in Equation (2) on page 1). This model applies reasonably well to the Earth.

The Earth is essentially a spheroid, with a slight flattening (0.335%) at the poles, a mean radius $\mathbf{R_E}$ of 6368 km, and a mean mass $\mathbf{M_E}$, of 5.98 x 10^{24} kg.

Inserting these values into Equation (2), we find that at the surface of the Earth, its mean value of gravity **g** (acceleration) is given by 9.80 m/s^2. At the equator it reduces to about 9.78 m/s^2, and at the poles it increases to about 9.83 m/s^2, reflecting the fact that one is farther from the center of the Earth at the equator than at the poles.

In lieu of using m/s^2 for acceleration, one often employs the unit of **Gal**, where

$$\mathbf{1\ Gal = 10^{-2}\ m/s^2} \quad \mathbf{(5)}$$

We will later, for convenience, use units such as **mGal**, (i.e. 10^{-5} m/s^2), and **μGal** (i.e. 10^{-8} m/s^2).

The mean sea level around the Earth is termed the *geoid*. This is an equipotential surface for the Earth's gravitational field, and includes centrifugal forces. Due to lateral variations in density, for example, from continental land masses to the ocean basins, the geoid is not a simple spheroid. It rises above the spheroid over the continents, and falls below the spheroid over the ocean basins, albeit in a complex fashion.

VARIATION WITH LATITUDE

The formula for the general increase of **g** with latitude θ, based on the most recently accepted spheroid approximation, is given by (Moritz, 1984).

$$\mathbf{g} = \mathbf{978.0327}(\mathbf{1} + \mathbf{0.0053024}\,\mathbf{sin}^2\theta - \mathbf{0.0000058}\,\mathbf{sin}^2\mathbf{2}\theta) \text{ in Gals} \qquad \mathbf{(6)}$$

This equation includes both the Newtonian attraction of the Earth as a spheroid and the centrifugal force caused by its rotation about its axis.

VARIATION WITH ELEVATION

THE FREE-AIR EFFECT

Since the Earth's gravitational attraction is very nearly that of a sphere with central symmetry, it attracts as though its mass were concentrated at its centre. Thus, as one rises (increases) in elevation above sea level, the gravitational attraction will decrease as the inverse square of the distance to the centre of the Earth (Equation (1) on page 1).

Since possible elevational changes on the Earth are only on the order of –0.1% of the Earth's radius, we may determine the effect of a change **ΔZ (m)** in elevation in terms of the resultant change in gravity by

$$\Delta \mathbf{g}_{\mathbf{FA}} = \frac{-\mathbf{2GM_E\Delta Z}}{\mathbf{R_E}^{\mathbf{2}}} = -\mathbf{0.3086}\ \text{mGal/m} \qquad \mathbf{(7)}$$

This is termed the *Free-Air* effect, and is the mean vertical gradient of **g**, above the surface of the Earth. In fact, the actual Free-Air gravity gradient measured at the surface can vary by up to 25 percent from this theoretical value due to non-uniform density of the sub-surface rocks in the area.

THE BOUGUER EFFECT

When one increases elevation on the Earth, it usually implies that there is an additional mass between the original level and the new level. This additional mass itself will exert a positive gravitational attraction, which acts to reduce the *Free-Air* (negative) gravity change. The Bouguer gravity effect $\Delta \mathbf{g_B}$ is calculated on the basis of the gravitational attraction of a horizontal slab, of infinite extent and of thickness equal to the elevation difference, in accord with Equation (8)

$$\Delta \mathbf{g_B} = +\mathbf{0.04192d} \text{ mGal} \qquad \textbf{(8)}$$

per metre of elevation difference, where **d** is the mean density of the slab in g/cm^3 or $tonnes/m^3$.

For gravity measurements beneath the surface of the Earth (e.g. in mine openings, boreholes and undersea) the Bouguer effect will be negative.

THE ELEVATION EFFECT

The Free-Air and Bouguer effects may be combined as the *elevation effect*, and written

$$\Delta \mathbf{g_E} = -(\mathbf{0.3086} - \mathbf{0.0419d}) \text{ mGal/m} \qquad \textbf{(9)}$$

of elevation increment on the surface, and

$$\Delta \mathbf{g_E} = -(\mathbf{0.3086} - \mathbf{0.0838d}) \text{ mGal/m} \qquad \textbf{(10)}$$

of depth increment in shafts and boreholes, etc.

The doubling of the Bouguer effect in the subsurface is due to the fact that a layer of rock is moved from beneath the point of measurement (positive gravity effect) and placed above the point of measurement (negative gravity effect).

Example: If **d** = 2.5 g/cm^3, then $\Delta \mathbf{g_E}$ = 0.204 mGal/m *above* the surface, and –0.0991 mGal/m *below* the surface.

For gravimeter measurements made on the sea-bottom,, the Bouguer effect is reduced by the difference between the density (d) of the underlying rock and that of the seawater (1.05 g/cm3), so that on the sea bottom, Equation (9) would become

$$\Delta \mathbf{g_E} = -(\mathbf{0.3526} - \mathbf{0.0419d})\ \mathrm{mGal/m} \qquad \mathbf{(11)}$$

It may be noted, from Equation (9) and Equation (11) that if a relative accuracy of a few µGal is desired on a particular survey, then the elevation of the gravimeter must be determined to within better than 1 cm. A proper estimate of d is also required, for precise correction for elevation. We shall see, in a later section, how this estimate may be made in the field.

Equation (10) provides the theoretical basis for the determination of the variation of **d** with depth from gravity gradient measurements in boreholes or shafts.

TERRAIN EFFECTS

Local irregularities in the topography around a gravity station may give rise to significant effects. Hills rising above the station will cause a reduction in gravity (upward pull) while valleys falling below the station will also cause a reduction in gravity due to the deficit of mass that would be included in the Bouguer assumption of an infinite slab. Thus, all topographic irregularities will cause a reduction in the observed gravity values.

A knowledge of the local topography and of the specific gravity of the surface rocks is required in order to calculate the resultant terrain effect at a gravity station. Methods of calculation for this purpose will be discussed below.

Figure 2 on page 7 diagrammatically illustrates the source of the Free-Air, Bouguer and terrain effects at a station **P**.

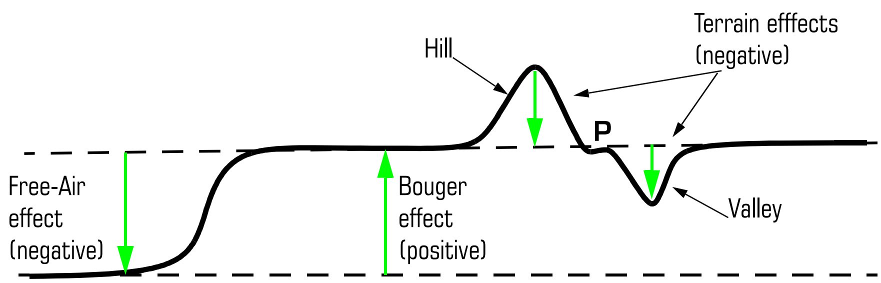


Figure 2 Free Air, Bouguer and Terrain Effects

VARIATION WITH TIME

EARTH-TIDES

The gravitational attraction of the Sun and the Moon are sufficiently large as to cause serious time-varying changes in the measured gravity values on the surface of the Earth, of as much as 0.3 mGal, in envelope. Figure 3 on page 8 shows the combined (measured) earth-tidal effects over a period of several days.

These tidal gravity effects may be calculated as a function of latitude, longitude of the station and the Universal Coordinated time (UTC) of the measurement, in accordance with various formulae (e.g. Longman, 1959; Tamura, 1982; or Rapp, 1983).

Providing that the UTC time is entered to the nearest minute, the tidal gravity effects may be calculated to within a few μGal of their actual value at any location. There are however, residual tidal effects of this same order, due to tidal deformation of the Earth and the attraction of and loading effects of the oceans.

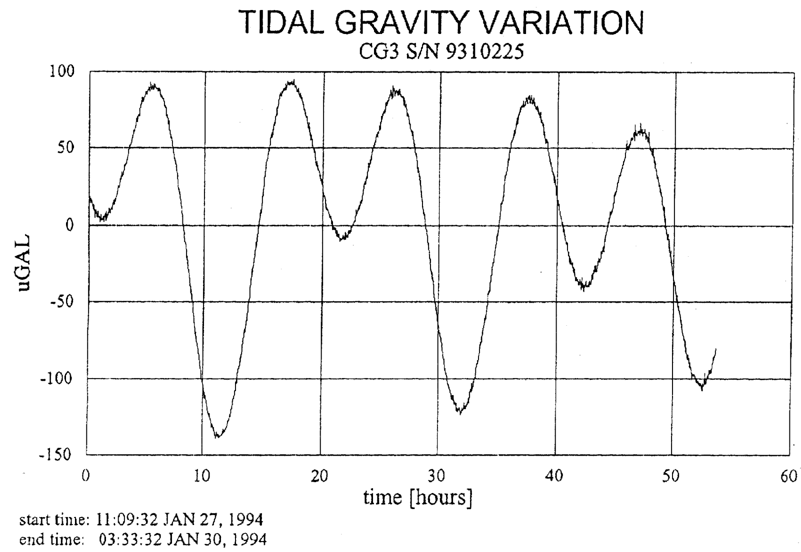


Figure 3 Earth Tidal Variations

ATMOSPHERIC PRESSURE

Changes in atmospheric pressure imply changes in the mass of the air column above the gravity point of measurement. An increase in atmospheric pressure will cause a decrease in the observed gravity, and vice-versa. The approximate relationship between these changes is given, experimentally by (Merriam, 1992):

$$\begin{aligned} \Delta \mathbf{g_P} &= -\mathbf{0.36\mu Gal/millibar} \\ &= -\mathbf{3.6\mu Gal/kPa} \end{aligned} \quad \mathbf{(12)}$$

If the atmospheric pressure changes by 10 kPa, then a $\Delta \mathbf{g_P}$ of 36 μGal may result. For precise gravity measurements, such a change could introduce a significant error, if not compensated for. It should be noted, however, that this factor may vary up to 20 percent from the above equation, depending on the lateral extent and configuration of a particular weather system.

Precipitation

Rainfall can affect precise gravity measurements by:

- ▲ increasing the moisture content and groundwater level in porous soils and rocks, and
- ▲ changing the level of lakes and rivers in the near vicinity of the station (e.g. see Lambert and Beaumont 1977 and Diagert et al 1981).

In areas characterized by heavy seasonal rainfall, or spring run-off from highland snow melt, the level of groundwater, lakes and rivers may vary considerably, on a seasonal basis. To calculate the possible effect of such seasonal rainfall or run-off, we may refer to Equation (8) using $\mathbf{d} = 1\text{g/cm}^3$ for rainwater:

$$\Delta \mathbf{g_R} = \mathbf{0.04192}\ \text{mGal/m} \qquad \mathbf{(13)}$$

Thus, 10 cm of rainfall, remaining in the soil or surface waters (no run-off) could increase the observed value of **g** by about 4 μGal.

Ocean Tides (Sea Level Changes)

Gravity measurements made near the sea coast may be directly affected by daily tidal changes. In the extreme, where a measurement is made on a cliff adjacent to deep water, the tidal effect ($\Delta \mathbf{g_T}$) could be as large as:

$$\Delta \mathbf{g_T} = \mathbf{0.02}\quad \text{mGal/m of tidal change} \qquad \mathbf{(14)}$$

i.e. one half of that predicted for an infinite sheet of water (Equation (13)). The same consideration would apply for seasonal changes in lake and stream levels.

VARIATION WITH GEOLOGY (DENSITY)

This is the very *raison d'être* of gravity measurements. The various rock types and individual minerals which constitute the Earth each have their characteristic range of densities. The distribution in the subsurface of the constituent rock types and minerals will therefore, be reflected through changes in the local gravitational field. The variation, from place to place, of the gravitational field of the Earth may, therefore, be interpreted in terms of the subsurface geology — with certain assumptions and limitations.

Gravimetric surveys are one of the fundamental means available to the geoscientist, to map the distribution of the subsurface geology, for both scientific and economic objectives. These objectives will be discussed below.

Table I on page 11 provides a list of typical rock types and minerals, with their density range and mean values. From this Table, it can be seen that the entire range of densities covers a factor of about eight— from 1.0 g/cm^3 for water to 8.1 g/cm^3 for cinnabar. There is considerable overlap between rock types, although in general, sediments are lower in density than igneous or metamorphic rocks, and acidic rocks are lower than mafic rocks.

Metallic minerals occupy the high end of the range, and when present in substantial amounts, in a deposit, they may facilitate the detection of that deposit through gravity measurements.

Table I: Densities of typical rock types and minerals

Rock Type	Range (g/cm^3)	Average (g/cm^3)	Mineral	Range (g/cm^3)	Average (g/cm^3)
Sediments(wet)			**Metallic minerals**		
Overburden		1.92	**Oxides, carbonates**		
Soil	1.2 – 2.4	1.92	**Bauxite**	2.3 – 2.55	2.45
Clay	1.63 – 2.6	2.21	**Limonite**	3.5 – 4.0	3.78
Gravel	1.70 – 2.40	2.0	**Siderite**	3.7 – 3.9	3.83
Sand	1.70 – 2.30	2.0	**Rutile**	4.18 – 4.3	4.25
Sandstone	1.61 – 2.76	2.35	**Manganite**	4.2 – 4.4	4.32
Shale	1.77 – 3.20	2.40	**Chromite**	4.3 – 4.6	4.36
Limestone	1.93 – 2.90	2.55	**Ilmenite**	4.3 – 5.0	4.67
Dolomite	2.28 – 2.90	2.70	**Pyrolusite**	4.7 – 5.0	4.82
Sedimentary rocks (av.)		2.50	**Magnetite**	4.9 – 5.2	5.12
			Franklinite	5.0 – 5.22	5.12
Igneous rocks			**Hematite**	4.9 – 5.3	5.18
Rhyolite	2.35 – 2.70	2.52	**Cuprite**	5.7 – 6.15	5.92
Andesite	2.40 – 2.80	2.61	**Cassiterite**	6.8 – 7.1	6.92
Granite	2.50 – 2.81	2.64	**Wolframite**	7.1 – 7.5	7.32
Granodiorite	2.67 – 2.79	2.73	**Sulfides, arsenides**		
Porphyry	2.60 – 2.89	2.74	**Sphalerite**	3.5 – 4.0	3.75
Quartzdiorite	2.62 – 2.96	2.79	**Malachite**	3.9 – 4.03	4.0
Diorite	2.72 – 2.99	2.85	**Chalcopyrite**	4.1 – 4.3	4.2
Lavas	2.80 – 3.00	2.90	**Stannite**	4.3 – 4.52	4.4
Diabase	2.50 – 3.20	2.91	**Stibnite**	4.5 – 4.6	4.6
Basalt	2.70 – 3.30	2.99	**Pyrrhotite**	4.5 – 4.8	4.65
Gabbro	2.70 – 3.50	3.03	**Molybdenite**	4.4 – 4.8	4.7
Peridotite	2.78 – 3.37	3.15	**Marcasite**	4.7 – 4.9	4.85
Acid igneous	2.30 – 3.11	2.61	**Pyrite**	4.9 – 5.2	5.0
Basic igneous	2.09 – 3.17	2.79	**Bornite**	4.9 – 5.4	5.1
			Chalcocite	5.5 – 5.8	5.65

Table I: Densities of typical rock types and minerals

Rock Type	Range (g/cm^3)	Average (g/cm^3)	Mineral	Range (g/cm^3)	Average (g/cm^3)
Metamorphic rocks			**Cobaltite**	5.8 – 6.3	6.1
Quartzite	2.50 – 2.70	2.60	**Arsenopyrite**	5.9 – 6.2	6.1
Schists	2.39 – 2.90	2.64	**Bismuththinite**	6.5 – 6.7	6.57
Graywacke	2.60 – 2.70	2.65	**Galena**	7.4 – 7.6	7.5
Marble	2.60 – 2.90	2.75	**Cinnabar**	8.0 – 8.2	8.1
Serpentine	2.40 – 3.10	2.78			
Slate	2.70 – 2.90	2.79	**Non – metallic minerals**		
Gneiss	2.59 – 3.00	2.80	**Petroleum**	0.6 – 0.9	—
Amphibolite	2.90 – 3.04	2.96	**Ice**	0.88 – 0.92	—
Eclogite	3.20 – 3.54	3.37	**SeaWater**	1.01 – 1.05	—
Metamorphic	2.40 – 3.10	2.74	**Lignite**	1.1 – 1.25	1.19
			Softcoal	1.2 – 1.5	1.32
			Anthracite	1.34 – 1.8	1.50
			Chalk	1.53 – 2.6	2.01
			Graphite	1.9 – 2.3	2.15
			Rocksalt	2.1 – 2.6	2.22
			Gypsum	2.2 – 2.6	2.35
			Kaolinite	2.2 – 2.63	2.53
			Orthoclase	2.5 – 2.6	—
			Quartz	2.5 – 2.7	2.65
			Calcite	2.6 – 2.7	—
			Anhydrite	2.29 – 3.0	2.93
			Biotite	2.7 – 3.2	2.92
			Magnesite	2.9 – 3.12	3.03
			Fluorite	3.01 – 3.25	3.14
			Barite	4.3 – 4.7	4.47

APPLICATIONS OF GRAVIMETRIC SURVEYS, AND THEIR REQUIREMENTS

Gravimetric surveys serve a variety of scientific and economic objectives. They are sometimes employed as the sole, preferred method of solving a particular problem, and are also used in combination with other methods, based on other physical properties. These objectives include: regional geological mapping; petroleum exploration; mineral exploration; geotechnical studies; archaeological studies; groundwater and environmental studies; tectonic studies; volcanology and geothermal studies.

We may briefly examine some of these applications, particularly to determine the precision of gravity measurements that may be required, and other survey specifications.

REGIONAL GEOLOGICAL MAPPING

Gravimetric surveys for regional geological mapping characteristically entail measurements on a grid whose stations are 5–10 km apart. The ultimate accuracy of individual regional gravity data is usually limited by the accuracy of the elevation control on the station, commonly 1–2m, i.e. equivalent to ±0.2 to 0.4 mGals in gravity.

The purpose of such regional gravimetric surveys is to provide geological information on the distribution of major rock units, and their tectonics, and information about the Earth's crust. The dimensions of features resolvable by such surveys are usually in excess of about 20 km.

Gravimeters with a reading resolution of 0.01 mGal and accuracy of the same order are more than adequate for this purpose, since the limitation on the elevation control is usually the limiting factor on the ultimate accuracy of the gravity data so determined.

PETROLEUM EXPLORATION

The objectives of gravimetric surveys in petroleum exploration include the mapping of sedimentary basins and their tectonic features. Stations for petroleum exploration surveys will be laid out on grid centres whose separation is predicated on the dimensions of the targeted structures. If the general shape of a large sedimentary basin is the objective of the survey, then the stations may be 2 to 5 km apart. If detail is required to accurately define a salt dome or a fault structure, then stations may be 100m to 500m apart. Similarly, the measurement accuracy required of the gravity measurement will be higher for such detailed surveys than for regional surveys. Gravimeters with a reading resolution of 1 μGal and an accuracy of about 5 μGals are preferred for detailed petroleum surveys. Sometimes subtle changes in gravity, e.g. of the order of 10 μGals, may have to be resolved, reflecting a relatively minor structural feature or facies change in the subsurface. For the same objective, it will be necessary to determine the relative elevation of each gravity station to within ±2cm.

MINERAL EXPLORATION

Gravimetric surveys are employed in mineral exploration, both to provide basic geological information about possible host rocks and controlling tectonic features and also to provide a direct indication of the presence of mineral deposits. The latter possibility may occur when the densities of the target minerals, or mineral deposit of economic interest, are significantly different from their host rocks. For example, as Table I on page 11 indicates, deposits of iron, chrome, base metals and barite may fall in this category, being of relatively high specific gravity, as well as salt and coal, being of relatively low specific gravity compared to the usual range of density in most rock types.

Since the dimensions of mineral exploration ore deposit targets are usually of the order of a few hundred metres, the gravimeter stations for such surveys are often only 25–30m apart, on lines that may be only 100m apart. High precision in the gravity measurements and in the station elevation control is generally useful and sometimes, absolutely necessary, for such surveys (i.e. reading resolution of 1 μGal, relative accuracy of 5 μGals and relative elevation accuracy of ±2 cm).

Geotechnical and Archaeological Studies

Geotechnical studies to which gravimetric surveys may be applied include: the mapping of subsurface cavities in karst areas or old mining camps, whether open or filled with water or clay; the mapping of overburden variations, particularly in urbanized areas; the mapping of tectonic features, i.e. faults and major shear zones, and the mapping of railway roadbeds to locate cavities or loose sections.

Archaeological studies are often concerned with the same objectives, namely the mapping of subsurface voids and overburden variations.

For all such purposes, it is imperative to be able to achieve highly accurate gravity data. Grid stations as close as 25–50m (or even at 3m intervals for detail) may be employed for such purposes.

Groundwater and Environmental Studies

These are similar in specifications to those just listed above, but their objectives differ. They may help to map aquifers which are formationally or structurally controlled, or to determine the extent of old landfill sites on which documentation is lacking.

TECTONIC STUDIES

In regions of major, active, tectonic movement, the build up of stress may be reflected in a warping of the ground surface over long periods of time. These stresses may, ultimately, lead to sudden release in the form of an earthquake. Very carefully controlled gravity measurements, carried out periodically, e.g. at one year intervals, on a grid of permanent stations in the area, can provide a sensitive measurement of such ground warping. The gravity values on the grid stations are measured relative to one or more stations which are deemed to be *stable*, with 1 μGal resolution and better than 5 μGal accuracy, on a stable pillar at each station.

In this manner, tectonically derived changes, in relative land elevations, of less than 3 cm may be determined.

VOLCANOLOGY AND GEOTHERMAL STUDIES

Periodic gravity measurements on a grid of permanent stations can provide useful information on changes which are taking place, with time, in respect of the upwelling of lava within a volcano, and therefore, provide a forewarning of harmful volcanic eruptions.

Likewise, in the case of geothermal fields which are under exploitation for energy production, periodic gravity measurements, at permanent stations, will provide useful information on changes in the level of water in the geothermal reservoir, and therefore information on the longevity of the geothermal resource.

In both types of applications, high precision gravity measurements are required, for maximum sensitivity.

GRAVIMETERS

Modern land gravimeters are of two basic types, namely absolute and relative. Absolute gravimeters now in use measure the free fall of a body in a vacuum, using lasers and optical interferometry, to obtain accuracies of better than 0.01 mGals under favourable conditions (i.e. Niebauer et al, 1986 and Torge, 1989). Whereas, these devices are transportable, they are still quite bulky and time consuming to set up and read. Typically, only one absolute reading per diem can be made. Nevertheless, such absolute gravimeters are being routinely employed in establishing the absolute values of gravity at selected stations, which then may serve as base stations for relative gravity surveys, so that the results of the latter may then be expressed in absolute gravity terms, with almost the same accuracy as the values for the absolute stations themselves.

Precise measurements with absolute gravimeters represents an art in itself, and are not the subject of this treatise. We will, henceforth, simply assume that absolute gravimeter bases have been established, which are accessible to the relative gravimeter survey areas, for the purposes, (see *Survey Layout* on page 51) of establishing the absolute level of such relative surveys.

Relative gravimeters are devices which can only measure differences in gravity from station to station. Those in use today, all rely on the elongation of a spring which supports a proof mass. When gravity changes, the force on the proof mass will likewise change, and this will be reflected in a change in the length of the supporting spring. The position of the proof mass is sensed by one means or another, and the amount of external force required to bring it back to a standard position provides a measure of the gravity value at the station, relative to other stations.

There are two basic types of field portable relative gravimeters with different spring balance configurations, in use today. These are known as *astatic* or *unstable*, and *stable* types. The former operate in a state close to unstable equilibrium, which gives them great mechanical sensitivity. The LaCoste-Romberg meters (**G** or **D** models) operate on this principle. The stable gravimeters are simpler in mechanical principles, but require much higher precision of sensing of the position of the proof mass. The Scintrex CG-3 and CG-3M gravimeters are of this type.

A recent review of the entire field of gravimetry, including a detailed description of these gravimeters, may be found in Torge, 1989.

As we have seen in Section 3, gravimeter surveys for different applications may have different requirements in respect of precision of measurement. This implies that there may be scope for gravimeters with different performance specifications. We may designate two levels of performance by the terms *standard* and *microgravity*. Both manufacturers, LaCoste-Romberg (L&R) and Scintrex, offer portable relative gravimeters in each of these levels. Table II gives comparative specifications of the pertinent gravimeters.

Table II: Current Relative Land Gravimeters

Model	Resolution mGal	Range (without reset) mGal	Accuracy[a] mGal
L&R - G	0.01	7,000	0.015
L&R - D	0.001	200	0.005
Scintrex CG-3	0.005	7,000	0.010
Scintrex CG-3M	0.001	7,000	0.005

a. We may define *accuracy* as the standard deviation of a single gravity tie at a station from the precise gravity value for that station, obtained by carrying out several gravity ties to that station, using more than one instrument.

Thus, the L&R-D meter and the Scintrex CG-3M may be used for *microgravity* surveys which require the higher precision, and the L&R-G meter and the Scintrex CG-3 may be used for *standard* surveys.

The L&R gravimeters (G&D) are essentially mechanical devices, using optical or electronic means for determination of the proof mass position and manual or electrostatic restoration of the mass to its null position. This mode of operation is typical of the portable land gravimeters available over the period of 1950–1989.

The CG-3 and CG-3M are examples of the trend to incorporate extensive electronics into the function of the gravimeter, for the sensing of the proof mass position and in its restoration to its null position. Under embedded software control, the gravity signal is processed and recorded in solid-state memory. Corrections are applied in real time for tilt errors, for long term drift, for the temperature of the sensor and for earth tides. These gravimeters communicate through an RS-232 port with computers, printers and modems, for data dumping, processing and presentation.

Further information on the Scintrex CG-3 and 3M design and operation may be found in *Appendix I*.

ACHIEVING HIGH PRECISION MEASUREMENTS

The precision of data from a specific gravimetric survey depends upon the precision of the gravity measurements themselves, of the determination of the elevation and the position of the stations, and of the various corrections that have to be made to the measurements, either in real time or off-line. As has been stated in Section 3, different levels of precision may be required for surveys with different objectives. The level of precision required will determine the field procedures and the types of corrections that are pertinent.

In this section we will examine the factors affecting the ultimate precision of gravity data generated by a gravimetric survey, and how to ensure that the required precision is achieved.

Instrumental Factors

Here we will examine the sources of possible error in the gravimeter readings themselves, and how to minimize them.

Shock and Vibration

All relative gravimeters are more or less subject to offsets (*tares*) due to shock and to changes in drift rate when subjected to severe vibration for long periods of time. Generally speaking, quartz elements are more tolerant to these factors than metal elements, even though the former are generally not clamped between readings, and the latter are clamped.

It may be noted that the CG-3 and CG-3M gravimeters are routinely subjected to shocks of the order of 25 g in final testing (Figure 8 on page 108).

Nevertheless, it is recommended that great care be taken in the transport and use of your gravimeter. In transport, in a vehicle or aircraft, you should provide a soft (foam) cushion support for your gravimeter, to reduce the effect of shock and vibration. Wherever possible, use the foam-padded shipping case provided by the manufacturer. In manual transport over a long distance, a padded backpack should be used.

When reading the gravimeter, avoid shocks when setting it on the tripod or on the ground between measurements. If you have, unavoidably, shocked your gravimeter, be sure to repeat the last station read, in order to determine if a tare has occurred, and thus, to be able to correct for it.

Power-Down

All gravimeters have a critical dependence on the stability of the temperature of their sensor. For this reason, the gravity sensor element is generally enclosed in a temperature stabilized environment (oven). In the case of the CG-3 and CG-3M, for example, a double oven controls the element temperature to within less than 10^{-3} °K.

The temperature at which the element is stabilized is set at about 10° above the maximum ambient temperature in which the gravimeter is expected to operate.

If your gravimeter is allowed to power-down, so that the temperature of its element is allowed to change drastically (i.e. by 20°K to 40°K) then it will have experienced a severe temperature shock. After restoration of power, the sensor may be fairly quickly restored to its set temperature, (i.e. in a matter of hours) but the physical effects of the shock will have an even longer duration. Typically, your gravimeter may demonstrate an anomalous drift rate for a day or more after power-up.

To ensure the maximum performance from your gravimeter, after power-down, set up the meter and monitor its return to its normal long term drift rate. Do not start your survey before you are satisfied that your long term drift has settled down to a reasonable level, where it is linear enough with time to be corrected by a combination of base ties and by software.

Best of all, do everything possible to keep your gravimeter powered on at all times, to avoid the loss of time in re-establishing it. Power-down occurs most often in the shipment of a gravimeter from one place to another. If you put extra batteries in parallel with the internal power supply and provide extra thermal insulation around the gravimeter to reduce heat and power dissipation, you can considerably extend the battery lifetime and the probability that your gravimeter will arrive at its destination, still on temperature and ready for survey.

Extreme Temperature Shocks

When your gravimeter is moved from one temperature regime to another (i.e. from an air-conditioned room at 25°C to the field at 40°C, or -20°C), there will be a temperature shock which can induce a transient response on your gravimeter. Not all gravimeters are as well shielded from such shocks as the CG-3 (see Figure 5 on page 105). The 20 μGal effect of 25°C shock on a L&R G meter is shown in Torge (1989).

During a survey, avoid unnecessary temperature shocks by keeping your gravimeter overnight in an environment that is essentially at the outside temperature.

Elastic Relaxation

All spring balance gravimeters exhibit an *elastic relaxation* effect, due to the fact that when the length of the spring is changed, due to a change in the position of the proof mass from its null position, it does not instantaneously return to its original length. It returns most of the way very quickly, then more slowly. Torge (1989) shows this effect for an L&R-G gravimeter after unclamping. This effect is of the order of 5 to 10 µGal, for 20 minutes of clamping, or larger if the clamping time is longer. It takes about 10 minutes to dissipate after being unclamped.

Whereas quartz element gravimeters are not clamped between readings, a similar relaxation effect will occur if the gravimeter has not been sufficiently levelled for the proof-mass to be maintained in its null position by the electrostatic restoring force system between readings.

These elastic relaxation effects are of relatively low order, usually less than 10 to 20 µGals, and will hardly be noticed on regional surveys. However, they are significant for microgravity surveys, and should be properly taken into account. They can be minimized by adhering to the following field practice.

1. **CG-3/3M**

    a. Whenever your gravimeter is not being transported, place it on its tripod and level it. The proof mass will then be in its customary null position, until just before measurement, or further transport. This will tend to minimize the elastic relaxation effect.

    b. If your meter has had an uncertain levelling history prior to taking a measurement, set it up at your station and observe its behaviour for a series of consecutive (e.g. 120 sec) readings. Ensure that the readings have stabilized to your satisfaction, i.e. that the elastic relaxation effect has dissipated prior to taking and recording the measurements.

2. **For all gravimeters**, wait approximately the same length of time (e.g. five minutes) after set-up at station, before taking your reading. If your field practice is routine, this should place you on the same point on the elastic relaxation curve, and reduce relative errors between readings from this source to a low level.

LEVELLING

The value of gravity at a station is that which is determined when the measurement system is aligned along the plumbline, i.e. the direction of the gravity vector at the station. When this is so, the force exerted by the proof mass on the spring is a maximum, and, likewise, the force (mechanical or electrostatic) required to bring the proof mass back to its equilibrium level.

Two tilt sensors are provided, (e.g. level bubbles, with or without electrical read-outs) which indicate when your gravimeter is truly level.

If the measurement system is not precisely *vertical* i.e. along the plumbline, but deviates by an angle θ then the measured value of gravity $\mathbf{g^1}$ will be reduced, from the true value $\mathbf{g}$, in accordance with the equation

$$\mathbf{g^1 = g\cos\theta} \qquad \textbf{(15)}$$

For small values of θ (radians), this becomes

$$\mathbf{g^1 = g\left(1 - \frac{\theta^2}{2}\right)} \qquad \textbf{(16)}$$

For example, if θ = 10" of arc, the error will be 1 μGal, but if θ = 20" of arc, then the error will increase to 4 μGal. Two orthogonal level indicators are provided on your meter, in order to allow you to achieve this accuracy. You must first ensure that the tilt sensors are properly aligned orthogonal to the plumbline. The procedure for so doing is provided in the *Operator Manual* for your gravimeter.

For the CG-3/3M meter, the level sensors are in an interior, temperature controlled oven enclosure, so that they are very stable under normal operating conditions. They should, however be checked, approximately every two months, according to the manufacturer.

For the L&R gravimeters, the spirit levels are subject to misalignment due to mechanical and thermal shocks. The manufacturer recommends that it is good practice to check their alignment after shipping or rough handling.

There may be conditions at a station which make it difficult to maintain your gravimeter in a sufficiently level condition during the measurement. Such conditions may include soft ground such as swamp, wet clay, sand, snow and ice. In addition, roots of large trees may underlie the station location and move due to wind on the trees. As well, under these same conditions, movement of the operator during the measurement may change the level of the gravimeter.

Gravity measurements on ice, on lakes and sea margins, often suffer from this problem.

Obviously, such adverse locations should be avoided, as much as possible. Where they cannot be avoided the operator must remain absolutely still during the measurement.

Modern software-controlled gravimeters incorporate a program whereby the output of the level sensors is used to apply a correction, on line, for the off-level condition, within certain limits. For example, the CG-3/3M level correction algorithm has been confirmed to be effective to within 5 μGals for level errors up to 130" (Liard, 1993).

As a further word on this level correction program, it should be noted that there are the options of continuous level corrections (i.e. each one second reading) or only terminal corrections (i.e. based on the level error at the end of the measurement). Since the liquid level sensors have some finite recovery time, it is recommended to use the terminal level option where the station is on relatively firm ground, and the continuous correction option when the footing is quite unstable.

Change of Battery

When a gravimeter supply battery reaches the end of its useful charge in the field and requires changing, some change in the observed gravity level may result. This change relates to the large difference in supply voltage, at least initially, between the two batteries (e.g. see Figure 6.46, Torge 1989). Such changes in gravity are generally small, but can be significant for microgravity surveys.

Thus, when changing a gravimeter battery in the field, it is advisable to repeat the station last measured. Observe a series of readings in succession at that station, until you are satisfied that they have effectively stabilized. This will happen when the battery voltage has essentially stabilized under load.

Calibration

All field-portable land gravimeters measure relative changes in gravity, in terms of the mechanical torque on a spring necessary to balance the changes, or in terms of electrostatic force required to do so, rather than in absolute terms (i.e. in m/s^2, by a free-falling body). Thus, they require calibration. In the case of the CG-3/3M, this may be done by placing the gravimeter on a tilt table and measuring the change in gravity, as the table is tilted out of the horizontal by known angular amounts θ, rotating about a horizontal axis at right angles to the beam holding the proof-mass.

As Equation (16) on page 25 shows, for small values of θ (radians) the change in observed gravity from its maximum value (i.e. at $\theta = 0$) can be written:

$$\Delta \mathbf{g} = \mathbf{g}\frac{\theta^2}{2} \qquad \textbf{(17)}$$

Then

$$\Delta \mathbf{g} = \mathbf{k}\Delta \mathbf{R} \qquad \textbf{(18)}$$

where $\Delta\mathbf{R}$ is the change in the gravimeter reading (**R**) from its maximum (vertical) position, and **k** is the calibration constant of the instrument for that region of gravity.

Then

$$\mathbf{k} = \frac{\mathbf{g}\theta^2}{2\mathbf{R}} \qquad \textbf{(19)}$$

Generally **g** is known to a high order of accuracy (e.g. 10^{-8}) at the point of calibration, and the factor limiting the accuracy of the determination of **k** is the determination of θ. Unfortunately, in practice, this is not much better than 10^{-3}.

Whereas this order of calibration precision may be adequate for surveys of very small areas (small differences in gravity), it is inadequate for surveys, where gravity differences of 100 mGals or more may be encountered, and where a calibration error of 10^{-3} can result in reading errors of up to 100 µGals.

More accurate calibration is achieved by the use of a calibration range, usually consisting of five or more stations, fairly evenly spaced, over a gravity range of at least 100 mGals. This range normally will include absolute gravity readings, at least at its extremities, and all other stations will have been tied, by repeated loop measurements, to the absolute stations. The accuracy of the absolute stations will be each of the order of ± 5 – 10 µGals. The intermediate stations will, similarly, have the same order of accuracy after repeated loops with relative gravimeters.

The precision of determination of the calibration constant of a gravimeter on a calibration range depends on the breadth of gravity values covered by the range. For example, if the gravity range is 100 mGals, and the station gravity values are known to be accurate to ± 10 – 20 μGals, then the calibration constant itself may be considered accurate to the order of 10^{-4}. This may be considered typical for most calibration ranges.

Appendix II covers the method of calibration using a calibration range which has been established as described above.

If the calibration range covers (say) 1900 mGals (e.g. the Ottawa – Inuvik range of the Geological Survey of Canada), then the calibration constant can be determined to the order of 10^{-5}.

For L & R meters, calibration in the laboratory may be achieved by means of placing auxiliary masses on the beam supporting the proof mass, i.e. effectively changing the proof mass. The change in gravimeter reading with change in mass may then be used to determine the calibration constant of the gravimeter. The accuracy of this approach to calibration is of the order of $2 – 3 \times 10^{-4}$, still not good enough for some applications.

To this point we have talked as though there is a single calibration constant, applicable over the entire 7000 mGal range of the gravimeters. In practice this is not so, and non-linear terms do arise. For example, Krieg, (1981) shows the variation of the calibration *constant* of an L & R gravimeter across its entire range. Variations of up to 3×10^{-4} are to be noted. For L & R gravimeters a table of 70 calibration values, laboratory determined, is provided, each valid for about a 100 mGal range of gravity.

In the case of the CG-3 and CG-3M, any non-linear calibration factor is cancelled by an appropriate procedure in the final manufacturing process of these gravimeters, so that the digital output of the gravimeter is expressed directly in standard gravitational acceleration units.

Calibration factors for gravimeters may change subtly with time. It is good practice to periodically check the calibration of your gravimeter by applying the method of calibration, as described in *Appendix II*, on your nearest calibration range.

As a word of caution, however, do not change the calibration factor that you are using for your gravimeter on the basis of any apparent change which is within the order of uncertainty of the accuracy of the values on your calibration range (i.e. typically $\pm 10^{-4}$ of the range of 100 mGal gravity values).

Calibration checks should be more frequent in the first year or so after the manufacture of the gravimeter (e.g. 3 month intervals), reducing to once per year thereafter.

Long and Short Term Drifts

By *long term drift* we refer to apparent changes with time in the gravity measurement, over periods of days or longer, which are due to instrumental sources, rather than external causes.

All relative, spring-balance gravimeters display long term drift related to the relaxation of spring tensions and the aging of critical components, mechanical or electronic. The long term drift of a gravimeter is specific to that instrument.

Generally, long term drifts are largest when the gravimeter is new, and progressively diminish with age (e.g. Liard, 1993). However, external temperature shocks, extreme vibration during transportation and mechanical shocks and gradual changes in battery voltage, may induce drifts which are of the order of some hours in duration.

Regardless of their origin, drifts with time of the gravimeter readings must be accounted for, by proper field procedure and by other means as well.

The CG-3/3M provides for software compensation of the long term drift of the instrument, using a procedure described in its *Operation Manual*. It is there suggested that the drift should be checked periodically and an updated correction factor keyed in. When the instrument is new, the long term drift correction should be checked weekly and thereafter monthly.

Nevertheless, software compensation for long term drift cannot be relied upon to completely remove the effect of instrumental drift. Any residual instrumental drift must be compensated by a procedure of base station readings — at least at the beginning and the end of each day, and even more frequently in the case of inadvertent rough handling of the instrument during the survey. This subject is dealt with at greater length on page 37.

External Factors

Here we will examine the sources of possible errors in gravity data which are external to the gravimeter itself, and the steps to be taken to minimize their effect.

Seismic Noise

There will always be some level of seismic noise (i.e. ground-motion) at each station. These will be caused by a combination of both man-made and natural sources.

Among the man-made sources are included traffic (passage of vehicles and trains) and industrial noise (motors, metal-working machines, construction work, etc.). These are particularly strong in urban areas but will also be encountered in the vicinity of highways, railways or industrial activity elsewhere.

Natural sources will include earthquakes, microseisms and local earth resonances. Earthquakes, of course, can give rise to accelerations of many **g**'s, causing serious damage to major structures, let alone gravimeters, which may be near their epicentres. However, even when a major earthquake occurs on the other side of the earth, it can give rise to ground motion causing accelerations exceeding 100 μGals or more with a period of some tens of minutes or longer. The primary shock effect from such an earthquake may be followed by a train of seismic noise bursts, of diminishing but significant amplitude, as the Earth continues to *ring* for some time.

During such a major earthquake event the noise levels may be so strong as to render precise gravity measurements futile for a period of minutes to even several hours.

Microseisms is the term given to relatively continuous levels of seismic noise, believed to be related to wave action on shore lines and to the passage of rapidly moving pressure fronts. These effects are evidenced by a train of almost sinusoidal noises, with energy concentrated in the range of 0.1 to 0.2Hz. Microseismic noise levels vary greatly from time to time and place to place. Their amplitude can readily exceed several 10's of μGals. Areas exhibiting high microseismic noises are commonly near the shores of rough seas, and on islands in such seas, (e.g. Ireland).

Seismic impulses can excite resonance effects in some areas, reflecting the local geology, for example, an overburden sheet overlying crystalline bedrock, or an ice sheet on a lake or arctic sea margin.

Other natural noise sources affecting gravity measurements would include wind-induced vibrations and tree root movements. Whatever their source, all of these noises are detrimental to the accuracy of gravity measurements. Their presence is readily reflected by an increase in the scatter (standard deviation) of successive measurements at the station.

However, by their nature, these noises must contain equal amounts of positive (downwards) and negative (upwards) acceleration components. As such, their effects will be statistically reduced by digital *stacking* of a series of successive gravity measurements. The signal/noise (S/N) enhancement achieved through the digital stacking of a series of $\mathbf{n}$ measurements is proportional to a factor of between $\sqrt{\mathbf{n}}$ and $\mathbf{n}$, depending on the frequency spectrum of the noise.

Gravimeters with electronic readout and software based processing facilities (e.g. CG-3/3M), automatically digitally stack successive measurements. They may also include smart signal processing, wherein individual measurements may be rejected on the basis of their departure from a predetermined mean by more than a certain number of standard deviations of the measurement.

When using a gravimeter with such signal processing facilities, the operator has the ability to extend his reading time until the mean of his suite of readings stabilizes (converges) to his satisfaction. The CG-3/3M also has the optional means for the measurement to automatically stop when the statistical accuracy of the measurement (i.e. the stacking) has achieved a required level. The assumption behind this approach is usually that a $\sqrt{\mathbf{n}}$ law will apply to the S/N enhancement, which is a conservative approach, and may result in unnecessarily long measurement times during periods of high microseismic activity.

Thus, to overcome ambient seismic noise, the measurement should be digitally stacked for a sufficiently long time to achieve the desired level of accuracy, as indicated by the convergence of successive mean values, or by the attainment of a specific probable error, on a statistical basis.

Selection of Station Location

We have already discussed the types of seismic noise which would be location dependent, such as highways, railways, metal-working plants and construction sites, etc.

Un-firm ground, such as swamp, deep snow, sand, ice, proximity to tree roots and measurements on ice sheets also result in the deterioration of gravity data quality.

All such locations are to be avoided, whenever possible, in choosing gravimeter stations.

Terrain effects due to topographic irregularities were referred to in *Terrain Effects* on page 6. They will be treated quantitatively in *Terrain Effects — CTE* on page 46, where corrections will be derived for them. At best, however, these corrections are but approximations, based on uncertain assumptions about the mean density of the nearby topographic features, and on the precision of determination of the elevations of these features, derived from whatever topographic maps may be available for the survey area.

The necessary terrain corrections should be minimized by selecting station locations which are on relatively flat areas, at least one metre away from any topographic features exceeding 10 cm in height or depth. The edges of cliffs or steep banks should be avoided at all costs.

Wind-Induced Vibration

Wind-induced vibration of the gravimeter during the course of the measurement will give rise to undesirable and, in fact, unnecessary noise on the measurement. It can be eliminated by simply using a windbreak.

A hand-held wind break can easily be made from a sheet of tough canvas or plastic, about 1.5 m square. Two opposing edges of this sheet are fastened to two wooden or aluminum poles, each about 2 m long. Once he has started his measurement, the operator stands up wind from the gravimeter, with arms outstretched, holding the poles upright and apart, thus forming a simple but effective wind break.

It is more convenient, for transport between stations, if the upright poles are folding or telescoping.

Alternatively, a large umbrella may also serve the same purpose.

STATION ELEVATION

As we have seen in *The Free-Air Effect* on page 4, *The Bouguer Effect* on page 5 and *The Elevation Effect* on page 5, the elevation of each gravimeter station must be determined with a precision which is determined by the accuracy required of the survey data.

We have seen, in *The Elevation Effect* on page 5, that if the density of the local rocks is 2.5g/cm^3 then a one metre elevation error will cause an error in the final gravity data of 0.20 mGals.

Section 3 dealt with the accuracy required of gravity data for surveys with different objectives.

For regional gravity surveys, practical (economic) limitations on the use of optical levelling methods have historically resulted in the use of much less precise means of elevation control, such as barometric altimeters, which yield elevations rarely accurate to better than ± 1 m, i.e. gravity values accurate to ± 0.2 mGals.

With the advent of the fully established GPS, satellite-based positioning system, it has now become feasible to determine relative elevations, routinely, with ± 10 cm accuracy, thus improving the resultant accuracy of the corrected gravity values to about ± 0.03 mGals.

Even this accuracy is not adequate for microgravity surveys, where one wishes to achieve gravity data which is reliable to ± 5 μGals. This would require that the relative station elevation be determined to within ± 2 cm accuracy. To be sure of achieving this accuracy at present still requires precise optical levelling of the station elevation.

At this point we must distinguish between the elevation of the station $\mathbf{E_s}$, and the elevation of the gravimeter $\mathbf{E_g}$. The former is the elevation of a marked point on a station marker, (wooden stake, or concrete or rock base), at a standard height above the local ground surface, which has been established by a prior elevation survey. The latter differs from $\mathbf{E_s}$ by the relative elevation of a specific reference point on the gravimeter itself, relative to the station elevation marker, i.e. $$\mathbf{E_g} = \mathbf{E_s} + \Delta\mathbf{E} \tag{20}$$

As we will see in *Variation with Elevation — CE* on page 44, the value of $\mathbf{E_s}$ will be employed to determine the combined *elevation effect* (Equation (9) on page 5), for the gravity measurement. However, still a further correction must be made for the fact that the gravimeter itself may stand somewhat higher or lower than normal relative to the ground surface (and to the station elevation marker) due to small differences in the height of its tripod and the amount of extension of its levelling screws. Such differences may readily achieve ± 2-3 cm; which could introduce significant errors into processed microgravity data.

Atmospheric Pressure

As has been described in the section *Atmospheric Pressure* on page 8, severe changes in atmospheric pressure can cause changes in the gravity measurements. These changes are significant for microgravity surveys. Where deemed important, these effects may be corrected by means of information provided by fixed or moving barometers, or by base ties, as will be described in *Atmospheric Pressure Changes — CP* on page 40.

Corrections to Observed Gravity Values

Having laid the foundations for quantifying the effects of various factors, both instrumental and external, on the gravity data, we will now proceed to quantify the corrections to be applied to compensate for these effects.

Variations with Time

In the section *Variation with Time* starting on page 7 and the section *Instrumental Factors* starting on page 22, we have discussed a number of factors, both internal to the gravimeter and external to it, which may cause changes in the observed gravimeter readings, with time. These include earth tides, long term instrumental drift, changes in battery supply voltage and atmospheric pressure changes.

Earth Tides Corrections – C_T

As Figure 3 on page 8 shows, corrections for the tidal gravity effects of the Sun and the Moon are essential for all types of gravimetric surveys, since they can contribute up to 0.3 mGal difference to the measurements.

These corrections become particularly significant in micro-gravity surveys, since tidal rates of up to 30 μGals per hour can readily occur.

Correction for Earth tides may be made in various ways, depending on the circumstances. The most convenient method, valid to the order of ±3μGals, is to apply the formula and tables of Rapp 1983 or Longman 1959. This correction is based on the UTC, latitude and longitude of the measurement. It may be applied off-line, or, in the case of software controlled gravimeters (e.g. CG-3/3M), on line by virtue of embedded software. The operator is only required to enter his latitude, longitude and difference between UTC and his real time clock.

Care must be taken, however, to enter the proper values and sign (conventions) of these parameters in order to avoid introducing extraneous errors.

For example, in the Longman formula embedded in the CG-3 software, the convention of sign is as follows:

Latitude	**N** is positive
	S is negative
Longitude	**W** is positive
	E is negative

Note:
Latitude and Longitude values must be stated in degrees and decimals, *not* minutes and seconds

Time The time parameter in the Longman formula is UTC. If the time to which the real time clock in the CG-3 is set differs from the UTC, then a UTC Difference parameter has to be entered into the CG-3, to provide the necessary information whereby the time UTC time may be obtained. If one sets the clock to UTC the UTC Difference is zero (0).

If the clock is set to local time, the difference is calculated by the following formula:

UTC Difference = UTC – CG-3 time

In general, this difference is defined *positive* for the zones west of Greenwich (0° Longitude) and *negative* for the zones east of Greenwich. These differences will change if the local time is moved ahead by one hour during summer months. For example, in Toronto, Canada, the UTC difference is 5 hours during *standard time* periods, but only 4 hours during *daylight savings time* periods. A reliable way to find the UTC difference is from the BBC shortwave radio news, which are broadcast hourly, with the time information given in UTC.

You should note that in some areas of the world their local time is one half hour different from that of their neighbouring time zones.

Examples:

a. Bangalore, India

Latitude 12° 56" N = +12.93°
Longitude 77° 40" E = −77.66°
Local time is UTC + 5 hours and 30 minutes (standard time)

Thus the correction is −5.5 hours.

b. Santiago, Chile

Latitude 33° 22" S = −33.37°
Longitude 70° 42" W = +70.70°
Local time is UTC −4 hours (standard time)

Thus the correction is +4 hours.

In theory, Earth tidal effects may by corrected by means of tie backs with sufficient frequency to a base, and regarding these effects to be just another time varying influence. However, since tidal-induced changes can readily reach 30 μGal/hr, it would hardly be realistic or economic to tie back often enough to ensure that corrections accurate to within 5 μGals are achieved.

Corrections using the Longman formula may leave residuals, due to ocean tide loading, etc. of ±3μGal in the interior of continents and ±10μGal within a kilometre or so of the coast (for example, see Figure 9 on page 109 in Appendix I). Corrections for these residuals have been computed for various sources:

- Timmen and Ulenzel (1994) for the global ocean tide loading
- Baker et al (1991) for Europe
- Lambert et al (1991) for Canada.

These residual corrections may be significant in the case of high precision microgravimetric surveys. They can be applied, off-line, using the references given above.

INSTRUMENTAL DRIFT – C_D

The various factors which may contribute to the instrumental drift of your gravimeter (long term drift, battery supply voltage changes, and vibration, etc.) have been dealt with in the section *Instrumental Factors* starting on page 22. If your gravimeter is software controlled, it may be assumed, for a start, that you have determined the mean long-term drift of your instrument by repeat measurements made over a period of at least 48 hours, at a convenient station. Such measurements must be corrected for tidal variations (see page 35), of course. Measurements can be made, for example, at the beginning and end of each day, or more frequently (e.g. even in a cycling mode, if convenient), over two or more days, for this purpose.

The slope of the best linear fit to the resultant curve of gravity values with time, will determine the residual long term drift rate of the gravimeter. This value is then used to adjust the drift correction factor, previously established in the instrument, in accordance with the instructions provided in your gravimeter's Operator Manual.

Update on the long term correction in software, should be made weekly within the first month or so when the gravimeter is new, reducing to monthly once the drift rate has essentially stabilized.

Once the long term drift has been compensated, then all gravity measurements will be automatically corrected, in real time, for this factor. There may, however, be residual drifts during the survey day, due to such effects as battery supply voltage changes and vibration induced short term drifts, as well as recent power-downs of the instrument (see page 22).

Such residual drifts are determined by means of repeat of measurements made at a *base* station, whose gravity value has been previously established, at least at the start of the day's survey and at its end. The reading at the start of the day will establish the correction for the offset of all that day's measurements, and for the cumulative residual drift since the start of the survey. The difference between the reading at the end of the day and that at the start of the day will determine the residual drift rate for that day. This drift will then be linearly apportioned to all intervening measurements for that day, in accordance with the time of each measurement.

Particular care must be taken in respect of these base station readings, to avoid any error in them, which would then be propagated throughout the final gravity values for all stations measured that day. This would include such steps as:

- **a.** take several repeat measurements at the base station, to ensure that any elastic relaxation effects have dissipated, and
- **b.** if in the course of the day your instrument has experienced rough handling (shock or extreme vibration), repeat the last reading taken before that occurrence, to ensure (or correct for)

any tares that may be erroneously interpreted as extraordinary drifts, and thus an error will be distributed throughout all readings. It may also be advisable to return to read that day's base station, at this point, before resuming the survey. In this fashion, if required, an allowance can by made for two rates of drift during that day, one before the occurrence and one after.

Example: Let us assume that the following gravity values are observed at a specific base station, corrected for tidal effects and for linear long-term drift.

$\mathbf{R_0}$ — base station gravity value, previously established and corrected

$\mathbf{R_1}$ — observed value at the start of the day, at time $\mathbf{T_1}$ at the base station

$\mathbf{R_2}$ — observed value at the end of the day, at time $\mathbf{T_2}$ at the base station

$\mathbf{R_3}$ — observed value at a new station, at time $\mathbf{T_3}$ (between $\mathbf{T_1}$ and $\mathbf{T_2}$)

Then, the residual correction $\mathbf{C_D}$ to be applied to the new station will be given by

$$\mathbf{C_D} = (\mathbf{R_0} - \mathbf{R_1}) - (\mathbf{R_2} - \mathbf{R_1})\frac{(\mathbf{T_3} - \mathbf{T_1})}{(\mathbf{T_2} - \mathbf{T_1})} \qquad \textbf{(21)}$$

The first bracket is the *day-to-day* correction, which in effect, corrects for all residual drifts since the start of the survey. The second factor accounts for the effect of the drift during the day, assuming that this drift is, in fact linear, between the repeated measurements at the station.

Example: (readings in mGals)

$\mathbf{R_0}$ = 5024.372 , $\mathbf{R_1}$ = 5024.583
$\mathbf{R_2}$ = 5024.592 , $\mathbf{R_3}$ = 5031.632
$\mathbf{T_1}$ = 0805 Hours , $\mathbf{T_2}$ = 1822 Hours
$\mathbf{T_3}$ = 1310 Hours

Then the drift corrected reading for the new station is given by

$$\mathbf{R^1_3} = \mathbf{R_3} + \mathbf{C_D} = 5031.632 - 0.211 - 0.009\ (5.10)/10.28$$
$$= 5031.417$$

ATMOSPHERIC PRESSURE CHANGES – C_P

The effect of atmospheric pressure changes on the observed gravity values has been presented in *Atmospheric Pressure* on page 8. Equation (12) on page 8 provides the simple relationship between such barometric pressure changes and their effects on the observed gravity values. On days with a normal weather pattern, barometric pressure variations are in the range of 0.3 – 1 kPa (i.e. 1 – 3 μGals) per day. There will be times, however, when a major pressure front (e.g. a thunderstorm) moves rapidly through the survey area. Such a weather system can give rise to pressure changes totalling 5 kPa (i.e. 18 μGals) in amplitude, with temporal gradients of the order of 0.5 kPa/hr (1.8 μGal/hr) and spatial gradients of the order of 0.2 kPa (0.7 μGal) in 10 km distances.

Whereas atmospheric pressure changes on normal weather days will only affect microgravimetric surveys (only in a minor way), there may be atmospheric conditions which can cause significant effects at the μGal level.

Corrections for these effects can be made in one of two ways:

1. For greatest precision, in microgravimetric surveys, carry a barometer with a resolution of 0.1 kPa, and read it at each gravity station, for correction to the observed gravity values. In relatively small survey areas (e.g. within a radius of 25 km) the barometer may be kept stationary and its variation recorded with time. On normal weather days the barometric pressure will be constant, within 0.5 kPa over such an area; thus C_p so derived will be correct to within 2 μGals.

   The correction to the observed gravity values for changes in barometric pressure is given (from Equation (12) on page 8), by

   $$\mathbf{C_P} = +\mathbf{3.6}(\mathbf{P_1} - \mathbf{P_0}) \text{ in } \mu\text{Gals}, \qquad \mathbf{(22)}$$

   where $\mathbf{P_1}$ is the atmospheric pressure at the field station (or at the field station time) and $\mathbf{P_0}$ is the atmospheric pressure at the base station (or base station time) at the start of the day, in kPa. For example, if $\mathbf{P_0}$ was 98.1 kPa and $\mathbf{P_1}$ was 101.3 kPa, then

   $$\mathbf{C_P} = +11.5 \ \mu\text{Gals} \qquad \mathbf{(23)}$$

   Note that when the pressure increases, the correction is positive, and vice versa.

2. Tie back to a gravity base station sufficiently often to correct for the pressure-induced effect through the linear drift correction (page 37). On normal days, a mid-day tie (as well as the usual start-of-day and end-of-day tie) will suffice. When a weather front is moving in, however, the ties will have to be more frequent. In the extreme, when a major pressure front is moving through, the pressure at the field station may be different from that at the base station, but this may have to be chanced.

In any case, implicit in the drift correction procedure outlined in *Instrumental Drift — CD* on page 37 (where a base station is read at the beginning and end of each day) is a correction for the barometric pressure at those times. This includes any day-to-day pressure changes since the start of the survey.

There will also be changes in atmospheric pressure with elevation, and consequent changes in the observed gravity values. Of course, these will, likewise, be compensated through the use of a moving barometer. If no moving barometer is employed, there is, nevertheless, little practical consequence because, as we shall see, the barometric pressure effect is negligibly small in respect of the elevation effect, and the uncertainty in the latter.

Near sea level the normal vertical atmospheric pressure gradient is approximately -1.44×10^{-2} kPa/m. This gives rise to a change of -0.052 μGals/m. For a surface density of 2.5 g/cm^3, the combined elevation effect (Free-Air plus Bouguer) will be (Equation (9) on page 5) 203.8 μGals/m. The pressure effect is clearly insignificant relative to the other elevation effects.

CHANGES IN GROUNDWATER AND SURFACE WATER LEVELS – C_{GW}

As has been discussed in *Precipitation* on page 9 and *Ocean Tides (Sea Level Changes)* on page 9, such changes may effect the measurements of the Earth's gravitational field. Changes in groundwater levels are likely to be seasonal and will reflect the wet and dry seasons, where such a specific seasonality is present (e.g. in monsoon-prone countries in South and Southeast Asia).

It would be tedious to attempt corrections for the seasonal variation of groundwater levels on an individual station basis, for this would require a measure of the porosity of the local soils and the local level of the groundwater. Such measurements could, however, be made periodically at one site, at least in topographically flat areas, and a seasonal correction applied to all readings, based on the variation of the water table level at the test site, and the porosity of the soil there.

According to Equation (13) on page 9, the correction $\mathbf{C_{GW}}$ for a variation Δ**w (m)** of the ground water level will be given by

$$\mathbf{C_{GW}} = \mathbf{-0.04192\Delta w \cdot b} \text{ mGals} \qquad \mathbf{(24)}$$

where **b** is the porosity of the soil.

In the case of surface water changes, such as measurements made near the margins of a sea, lake or river, these would have to be made with a knowledge of the location of the station relative to the body of surface water.

Sea tide variations can be rapid and large in some parts of the world, reaching up to 10m in level, for example. As Equation (14) on page 9 indicated, for a station at the very edge of the sea coast, the correction for tidal action will be given by $\mathbf{C_{ST}} = -0.02$ mGals/m of tidal level change.

Note that when the tide rises the correction is negative. This correction can be made by the use of available tidal information for the local area, or by physical measurements of the tidal level at the time of the gravity reading.

Changes in lake and river levels are usually smaller and slow to occur. They are best corrected for by measurements of water levels in the field.

All of the above corrections may be pertinent in the case of microgravimetric surveys and for precise calibration of your gravimeter on a calibration range. The sea tide correction $\mathbf{C_{ST}}$, can, however, be sufficiently large to affect all types of gravimetric surveys in coastal regions.

VARIATION WITH LATITUDE – C_L

As Equation 6 indicates, there is a general increase in gravity with latitude θ. By differentiation of this equation we find, the rate of increase of gravity with distance (north or south of the equator) to be given by

$$\Delta g_L = 0.813 \sin 2\theta - 1.78 \times 10^{-3} \sin 4\theta \qquad (25)$$

in mGals/km.

Table III presents this *terrestrial gradient* as a function of θ, north or south, determined directly from Equation (6) on page 4.

Table III:
Variation Of Terrestrial Gradient With Latitude

θ°	Δg_L mGal/km
0	0
5	0.137
10	0.278
15	0.397
20	0.522
25	0.609
30	0.704
35	0.759
40	0.803
45	0.813

θ°	Δg_L mGal/km
50	0.803
55	0.773
60	0.706
65	0.634
70	0.524
75	0.417
80	0.280
85	0.145
90	0

Thus, it can be seen that this terrestrial gradient is predicted to peak at almost 1 μGal/m in mid latitudes.

It is customary, therefore, to apply a terrestrial correction C_L for the variation of gravity with latitude, using the above tables. These corrections are negative with increasing latitude; north or south of the equator. Once these strong gradients are removed, then lesser gradients, due to subsurface geological variations will become more evident.

VARIATION WITH ELEVATION – C_E

As indicated in Equation (9) on page 5, the correction for the combined Free-Air and Bouguer effects may be written as

$$\mathbf{C_E} = +(\mathbf{0.3086} - \mathbf{0.0419d})\mathbf{h} \text{ in mGals,} \qquad \mathbf{(26)}$$

where **d** is the mean density of the near-surface rocks, in g/cm^3; and **h** is the elevation of the gravimeter station in metres relative to a datum level. The value of **d** may be determined by measuring the density of rock samples, but another method, originally suggested by Nettleton (Nettleton, 1976) is more useful in providing a macroscopic estimate of the value of **d**. It consists of running a gravity profile over a topographic feature hill or valley.

Figure 4 on page 45 illustrates the application. It shows a hypothetical profile over a hill, and the observed gravity values, corrected for drift only. Several profiles of the same data are shown, corrected for $\mathbf{C_E}$ on the basis of different values of density. The corrected profile most nearly approximating a *straight line* across the topographic feature determines the *optimum* value for the density of the rocks in the vicinity, i.e. 1.9 g/cm^3 in this case.

A few other points to note in applying this scheme would include:

1. Try to pick broad topographic features, so that terrain corrections will not be large (see Section 7.4) and the one-dimensional approximation to the Bouguer correction may be reasonably valid
2. Pick a topographic feature which is of erosional origin, rather than geologically controlled, for the latter may be associated with lateral density changes
3. In determining the best-fit value of **d,** remember that the best straight line gravity profile may be tilted, reflecting a broad regional gradient. It need not be horizontal.
4. If you are doing a microgravimetric survey and attempting to achieve accuracies in the low µGal range, you will have to determine your relative station elevations to within ±1 cm (i.e. ±2 µGals in Equation 20). Furthermore, you will have to determine the elevation of a reference marker on your gravimeter, to the same preci-

sion. This relative elevation then determines the station elevation to be applied in determining $\mathbf{C_E}$ in Equation 20.

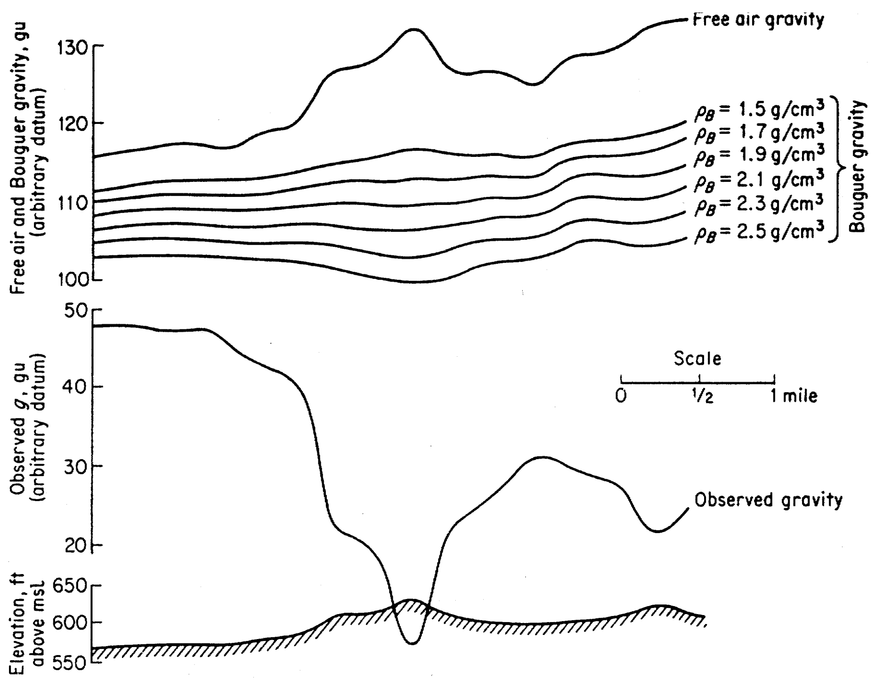


Figure 4 Nettleton's Method for estimating the density of surface rocks
(Gravity values in units of 10 μGals = 1 gu)

Corrections

Example: The station marker is at 168.53 m above the survey datum point. The reference point on the gravimeter is 0.06 m below the station.

If we have separately determined **d** to be 2.3 g/cm^3, for example, then from Equation (26) on page 44

$\mathbf{C_E}$ = (0.3086 – 0.0419 x 2.3) 168.53 = 35.779 mGals.

We must, however, add to this the Free-Air correction for the relative elevation of the gravimeter and the station marker, in order to determine the value of gravity at the station marker level. This additional correction is given by Equation (7) on page 4, to be –0.019 mGals. Thus the total correction is

$\mathbf{C_E}$ = 35.760 mGals.

TERRAIN EFFECTS – C_{TE}

As was discussed in *Terrain Effects* on page 6, topographic features can influence gravimeter measurements on stations in their vicinity. All such effects are negative, i.e. act to reduce the observed gravity results.

The reduction of terrain effects to acceptable levels requires a combination of good field practice, detailed topographic information and the proper assumption of the density of the formation forming the topographic features.

Firstly, in choosing a station location, try to pick a location which is flat for at least 2 m radius about the station, i.e. less than 10 cm relief out to 2 m. Even further, avoid locations near severe topographic features such as cliffs, and steep-sided valleys, etc.

If the maximum vertical angle subtended by any topographic feature, relative to your station elevation is less than about 5° you need not worry about making topographic corrections. Alternatively, if there are large topographic features which subtend much larger vertical angles, but are remote (2 km or more from all your stations) you can allow their influence to appear as a regional gradient in your data, and be removed as such by a later signal processing stage (see *Corrections* on page 59).

If the above conditions are not satisfied, and your survey area includes prominent topographic features, then you should make corrections for the gravity disturbances due to these features. There are several ways of accomplishing this. All are based on breaking the survey area and its surrounding area into cells or prisms, assigning an average height (relative to the level of the station) and density to each, calculating the gravity contribution of each prism and summing all the contributions to determine the topographic effect (and correction) for that station.

The average elevation of each cell relative to the station elevation is determined from a combination of elevations, some determined in the field for cells near the station, and (most) elevations taken off the most detailed topographic plan available for the survey area and the surrounding vicinity, or in some cases, from digitized terrain models.

The traditional method of making topographic corrections is based on that of Hammer, 1939. He uses transparent templates which are prepared on the scale of the topographic maps from which the topographic elevations are to be obtained. These templates are placed over the topographic map, centered on the location of the station for which the topographic correction is to be determined. The mean elevation for each cell can be determined from the elevation of its mid point or, more accurately, from the mean of its mid-point and its four corners.

Table IV on page 48 presents the Hammer terrain correction data. It is divided into 8 concentric zones, covering the distance from about 2 m to about 4.4 km about the station. Each zone is divided into angular sectors, ranging from 4 sectors in zone B to 12 sectors in zones G to I inclusive. Since the larger zones are so different in scale from the smaller ones, the usual practice is to have two or more templates, each covering a subset of the zones and scaled to different topographic maps (if available). Relative sector elevations $\Delta \mathbf{Z}$ are given in feet and the terrain correction per sector $\Delta \mathbf{C_{TE}}$ is given in mGals.

It will be noted that no corrections are shown for zone A (to 2 m). This assumes that the station location has been chosen in a locally flat area, as described above. The elevations for the four sectors in zone B (mean radius equals 10 m) are usually obtained by means of rough levelling around each station, at 90° orientation, to four points, each 10 m from the station. If the station is on a sloping surface, only two elevations are required, one directly up-slope and one directly down slope.

The elevations for zones C to I are obtained using the templates on the appropriate topographic maps. The elevation differences are obtained by subtracting the elevation of the station from the mean elevation of each cell.

It should be noted that, for convenience, the corrections in Table IV on page 48 have been calculated on the basis of the density of 2.67 g/cm^3. The terrain corrections for other densities can be obtained by proportionality with the densities. Where major changes in surface rock types and densities are expected, different densities may be employed for the individual cells overlying the different rocks.

The density value or values to employ in these terrain corrections can be estimated from that determined for the Bouguer correction over topographic features (Figure 4 on page 45), or from rock samples.

Figure 5 on page 50 shows a Hammer terrain template overlain on a topographic map.

Table IV: Hammer Terrain Correction Table

ZONE B 4 SECTORS 6.56'–54.6'		ZONE C 6 SECTORS 54.6'–175'		ZONE D 6 SECTORS 175'–558'		ZONE E 8 SECTORS 558'–1280'		ZONE F 8 SECTORS 1280'–2936'		ZONE G 12 SECTORS 2936'–5018'		ZONE H 12 SECTORS 5018'–8578'		ZONE I 12 SECTORS 8578'–14612'	
ΔZ	ΔC_{TE}	ΔZ	ΔC_{TE}	ΔZ	ΔC_{TE}	ΔZ	ΔC_{TE}	ΔZ	ΔC_{TE}	ΔZ	ΔC_{TE}	ΔZ	ΔC_{TE}	ΔZ	ΔC_{TE}
0.0–1.1	0.00000	0.0–4.3	0.00000	0.0–7.7	0.00000	0–18	0.00000	0–27	0.00000	0–58	0.00000	0–75	0.00000	0–99	0.00000
1.1–1.9	0.00133	4.3–7.5	0.00133	7.7–13.4	0.00133	18–30	0.00133	27–46	0.0133	58–100	0.00133	75–131	0.00133	99–171	0.00133
1.9–2.5	0.00267	7.5–9.7	0.00267	13.4–17.3	0.00267	30–39	0.00267	46–60	0.00267	100–129	0.00267	131–169	0.00267	171–220	0.00267
2.5–2.9	0.0040	9.7–11.5	0.0040	17.3–20.5	0.0040	39–47	0.0040	60–71	0.0040	129–153	0.0040	169–200	0.0040	220–261	0.0040
2.9–3.4	0.0053	11.5–13.1	0.0053	20.5–23.2	0.0053	47–53	0.0053	71–80	0.0053	153–173	0.0053	200–226	0.0053	261–296	0.0053
3.4–3.7	0.0067	13.1–14.5	0.0067	23.2–25.7	0.0067	53–58	0.0067	80–88	0.0067	173–191	0.0067	226–250	0.0067	296–327	0.0067
3.7–7	0.0133	14.5–24	0.0133	25.7–43	0.0133	58–97	0.0133	88–146	0.0133	191–317	0.0133	250–414	0.0133	327–540	0.0133
7–9	0.0267	24–32	0.0267	43–56	0.0267	97–126	0.0267	146–189	0.0267	317-410	0.0267	414–535	0.0267	540–698	0.0267
9–12	0.040	32–39	0.040	56–66	0.040	126–148	0.040	189–224	0.040	410–486	0.040	535–633	0.040	698–827	0.040
12–14	0.053	39–45	0.053	66–76	0.053	148–170	0.053	224–255	0.053	486–552	0.053	633–719	0.053	827–938	0.053
14–16	0.067	45–51	0.067	76–84	0.067	170–189	0.067	255–282	0.067	552–611	0.067	719–796	0.067	938–1038	0.067
16–19	0.080	51–57	0.080	84–92	0.080	189–206	0.080	282–308	0.080	611–666	0.080	796–866	0.080	1038–1129	0.080
19–21	0.0935	57–63	0.0935	92–100	0.0935	206–222	0.0935	308–331	0.0935	666–716	0.0935	866–931	0.0935		
21–24	0.107	63–68	0.107	100–107	0.107	222–238	0.107	331–353	0.107	716–764	0.107	931–992	0.107		
24–27	0.120	68–74	0.120	107–114	0.120	238–252	0.120	353–374	0.120	764–809	0.120	992–1050	0.120		
27–30	0.133	74–80	0.133	114–120	0.133	252–266	0.133	374–394	0.133	809–852	0.133	1050–1105	0.133		
		80–86	0.147	120–127	0.147	266–280	0.147	394–413	0.147	852–894	0.147				
		86–91	0.160	127–133	0.160	280–293	0.160	413–431	0.160	894–933	0.160				
		91–97	0.174	133–140	0.174	293–306	0.174	431–449	0.174	933–972	0.174				
		97–104	0.187	140–146	0.187	306–318	0.187	449–466	0.187	972–1009	0.187				
		104–110	0.200	146–152	0.200	318–331	0.200	466–483	0.200	1009–1046	0.200				

Note: ΔZ in feet (without regard for sign)
ΔC_{TE} in mGals, assuming topographic feature density of 2.67 g/cm^3

Computer programs have been developed for calculating terrain corrections when topographic maps of the survey area are available in digital form. For computation purposes the cells employed are usually rectangular in cross-section, rather than sectorial, as above. Even using digital topographic data it is not possible to dispense with manual correction for near-station topography, using, for example, the Hammer tables.

A computer program for terrain corrections using digitally gridded elevational data is available from the U.S. Geological Survey (Plouffe, 1977). A refinement to it has been presented by Oliver, 1981.

The distance from each station out to which terrain corrections may be recommended is related to the scale of the map on which the gravity data will be finally presented. For example, if the scale is 1:1000 to 1:2000, terrain out to 300m from each station should be taken into account. For scales of 1:10,000 to 1:50,000, corrections to 3km would be desirable, and for scales of 1:100,000 to 1:500,000 corrections to 30kms, etc.

At best, however, correction for topographic effects is tedious, time consuming and, in the end, not terribly accurate in areas of rough topography.

Despite this, it is necessary to perform these corrections, for the alternative may be gravity data which is of little value in geologic terms, in mountainous areas.

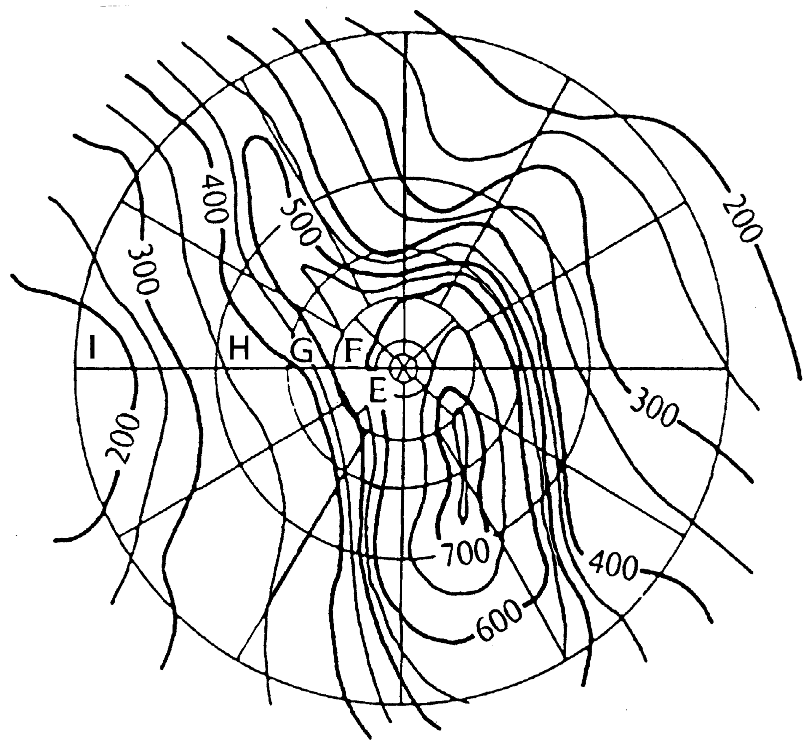


Figure 5 Hammer Terrain Correction Template Overlying Topographic Map

SURVEY PROCEDURES

SURVEY LAYOUT

We have, in Section 3, briefly described the various applications for gravimetric surveys and the organization of the gravimeter grids and stations for each application. We have seen that for some applications, namely regional geological mapping and petroleum exploration, stations are placed on a regular grid pattern, as nearly as practical, with a station interval that may range from 100m to 10km. For smaller targets, such as geotechnical, environmental and archaeological studies a much higher density of stations, perhaps as close as 10m centres, may be required, in order to provide the resolution required for small features.

For mineral exploration purposes, gravimeter readings are often taken on lines oriented at right angles to the geologic strike. These lines may be 100m to 1km apart. Stations on these lines may be at 25m to 50m intervals.

For tectonic, geothermal and volcanological studies a set of irregular but strategically located stations are occupied, on a periodic basis (e.g. six to twelve month intervals) to observe subtle changes in the gravitational field.

For maximum utility, all gravimetric surveys using relative gravimeters, ultimately should be tied into one or more absolute gravity bases. This is in order to both establish their absolute (rather than relative) levels and to bring all independent gravimetric surveys to a common level. In this manner, all gravity survey data may also be incorporated into a national GIS data base.

There is a growing number of *permanent* absolute gravity stations throughout the world, and, ultimately, every country will have at least several of these. Their gravity values will usually be reliable to within a value better than 10 µGals. These absolute stations will be the primary support for national gravity networks of *permanent* stations, established using relative reading gravimeters, but accurately tied, by repeated measurements, to the absolute stations. Station grid intervals on these national networks may be of the order of 10km – 100km, depending on the size of the country (and its budget for such surveys). Stations on national networks are intended to be suitable for precise re-occupation and, for this reason, are usually marked by a solid concrete pillar sunk deeply into the soil, or by a metal plate sealed into outcrops. Precise descriptions of their location are usually available from government organizations.

Such large spacing national gravity grids are termed *1st Order*. Grids with smaller spacings (5 – 10km) are called *2nd Order*, and closer spaced grids, for detail purposes (e.g. 1 – 2km) are termed *3rd Order*.

A high degree of accuracy is required for permanent stations on national gravity networks. This is usually accomplished by repeat measurements, with well calibrated (relative) gravimeters, in the form of loops. The gravity value for each station is ultimately arrived at through a least squares adjustment, using a suitable computer program (Torge, 1989 p.339). Figure 6 on page 53, after Torge 1989, shows such a gravity network, with the misclosure for each closed loop.

Second and Third Order grid stations will be made suitable for reoccupation, by establishing some reasonably permanent marker for the station position and elevation — e.g. a metal pipe or stout wooden stake sunk at least one metre into the ground.

Individual stations on detailed surveys, e.g. for mineral exploration purposes, not intended for reoccupation, need not be marked beyond the extent necessary for the initial occupation, e.g. by a thin wooden stake, set firmly in the ground, on which a mark indicated the station elevation level, which has been established by a levelling survey.

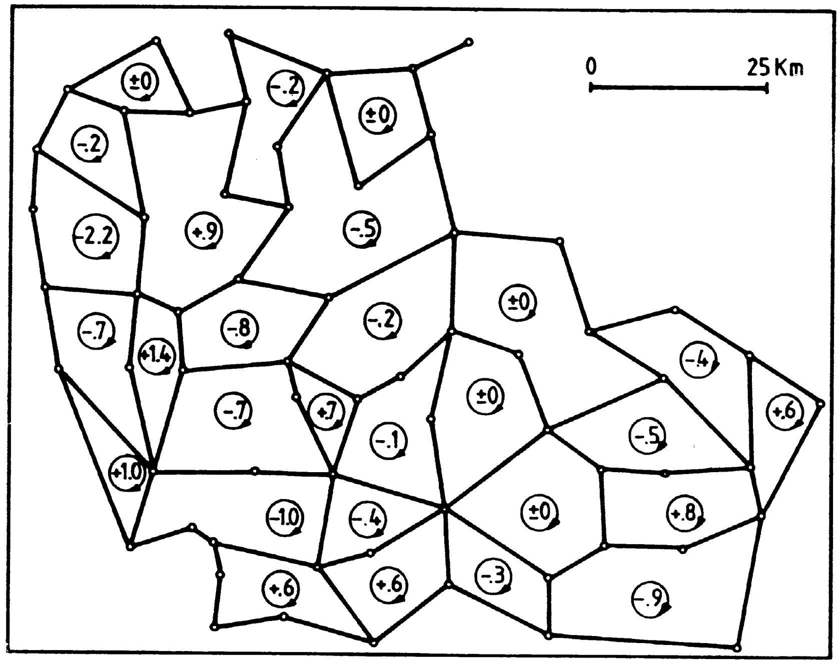


Figure 6 National Gravity Network, showing misclosures in μms^{-2} (after Torge)

Elevation and Positional Accuracy

As has been indicated in Section 3, there are different standards of accuracy of the gravity data expected of surveys carried out for different purposes. This implies different standards for the accuracy of determination of the station coordinates (elevation and location).

Elevation

So far as elevation accuracy is concerned, we have seen that microgravimetric surveys require relative accuracies of station elevation of better than ±1cm to achieve accuracies of a few μGals in the final gravity values. This, of course does not apply to applications for volcanology, geothermal and geotectonic studies, where only the change of gravity with time at repeated stations is significant.

At present the usual way of assuring such a high precision of elevation control is by optical levelling.

The next order of precision of elevation control, to within ±10cm, is now afforded by the use of satellite-based positioning systems (Global Positioning System or GPS), (Energy, Mines & Resources, 1993).

Even higher GPS precisions are claimed as well, and it may be expected that these will be achieved and proven, in due course, and then may totally displace optical levelling for land gravity surveys. The differential mode, entailing the use of a second, fixed, reference receiver and dual frequency receiver, provides the highest accuracy of measurement available by GPS.

At ±10cm accuracy, GPS-based elevations can achieve ±30μGals gravity data accuracy, even for widely-spaced, regional gravimetric surveys. This represents at least a ten-fold improvement in accuracy over the use of microbarometers for such regional surveys.

Of course, GPS positioning requires a clear view of the sky, to be able to receive signals from a sufficient number of transiting satellites, simultaneously. It is feasible to do this in open country, but not in heavily wooded terrain. In the latter circumstances, one falls back on optical levelling or, as an alternative for closely spaced stations, a device based on a liquid-filled tube. The pressure differential between the two ends of the tube (e.g. up to 60m long) can be converted into the elevation differential of these ends. The elevation accuracy claimed for this device is within ±1cm per individual measurement, i.e. adequate for closely spaced microgravity stations.

POSITIONAL ACCURACY

Positional accuracy of gravity stations is far less critical than elevational accuracy. For example, so far as the terrestrial (latitude) gradient is concerned (Table III on page 43), the maximum result of an error of ±5m in the north-south position of a station will give rise to an error of ±4 μGals at mid-latitudes, and less elsewhere. This accuracy of positioning is readily achieved by differential GPS control.

It is clear that differential GPS-based positioning and elevation control, where it can be used (in open country), will greatly facilitate the use of gravimetric surveying in general, and raise the standards for accuracy of regional surveys.

The elevation and positioning control for gravity stations may be obtained before, during, or after the actual gravity measurement, so long as the elevational information is properly incorporated into the gravity corrections. Optical levelling is always carried out at a different time from the gravity measurements, because it requires a different time scale. GPS positional measurements are commonly made at the same time as the gravity measurements, and by the same two-person field party, since the GPS equipment is very small and light weight. Also, the GPS measurement time is compatible with the usual gravimeter measuring time (two to four minutes per station).

STANDARD FIELD PROCEDURE

The steps to be taken in carrying out a gravimetric survey of a new area are as follows:

1. Set up your gravimeter and ensure that it is operating stably. This is particularly important if the gravimeter has been subjected to rough transport, or has been off-power prior to the start of the survey. If the setting of its levels has not been checked for some time, do so, following the manufacturers instructions. Charge up your complement of batteries.

   On software controlled gravimeters, also check and adjust the long-term drift correction and the temperature compensation, in accordance with the manufacturer's instructions. Also conform to the other software set-up procedures appropriate to your gravimeter.

2. Establish your grid of proposed gravity stations, keeping in mind the recommendations for stability and freedom from nearby topographic irregularities (See *Selection of Station Location* on page 32.). Mark each station. For example, use a 1.5m long wooden picket driven firmly in the ground, and attach to it a length of red flagging material, for good visibility.

3. Select a number of these stations, which extend across the proposed survey grid, for use as base stations. These stations should be relatively easy for access, e.g. along roads or cleared lines, etc.

4. Conforming to the recommendations of Section 5 starting on page 51, make gravity measurements at your proposed base stations, starting at one of these stations and returning to it at the end. Repeat the loop of these base stations at least once, so that each of these is read at least twice. If your base stations are reasonably in a line, you will read each twice on each loop (going and coming). Make and distribute the appropriate drift corrections for each loop and station. (See *Instrumental Drift — CD* on page 37.)

5. In the case of microgravimetric surveys, in times of major weather frontal movements, take the barometric pressure readings, preferably at the same time and place as the gravity readings, and make the appropriate correction for atmospheric pressure to each gravity measurement. (See *Atmospheric Pressure Changes — CP* on page 40.)

6. Take the mean of the two or more sets of base station gravity values, corrected for drift, instrumental level, tides and barometric pressure changes, etc., as being the correct values for each base station. All such values will then have been corrected to a common time of measurement, so far as barometric pressure and instrumental drift is concerned. Their gravity values may be considered to be equally valid and accurate, for use as base stations for other survey stations in their vicinity. Therefore, it will not be necessary to use the same base station each day.

7. Complete the gravimetric survey by measuring at all stations systematically by sections. For each section, use one of the stations which was established under Step **4.** as a base station. Through the use of these base stations, at the beginning and end of each day, or portion thereof, you will automatically correct all the newly established station values for cumulative instrumental drift and barometric level changes from the time you read your first station on the survey.

Example: If at base station 10, the relative value of gravity at the station under Step **6.**, was found to be 3825.183 mGals. If at the start of day 5 of the survey its value was measured at 3825.312 mGals, then the difference (0.129 mGals) will be subtracted from all gravity measurements that day, to correct for cumulative instrumental drift and barometric change over the five days.

8. Establish the elevation and coordinates of each gravimeter station on the grid, by means appropriate to the accuracy required of the survey. This may be done prior to, at the same time as, or after the making of the gravity measurements themselves, depending on expediency and the type of elevation and positional control employed.

If the gravity measurements occur first, then the level of a set reference mark on the gravimeter (e.g. the top of its chassis) must be marked on the station picket. This will then become the station elevation level, whose value is to be determined by the levelling party. If the levelling has been done first, the levelling party will mark the measured station elevation on the station picket. The gravimeter operator will then note the elevation of the reference mark on his meter, relative to the station mark, so that his gravity values can be corrected for this difference, as per *Variation with Elevation — CE* on page 44. If the levelling and gravity measurements are concurrent (e.g. by GPS), then the station level and instrumental level will coincide.

In any event, therefore, the final gravity value determined for a station, when corrected for elevations, etc., shall refer to the station elevation as determined by levelling, if the latter differs from the instrumental level. Make the appropriate correction for elevation, as per *Variation with Elevation — CE* on page 44.

9. Tie to national gravity grid. To determine the absolute level of your gravity stations, to allow your survey data to be incorporated into a regional or national data base, and to be able to utilize the results from other, independent, gravimetric surveys, it is recommended that you tie one or more of your set of gravity base stations to the nearest station of the national gravity network. A double loop is recommended for greater precision of such a tie.

DATA PROCESSING AND PRESENTATION

CORRECTIONS

All the corrections of Section 6 are to be applied to the observed gravity measurements. Of these, the tidal correction and a measured long term drift correction may be applied, in real time, on software controlled instrumentation, or else they are made, off-line, later. The remainder of the corrections, viz: residual drift, elevation, terrain, barometric pressure and latitude, are applied off-line.

It is most convenient to perform these corrections by computer, using computer programs that are available from the manufacturers of gravimeters or from software consultants.

Then prepare listings of the corrected gravity values and their coordinates. Gravity values to which all of the above corrections have been made, are often designated as *Bouguer Anomaly values*.

DATA PRESENTATION

Presentation of the corrected gravity values is commonly made in the form of isoanomaly contour maps, particularly where the survey has covered a grid of more-or-less evenly spaced stations. Exceptionally, where well-isolated profiles have been surveyed, to obtain *cross-sectional* information on a structure, then the results may be presented in the form of profiles. A sequence of profiles may be shown in stacked form, in proper relative location, on a plan map.

In either case, the horizontal scale of the presentation should be inversely related to the distance between the gravimeter stations. Also, the contour interval (mGals) may be inversely related to the scale of the presentation. Table V shows such a typical suggested relationship between these quantities. Special circumstances may require a divergence from this Table.

Table V
Relationship Between Station Spacing, Contour Interval and Scale of Presentation

Map Scale	Station Interval (m)	Contour Interval (mGal)	Station Density per km^2
1:1,000,000 to 1:500,000	2,500 – 5,000	2 – 5	0.04 – 0.1
1:200,000	1,000 – 2,000	1 – 2	0.1 – 0.25
1:100,000	500 – 1,000	0.5 – 1	0.25 – 1
1:50,000	100 – 500	0.5 – 1	2 – 30
1:25,000	50 – 250	0.25 – 0.5	4 – 50
1:10,000	20 – 50	0.1 – 0.2	20 – 200
1:5,000	10 – 50	0.05 – 0.1	100 – 500
1:2,000	10 – 20	0.02 – 0.05	2,000 – 10,000

In the case of a profile presentation, the same relationship should exist between the profile horizontal scale and the station intervals, as per the first two columns of Table V. The vertical scale of the profile presentation will be selected on the basis of the total range of gravity values observed on the profile.

Software programs are available, by means of which either isoanomaly contour plans or profile presentation may be conveniently and quickly made. The contour programs incorporate the step of creating a uniform orthogonal grid of interpolated gravity values from the (usually) somewhat irregularly distributed gravity stations. The actual contour presentation is based on the interpolated grid values, not on all the original gravity data. In this fashion, unfortunately, some detail is lost where the density of stations in a portion of the survey is much greater than the average for the survey grid, and therefore the stations are much more closely spaced than the grid spacing employed in the computer program.

It is also current practise to plot the station locations on the Bouguer anomaly map, or to plot them on a small index map.

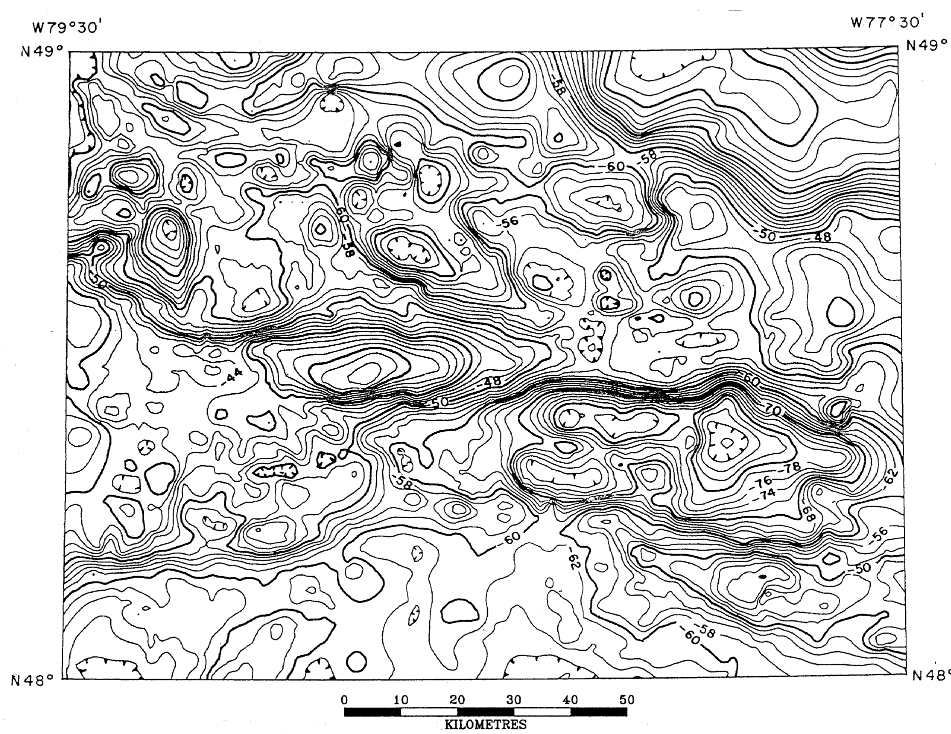


Figure 7 Typical Regional Bouguer Gravity Anomaly Contour Plan (after Keating) Contour Interval 2 mGal

Figure 7 (after Keating, 1992), shows a Bouguer anomaly contour plan that was derived from an irregularly distributed data set of over 13,000 gravity stations. The station spacings ranged from 500m to 10km. The original presentation was on the scale of about 1:500,000, and the contour interval selected was 2 mGal. This plan was generated for the purpose of regional geological mapping.

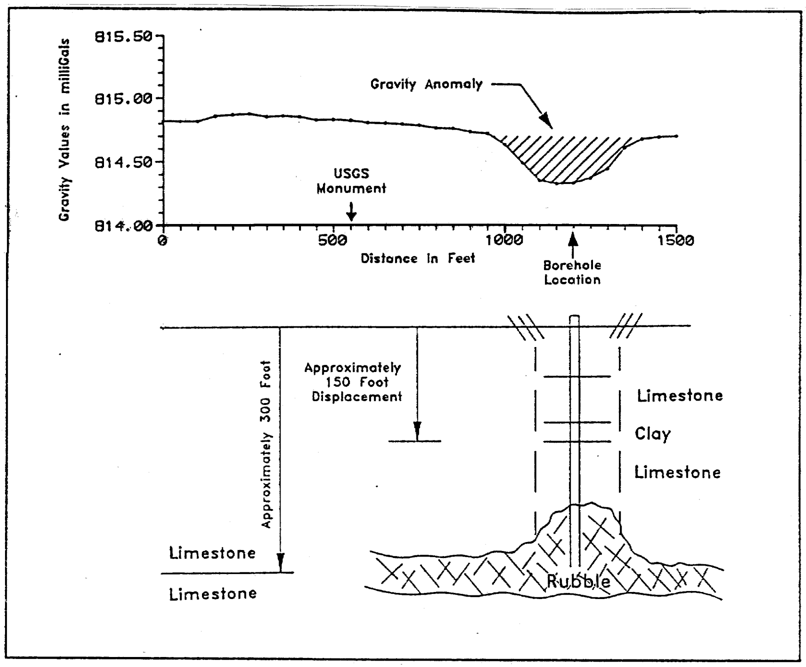


Figure 8 Bouguer Microgravity Profile over Paleokarst Collapse Structure (after Yuhr)

Figure 8 (after Yuhr et al, 1993) shows a Bouguer microgravity profile over a paleokarst collapse structure. In this case, stations were at 30m intervals on the profile.

Once the corrected Bouguer gravity data of a survey area have been reduced to a grid of digital data, it is very easy to manipulate these data by computer, to produce certain desired effects. For example, local changes in gravity reflecting local changes in rock densities (geology) can be enhanced by means of the computation of horizontal or vertical derivative maps.

For example, Figure 9, after Keating, 1992, shows the first vertical derivative of the Bouguer gravity anomaly data shown in Figure 7. The effect of the derivative calculation is to emphasize local density changes and, also, to remove regional gradients due to large (e.g. crustal) scale geological feature. The data of Figure 9 have also been upward continued, to a height of 120m, in order to reduce the noise level somewhat (i.e. to smooth the data).

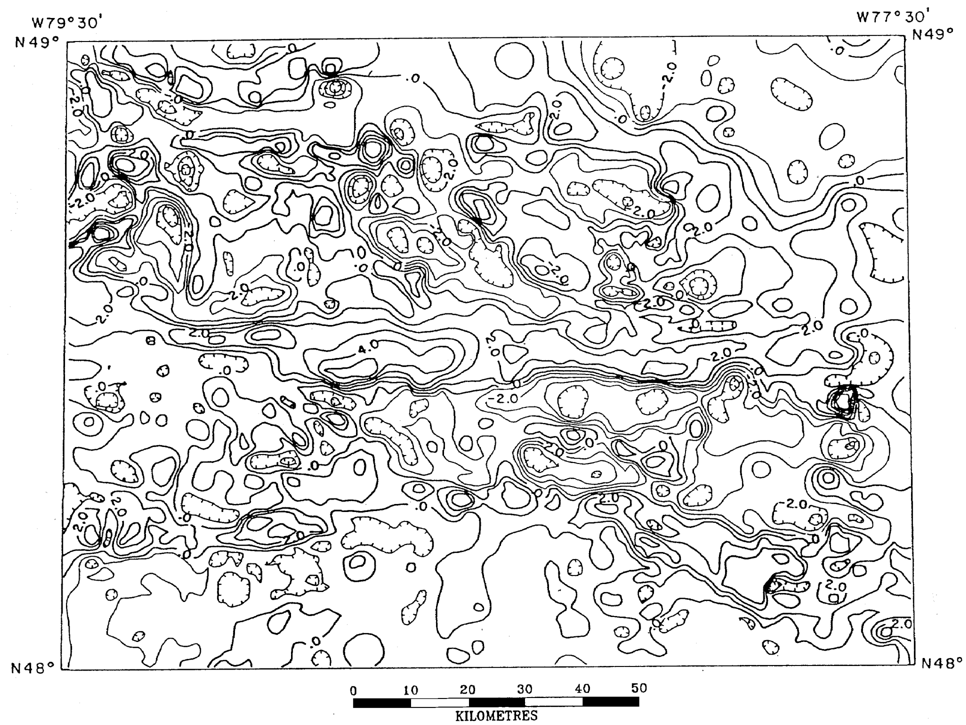


Figure 9 First Vertical Derivative of the Bouguer Gravity Anomaly of Figure 7 (after Keating) Upward Continued to 120m

Horizontal gradient presentation of Bouguer gravity anomaly data is also employed by the Geological Survey of Canada (e.g. see Sobczak et al 1992), to reduce regional gradients and to emphasize more local geologic trends. The computation employed by the Geological Survey of Canada, derives and plots the amplitude of the horizontal gradient vector (i.e. square root of the sum of the squares of the horizontal gradients in two orthogonal directions).

The geological formations of interest in a specific gravimetric survey usually have areal dimensions which are broadly known — e.g. some tens of metres in the case of very detailed surveys for archaeological or geotechnical surveys, to some tens or hundreds of km in the case of regional surveys for geological mapping or crustal study purposes.

Where the dimensions of the survey area are far greater than the dimensions of the targets of specific interest, there will be, superimposed on the gravity anomalies due to these targets, the longer wave length anomalies due to larger and deeper structures. The latter anomalies give rise to what may be termed *regional gradients*, which tend to somewhat distort the shorter wave length gravity anomalies due to the targets. The removal of regional gradients helps to bring the target anomalies into clearer focus and facilitate their interpretation.

The removal of regional gradients may, in small survey areas, be done by a visual inspection of selected profiles. This is a matter of subjective judgement and, therefore, is something of an art. It may be done, more objectively, by computer, using a high-pass, two-dimensional filter, with a spacing much greater than the dimensions of the target bodies, e.g. see Pawlowski, 1994. Some distortion of the target anomalies will result, however.

Digital *image processing* by computer is gaining popularity as a means of significantly improving the structural interpretation that may be made from contour plans of geophysical data, including gravity. One technique that is favoured is the use of *sun-angle illumination* for selective directional filtering (e.g. see Seigel, 1989), with grey-scale, monochrome presentation.

Computer-based colour-contour plotting also enhances the structural interpretability of gravity data and has become more common since the availability of low cost colour plotters.

Computer software programs which permit the above-mentioned presentations of gravity data to be made are available from software service companies and from gravimeter manufacturers.

INTERPRETATION OF GRAVITY DATA

The objective of all gravimetric surveys is to deduce the subsurface distribution of density, and, thereby, to obtain information about the distribution of the subsurface geological formations and their structures, as well as variations in the nature and thickness of the overburden. In turn, this provides information which is pertinent to the specific purpose of the gravimetric survey, be it geological mapping, resource exploration, geotechnical or environmental, etc.

Equation (4) on page 1 gave us the basic formula for calculating the gravity effect of a buried object. We can, however, only detect the gravity anomaly $\Delta\mathbf{g}$ due to that body, which arises because of its density contrast $\Delta\mathbf{d}$ with the other rocks in the area. We may then rewrite Equation (4) as:

$$\overrightarrow{\Delta \mathbf{g}} = \mathbf{G}\int \frac{\Delta \mathbf{d} \cdot \vec{\mathbf{r}}}{\mathbf{r}^3}\mathbf{dV} \qquad \textbf{(27)}$$

integrated over the volume **V** of the object.

There are two approaches to the interpretation of gravity data. These are known as the *forward* or *indirect* and *inverse* or *direct* approaches. In the forward approach, one sets up simple geometric models of geologic formations and structures, assigns them individual densities, and calculates their gravity anomalies in the region of measurement. In the inverse interpretation, one attempts to directly invert the gravity data to determine the distribution of subsurface densities.

The latter approach is rarely used, for the very good reason that there are many possible distributions of density which can cause the observed gravitational field variations. For example, a rather broad positive gravity anomaly, which might be attributed to a deeply buried higher density, source could also be caused by a broader distribution of shallower high density sources. Of course, this same fundamental uncertainty applies, as well, to the forward solution approach.

Essential to any approach to interpretation of gravity data is a sound understanding of the local geology, and therefore of the models which may most likely approximate the subsurface geology. One then incorporates these models into the forward solution, and adjusts their parameters (dimensions, shapes and densities), to obtain the closest desired fit to the observed gravity anomaly data. Interpretation thus becomes an iterative process, and is (properly so) highly subjective, that is, biased by the interpreter's hypothesis of the more likely geological structures in the area.

There are, however, two applications of inverse interpretation that are not subjective. These are the determination of excess mass, and the production of an equivalent apparent density map.

DETERMINATION OF EXCESS MASS

If we have the distribution in a plane **A**, of the gravity anomaly $\Delta \mathbf{g}$ due to a single causative body, after removing any regional gradients, then we can calculate the total excess (or deficit) mass, $\Delta \mathbf{M}$, of the body, relative to its surrounding rocks. This is based on Gauss' theorem (e.g. Grant, 1965).

$$\Delta \mathbf{M} = \frac{\mathbf{1}}{\mathbf{2\pi G}} \iint_{\mathbf{A}} \Delta \mathbf{g}(\mathbf{x}, \mathbf{y}) \mathbf{dx\,dy} \qquad \mathbf{(28)}$$

If **X** and **Y** are in m, and $\Delta \mathbf{g}$ is in mGal,

$$\text{then } \Delta \mathbf{M}(\mathbf{tonnes}) = \mathbf{1.5} \times 10^{\mathbf{2}} \iint \Delta \mathbf{g}(\mathbf{x}, \mathbf{y}) \mathbf{dx\,dy} \qquad \mathbf{(29)}$$

If one may assume that the density of the body is $\mathbf{d_1}$ and that of its surrounding rocks is $\mathbf{d_0}$, then the total mass **M** of the body is given by

$$\mathbf{M} = \left(\frac{\mathbf{d_1}}{\mathbf{d_1} - \mathbf{d_0}}\right) \Delta \mathbf{M} \qquad \mathbf{(30)}$$

An example of the useful application of this theorem to an actual exploration case history is given by Seigel, 1957, and Figure 10 on page 67 of this treatise. This case history concerns the discovery of the Mobrun Cu-Zn-Ag-

Au ore body. This is a massive pyritic body in a precambrian volcanic environment. The density of the pyrite was taken to be 4.6 g/cm^3. The density of the volcanics was taken to be 2.7 g/cm^3. The excess mass $\Delta\mathbf{M}$ was calculated, by integration using Equation (29), to be 1.5 million tonnes. The total mass **M** was calculated by 24 to be 3.6 million tonnes. The actual body of massive pyrite was later found, by drilling to total about 3 million tonnes to 300m depth.

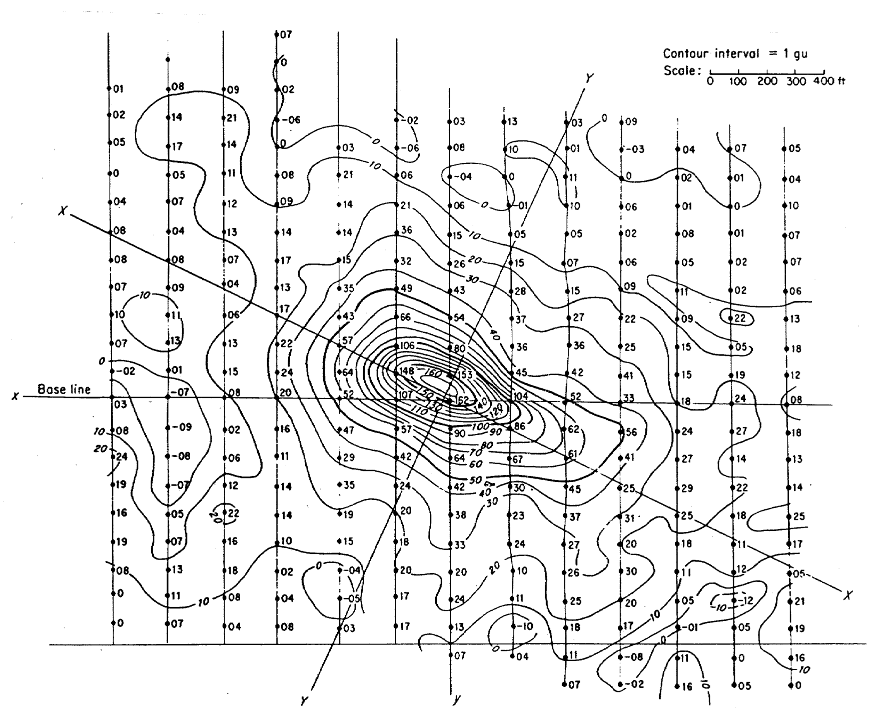


Figure 10 Bouguer Gravity Anomaly Contour Plan Mobrun Mine, Quebec (after Seigel) Contour Interval 0.1 mGal (10gu)

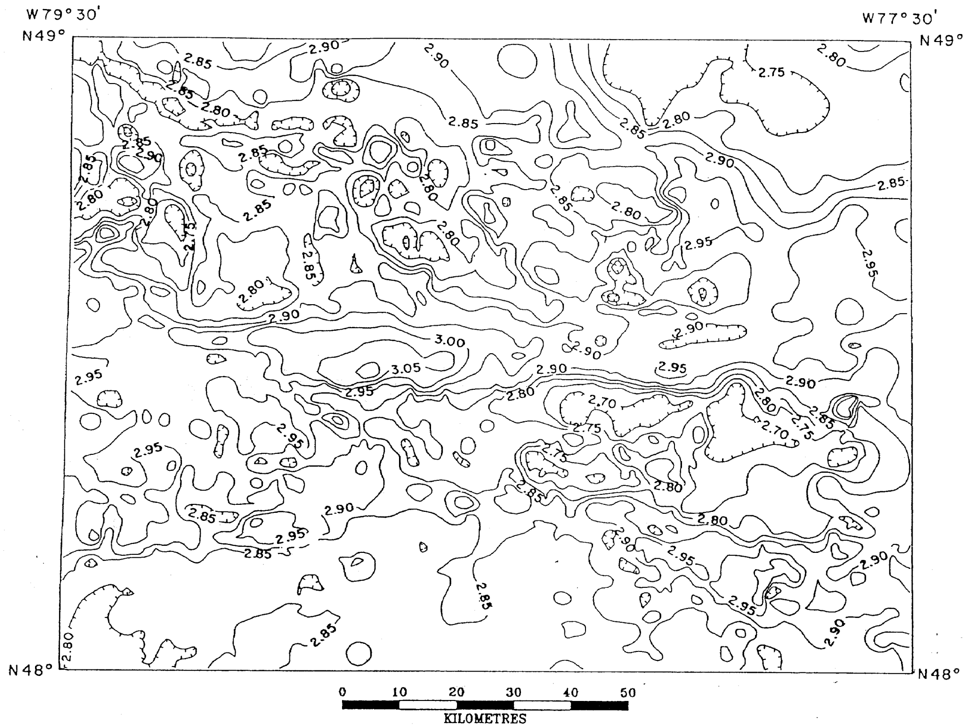


Figure 11 Apparent Density contour Plan (after Keating)
Contour Interval 0.05g/cm^3

APPARENT DENSITY MAPS

In areas of steeply dipping rock formations one may produce an apparent density map, based on the model of vertical-sided, right rectangular prisms extending to a certain depth, each with a constant but unknown density, (Keating, 1992). Figure 11, from Keating, 1992, shows the apparent density contour plan, obtained from the gravity anomaly data, for the area shown in Figure 7 on page 61.

Two Dimensional Models

The most convenient method of interpretation of the gravity anomalies due to bodies of long strike extent, is to use a two dimensional approximation, where the cross-section of the body **S** is assumed to be constant and its strike extent is unlimited. Figure 12 shows such a cross-section.

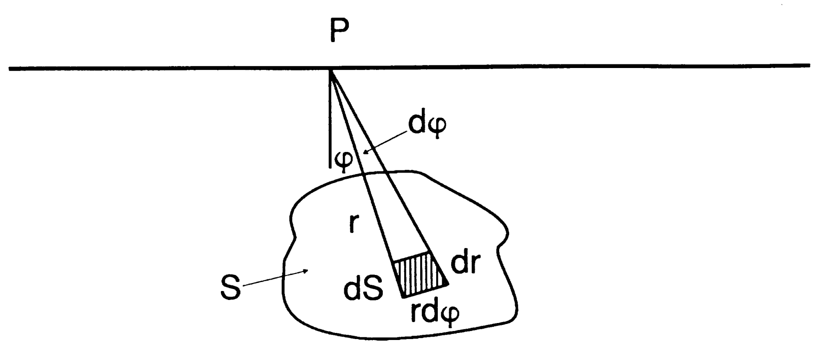


Figure 12 Gravity Computation Basis for Two Dimensional Bodies

The vertical gravitational effect at point **P** of the horizontal prism, of area **ΔA** (**dr** * **rd** φ) may be shown to be, (Grant, 1965)

$$\Delta \mathbf{g} = \mathbf{2G\Delta d\cos\varphi d\varphi dr} \qquad \mathbf{(31)}$$

where ø is the angle of the prism relative to the vertical at **P**, and **Δd** is the density contrast of the prism. If we sum the gravity effects of all such prisms over the cross sectional area **A** we can determine the gravity effect of the entire body with that cross-section.

$$\text{i.e. } \Delta \mathbf{g} = \mathbf{2G\Delta d}\sum \mathbf{\Delta\sin\varphi\Delta r} \qquad \mathbf{(32)}$$

We can accomplish this summation manually, by constructing a template which has equal angular sections **Δsin**φ and equal annular rings **Δr** and then superimposing this on the hypothetical section.

Interpretation

Figure 13 on page 71 shows one example of the application of such an approach to the interpretation of the gravity profile over the central section of the Mobrun ore body (Seigel, 1957). In this case, the precision of the curve fit was such that it enabled a rather accurate prediction of the thickness, density and dip of the pyritic ore body, to be made prior to its drilling.

Figure 14 on page 72 shows a gravity profile over a very large (90 million tonnes) lead-zinc ore body in the Bathurst, New Brunswick, area. The geological section, based on drilling, has been employed to produce a theoretical Bouguer gravity anomaly for this body, using the two dimensional approximation and manual computation, with a suitable template. Density values for the massive sulphide ore, for the adjacent iron formation and for the Ordovician host rocks, have been determined by measurements on core samples.

There is reasonably good agreement between the observed and theoretical Bouguer anomaly profiles. Both provide a peak anomaly of about 4.5mGals over this large ore deposit.

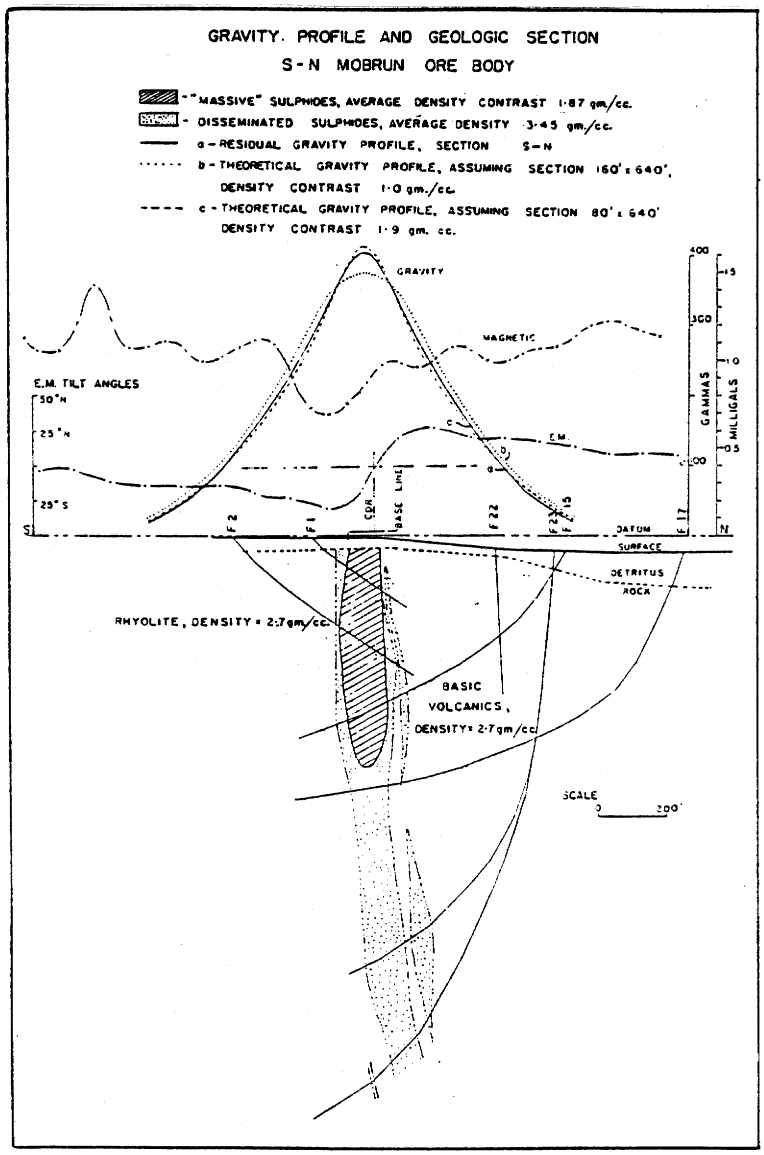


Figure 13 Gravity (observed and theoretical) Magnetic and Electromagnetic Profiles, Mobrun Ore Body, Quebec (after Seigel)

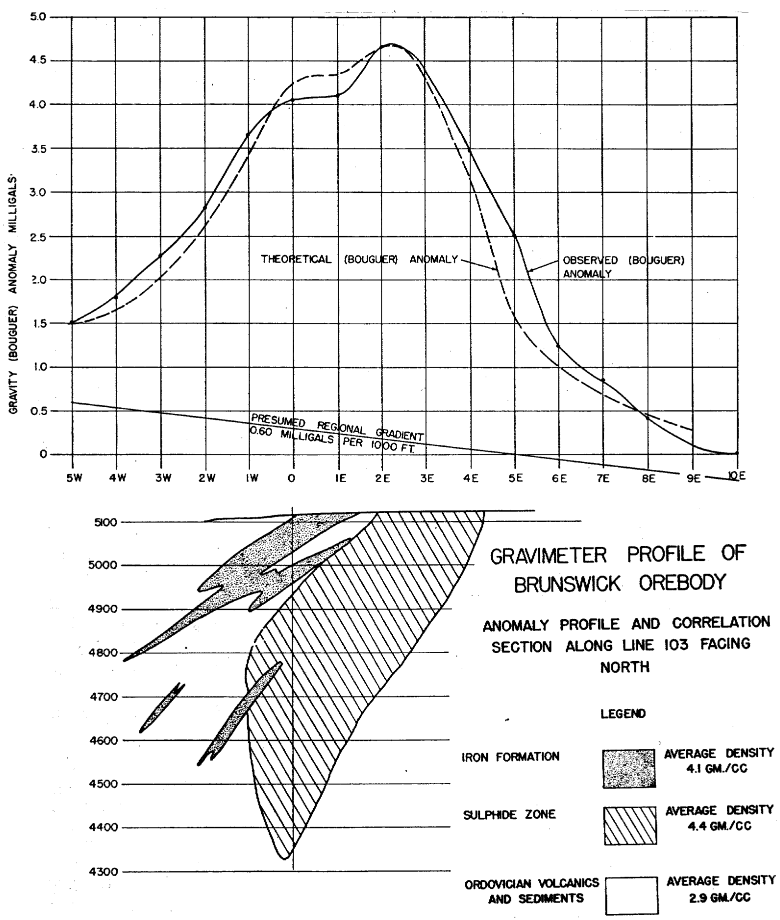


Figure 14 Bouguer Gravity Profiles (observed and theoretical) over Brunswick M & S Ore Body, New Brunswick (after Seigel) (distances in feet)

Figure 15 on page 73 (after Grant, 1965) shows the application of this interpretive approach to a gravity profile across the Salmon glacier in British Columbia. The observed gravity profile, after corrections for the mountainous topography, was curve-fitted, to achieve an excellent fit, as shown. The interpreted cross section of the glacier is shown, as well as the cross section based on drilling.

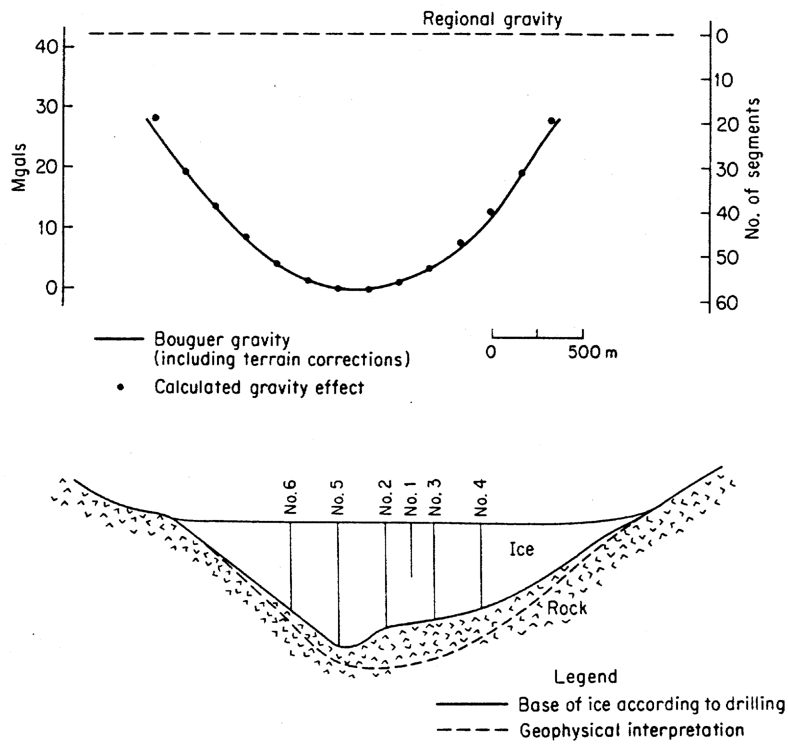


Figure 15 Bouguer Gravity Profile, Observed and Theoretical over the Salmon Glacier

Using a PC-based computing program, the same type of two dimensional interpretation may be made very quickly. Figure 16 on page 74 shows a fairly complex section, interpreted on the basis of a gravity profile in a sedimentary basin area. The agreement between the interpreted gravity profile and the observed one is excellent. This is more a tribute to the ease of constructing such an interpretive section using the computer, rather than, necessarily, to the validity of the interpretation; which has not yet been tested.

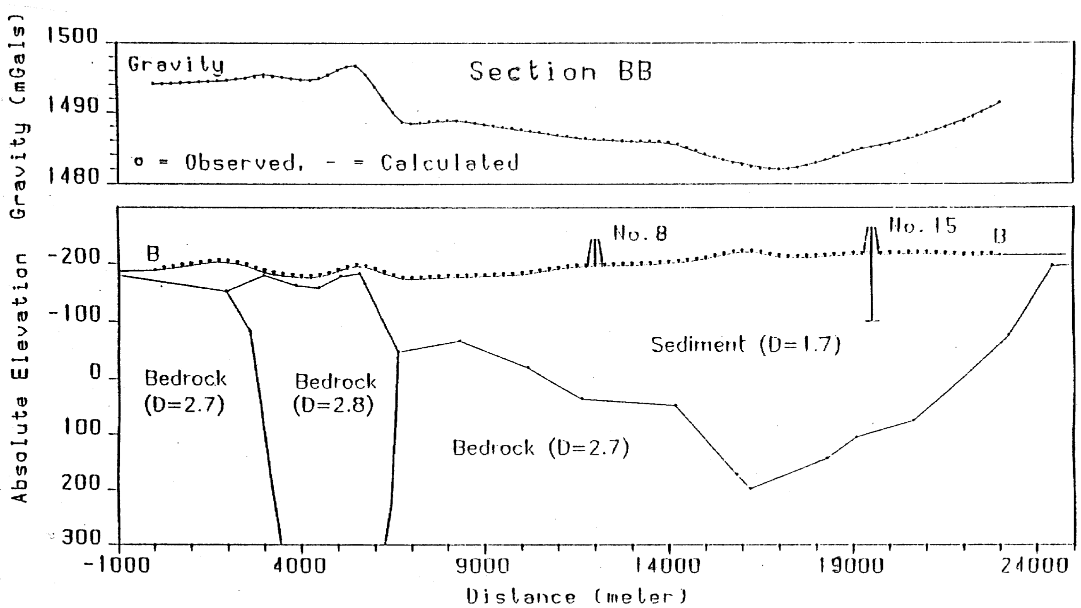


Figure 16 Bouguer Gravity Profile and Interpreted Section over Sedimentary Basin (Courtesy of Scintrex Ltd.) Distances in metres

Determination of Depth

As has been indicated above, there is no unique geological interpretation to any observed gravity data. Thus, the depth to the source of a specific gravity anomaly cannot be precisely determined.

Some approaches to depth determination include Grant, 1965 (pages 283-286) for *step* models, i.e. fault blocks, and Abdelrahman 1993 and 1993A.

Regardless of the approach employed, it must be borne in mind that all that can be determined is the maximum depth to the source of an observed gravity anomaly.

Example: To illustrate this limitation, let us consider a simple model. As stated in *Section 2*, the gravitational attraction of a sphere of uniform density is the same mathematically as though its entire mass was concentrated at its centre.

Figure 17 shows two concentric spherical bodies, each of which has its centre at 150m depth. One sphere (**A**) has a radius of 50m and a density of 3.40 g/cm^3. It could represent a 2 million tonne base metal sulphide body.

The second sphere (**B**) has a radius of 100m and a density of 2.70 g/cm^3. This could represent a granodiorite intrusive body. The host rock containing both spheres has a density of 2.60 g/cm^3. It could be acid to intermediate volcanics, for example.

Since the excess mass and depth to centre of each of these spherical bodies are identical, then their gravity anomalies at surface will be identical in every respect. This will be true despite the fact that the upper surface of sphere **A** is buried at 100m depth and that of sphere **B** at only 50m depth.

Whereas both bodies will be equally detectable by gravity measurements, their relative importance may have to be determined by other means.

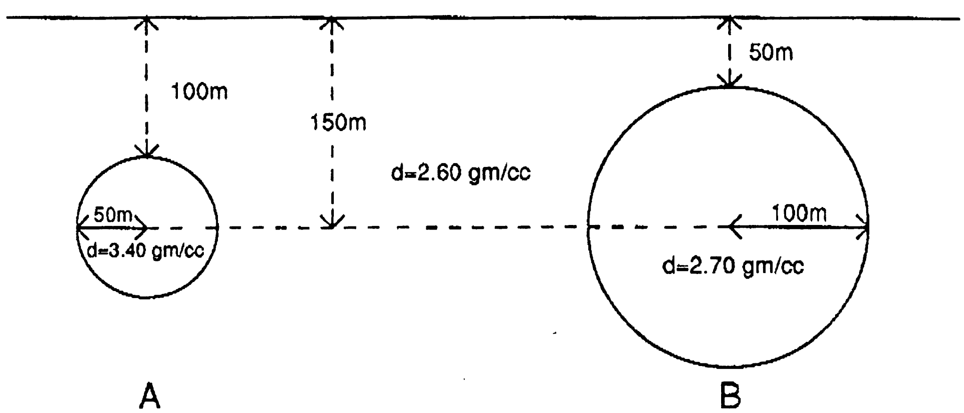


Figure 17 Non Uniqueness of Depth Determination

Interpretation

CASE HISTORIES

In Section 3 we have listed the main fields of application of gravimetric surveys. To illustrate various aspects of data presentation and interpretation we have already referred to some case histories. We will now use these, as well as provide a number of other case histories, to illustrate the contribution of the gravity method to these applications.

GEOLOGICAL MAPPING

The gravity method is one of the most effective means for mapping the subsurface geology. It is particularly useful in differentiating rock types which are not distinguishable by virtue of their magnetic or electrical properties.

Figures 7 and 11, by Keating, 1992, show how the results of regional gravimetric surveys can be inverted to produce a density map of the subsurface rocks. This density map, in turn, may be used to produce a geologic map of the area, based on measurements of samples, and/or on reasoned assumptions about the density of the rock formations in the area. Of course, the resultant geologic map will have to incorporate, and be consistent with, all known geological information and the available magnetic maps of the area.

PETROLEUM EXPLORATION

In petroleum exploration, gravimetric surveys are second in importance only to seismic surveys. They are commonly employed, on a regional basis, to determine the general configuration of sedimentary basins in advance of seismic programs.

We may take Figure 16 as an example of a sedimentary basin (lower density) lying on crystalline rocks (higher density), which can be mapped by a gravimetric survey to determine its approximate dimensions.

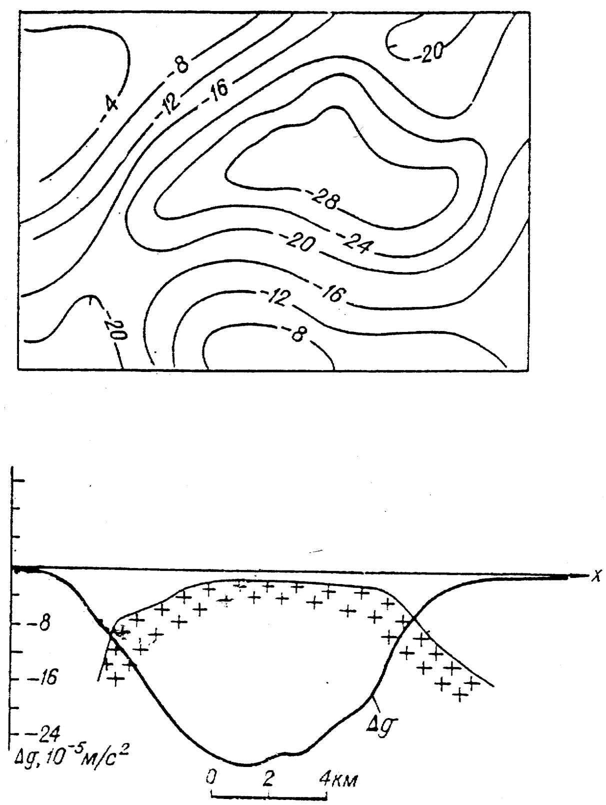


Figure 18 Bouguer Gravity Anomaly Contour Plan (Contour Interval 4 mGal) and Profile over Salt Dome (after Mironov)

As a special case of petroleum exploration we may readily determine the location and dimensions of a salt dome. As Table I on page 11 indicates, the specific gravity of salt (2.22 g/cm^3) is less than that of most consolidated sedimentary rocks (2.35 to 2.70 g/cm^3) in which it is emplaced. Figure 18 (after Mironov, 1980) shows a gravity depression of about 26 mGal over a salt dome about 12 km in diameter. Both a gravity anomaly contour plan (4 mGal contour interval) and a section over the salt dome are shown.

COAL EXPLORATION

The basin of Figure 16 on page 74 is, in fact, of interest for soft coal (lignite). Figure 19 (Mironov, 1980) shows the gravity anomaly contour plan over a coal basin in northern Australia. Bedrock basement outcrops are shown as crosses. Contours are in mGal. In both examples, negative gravity anomalies of the order of 10 to 20 mGal clearly show the shape of the sedimentary basin and will serve to guide exploratory drilling.

As Table I on page 11 shows, all types of coal have very low densities ranging from about 1.19 g/cm^3 for lignite to 1.5 g/cm^3 for anthracite. Other things being equal, therefore, the areas of larger negative Bouguer gravity anomalies, within the sedimentary basin, are more favourable for the occurrence of the thicker coal beds.

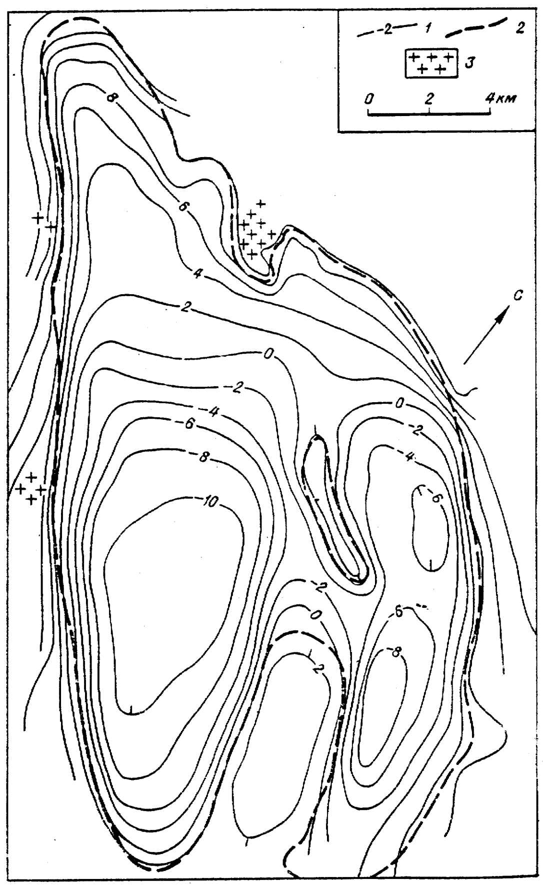


Figure 19 Bouguer Gravity Contour Plan over Coal Basin (after Mironov)

Mineral Exploration

Base Metal Exploration

The gravity method can often map the distribution of massive sulphide base metal deposits in a reasonably direct fashion, because of the relatively high density of metallic sulphides, including pyrite, pyrrhotite, which constitute the bulk of the ore deposits themselves. As Table I on page 11 indicates, the mean density of pyrite is 5.0 g/cm^3; of pyrrhotite is 4.65 g/cm^3, and of the ore minerals the mean densities range from 3.75 g/cm^3 for sphalerite to 7.5 g/cm^3 for galena.

We have already seen, in Figure 10 and 13, that a massive pyrite body (Mobrun) of about 3 million tonnes, gave rise to a very distinctive anomaly, of about 1.6 mGal peak amplitude. It should be noted that the gravimetric survey over this body contributed materially to its discovery, as it is quite non-magnetic. In addition, the gravimetric survey provided guidance to the exploratory drilling program.

Figure 20 on page 81, (after Seigel, 1968), demonstrates that a gravimetric survey can map the distribution of a bedded lead-zinc deposit, the Pyramid ore body, North West Territories, Canada, which is low in pyrite or pyrrhotite, but high in sphalerite and galena. A clear-cut, broad positive anomaly, of peak amplitude 0.8 mGals, maps the distribution of the flat-lying lead-zinc body. Since the body is not magnetic, and since it is high in sphalerite, which is not electrically conducting, the gravity anomaly contour plan provided the best guidance for the subsequent drilling program. Figure 21 on page 82, (Seigel, 1968), presents all the various geophysical results and the geological section (from drilling) on a central section of this ore body. It shows that the gravity results most clearly define the distribution of this body.

The Pyramid body contained over 12 million tonnes of 12% combined lead and zinc.

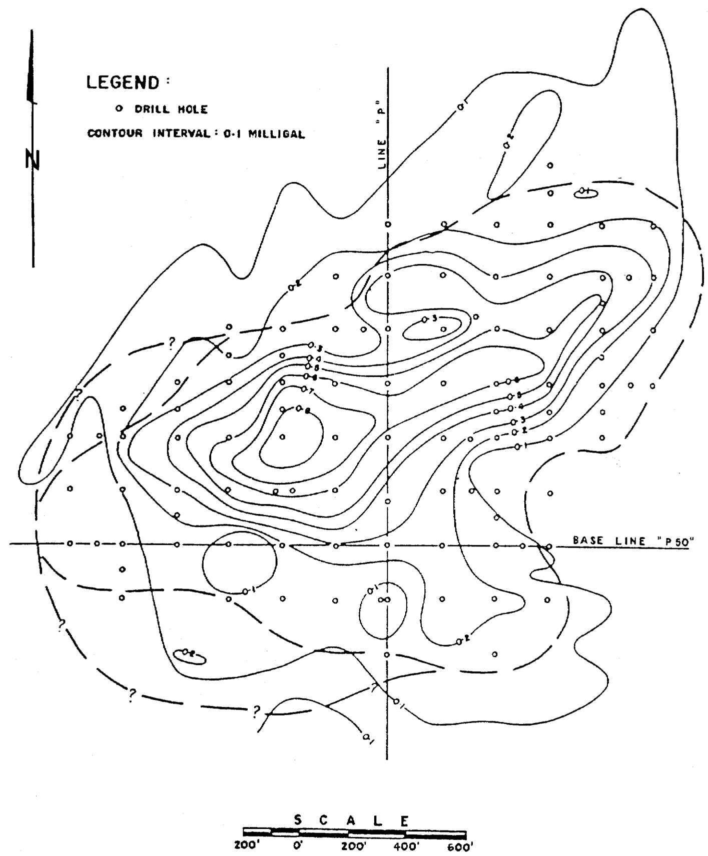


Figure 20 Bouguer Gravity Contour Plan, Pyramid Ore Body (after Seigel) Contour Interval 0.1 mGal

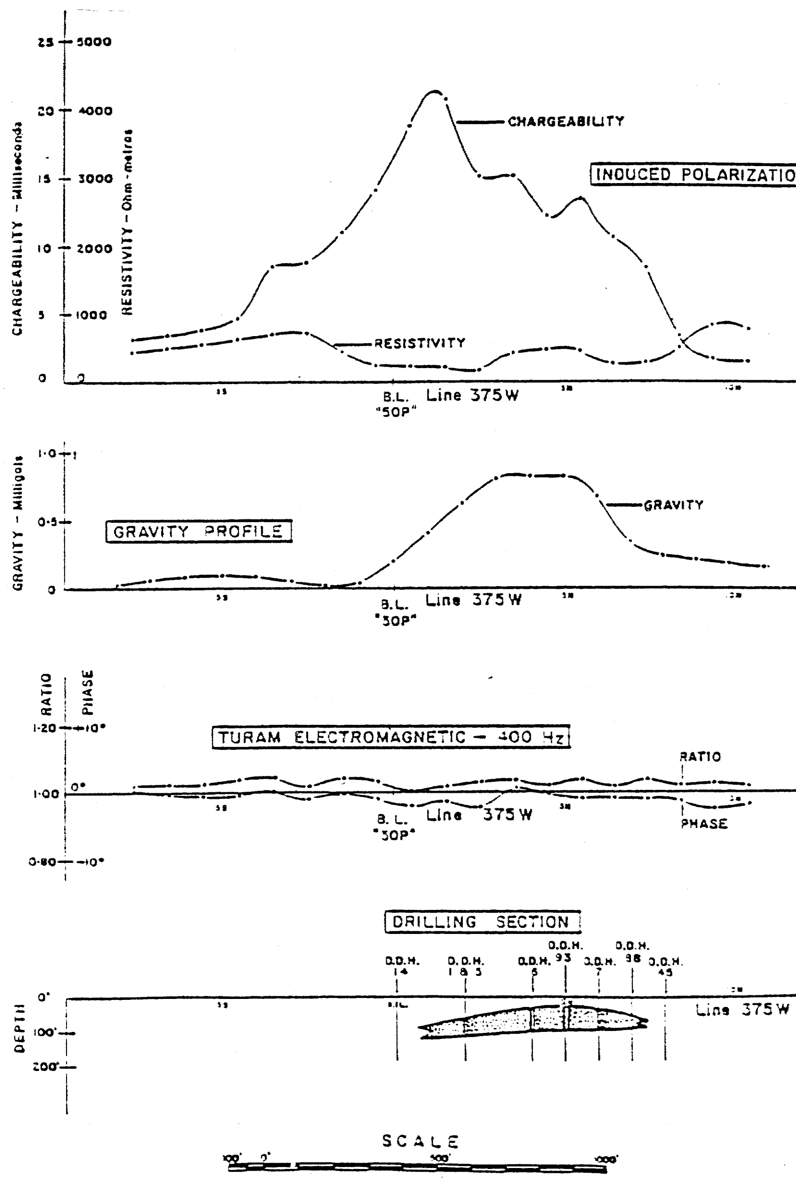


Figure 21 Multi-Geophysical Method Profiles, Pyramid Ore Body (after Seigel)

Chromite Exploration

Figure 22 (Mironov, 1980) shows a gravity anomaly contour plan of a Russian chromite deposit. A positive gravity anomaly of the order of 1.2 mGal is to be seen. As can be seen from Table I on page 11, chromite has a mean density of 4.36 g/cm^3, which is about 1.4 g/cm^3 higher than the basic intrusive rocks in which it normally is found.

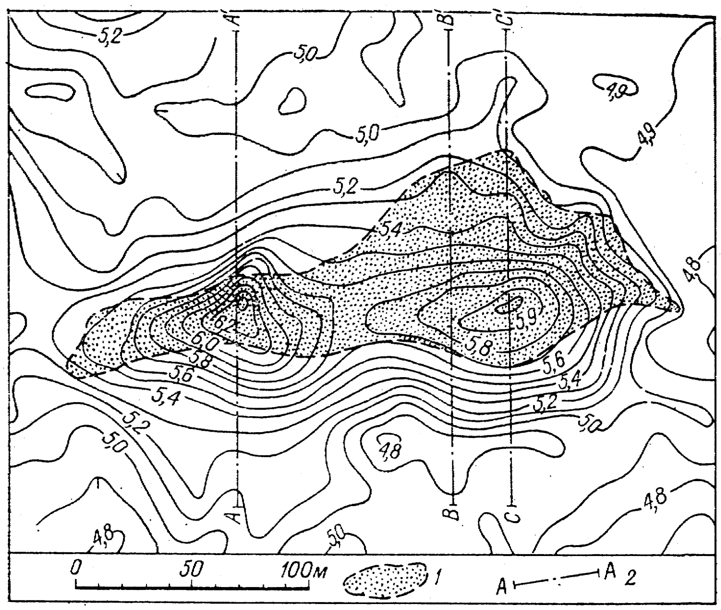


Figure 22 Bouguer Gravity Anomaly Contour Plan over a Chromite Deposit (after Mironov)
Legend: Contour Interval — mGals
1. Outline of Deposit

KIMBERLITE EXPLORATION

Figure 23 on page 84 (Mironov, 1980) shows the use of the gravity method to differentiate between intrusives of kimberlite (upper example) and trap rock (lower example) into limestones. Both intrusives show up as positive magnetic anomalies ($\Delta\mathbf{Z}$). However, the kimberlite shows up as negative gravity anomaly, $\Delta\mathbf{g}$, while the trap rock shows a positive gravity anomaly. (Unfortunately, no scale is given for the gravity profiles).

The density of kimberlites (2.33 – 2.60 g/cm^3) is somewhat less than that of carbonate rocks (2.40 – 2.65 g/cm^3), which is still less than that of trap rocks (2.7 – 3.1 g/cm^3). In addition, kimberlite weathers readily near surface, which reduces its mean density still further.

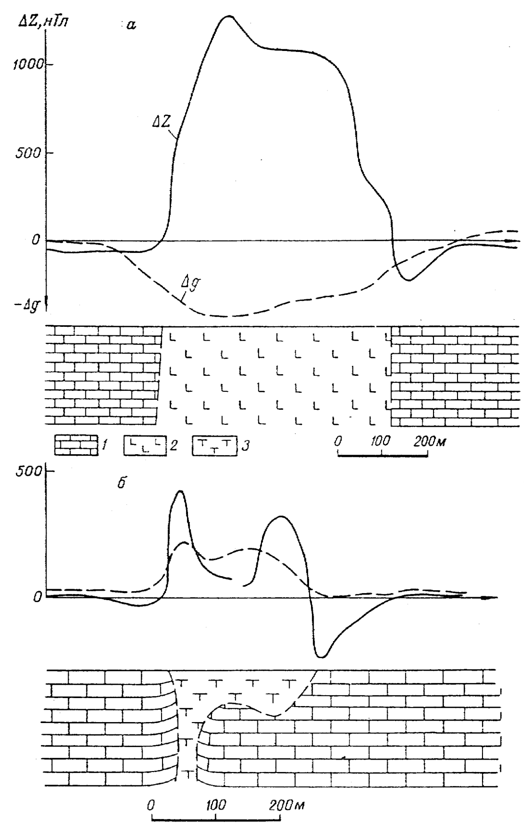


Figure 23 Gravity and Magnetic Anomalies over Kimberlite (upper) and Traprock (lower) Intrusives (after Mironov)
Legend: 1. Carbonate Rocks 2. Kimberlite 3. Traprock

BAUXITE EXPLORATION

Figure 24 (Mironov, 1980) shows negative gravity anomalies related to deposits of bauxite and bauxite-clays in a contact zone between limestones and siltstone, which are covered with overburden. (Unfortunately, no distance scale is given for these two sections).

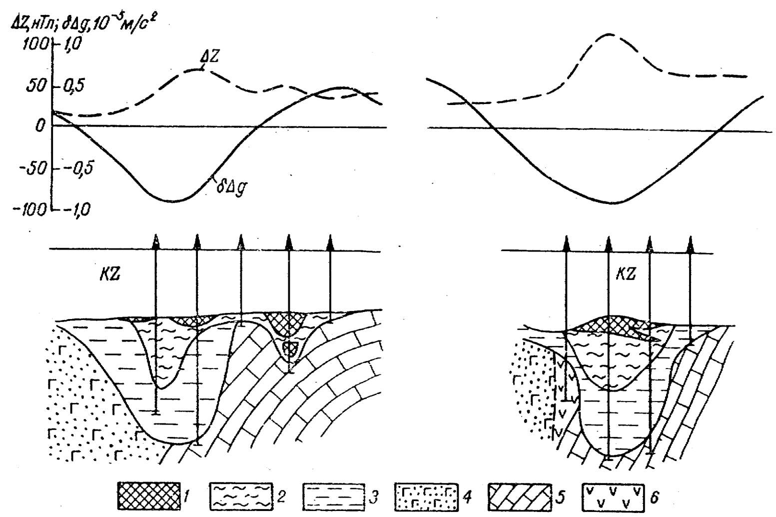


Figure 24 Bouguer Gravity (Δg) and Magnetic Profiles (Δz) over Bauxite Deposits (after Mironov)
Legend: 1. Bauxite
2. Bauxitic Clay
3. Speckled Clay
4. Tuffaceous Siltstone
5. Limestone
6. Diorite, Diorite Porphyry

Case Histories

GEOTECHNICAL STUDIES

The mapping of subsurface cavities, of either natural or man-made origin, is important from a geotechnical standpoint.

Figure 8 on page 62, (Yuhr, 1993) shows gravity and electromagnetic profiles over a paleokarst collapse structure, in limestone terrains, in western Texas. A gravity depression of about 0.3 mGal amplitude clearly shows the lower density zone characterising this structure.

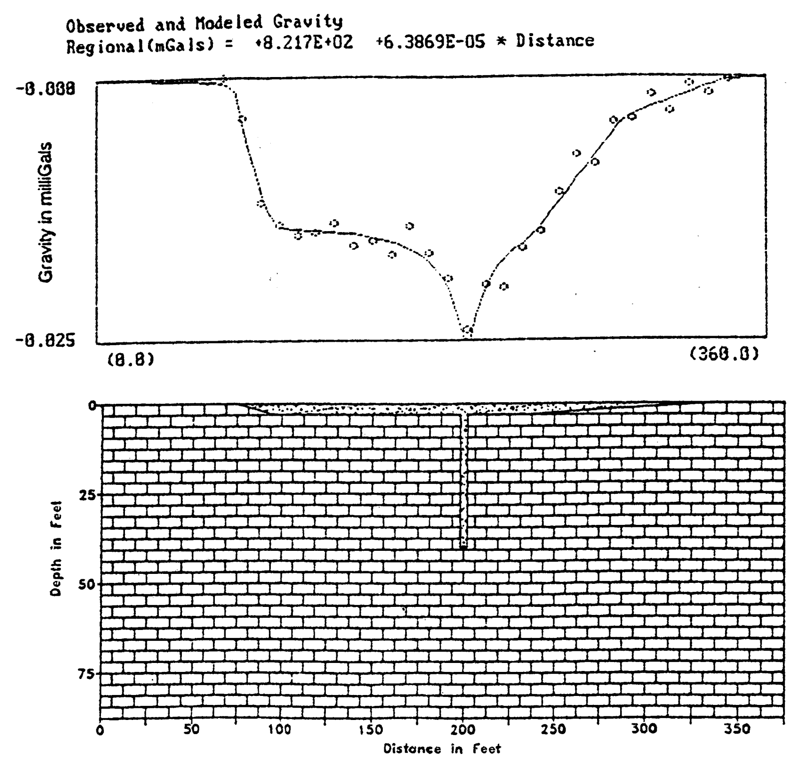


Figure 25 Observed and Modeled Bouguer Microgravity Profiles over Alluvium — Filled Dis-solutioned Joint in Limestone (after Yuhr)

In the same area, Figure 25, shows a much smaller (0.01 mGal) anomaly, marking a single vertical dis-solutioned joint (alluvium filled) in the limestone, within a broader gravity depression. Clearly, very precise microgravity measurements are required in order to provide such detail.

Figure 15 on page 73 shows the mapping of the cross section of the Salmon glacier in British Columbia, Canada. The quantitatively interpreted section agrees rather well with the section determined from drilling.

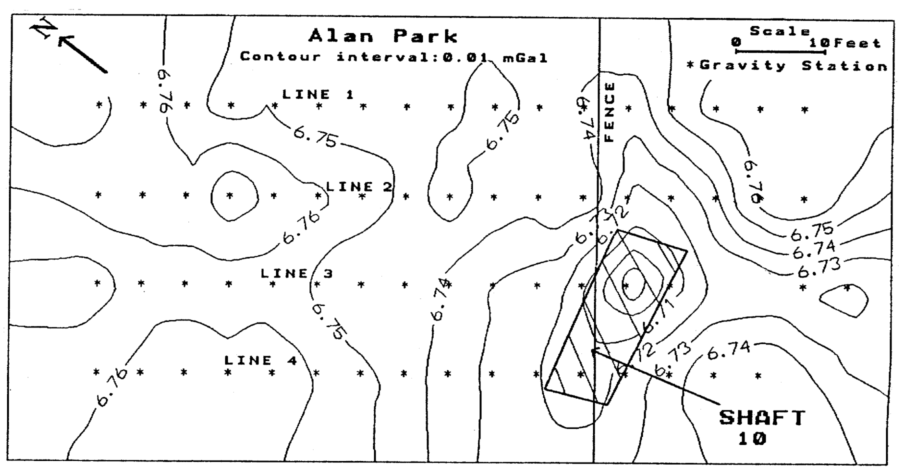


Figure 26 Bouguer MicroGravity Anomaly over Buried Mine Shaft, (after Ghatge) Contour Interval 10 μGals

Figure 26, (Ghatge, 1993) shows the results of a microgravimetric survey over a section of the former Schuyler Copper Mine, in northeastern New Jersey. The object of this survey was to locate abandoned shafts, some of which are now beneath houses and form a considerable hazard. Very detailed gravity measurements were made, at 5 foot intervals on lines only 10 feet apart. A local gravity depression of only 0.06 mGal marks the location of the abandoned Shaft 10.

ENVIRONMENTAL STUDIES

There are numerous old landfill sites on which documentation is not available. Some are, in fact, now covered with soil and their very existence is unknown. The gravity method can determine their location and determine their approximate dimensions.

Figure 27 on page 89, (Roberts, 1989), shows the results of a gravimetric survey over a farm in Indiana, which contains a landfill site. The landfill area is marked by a negative gravity anomaly of the order of 0.26 mGal. The details of this anomaly provide the basis for determining the relative shape of the fill site, assuming that the density of the fill is uniform. Alternatively, where the original contours of the pre-fill land surface are known (as in this case), the relative fill density in different points of the site can be determined.

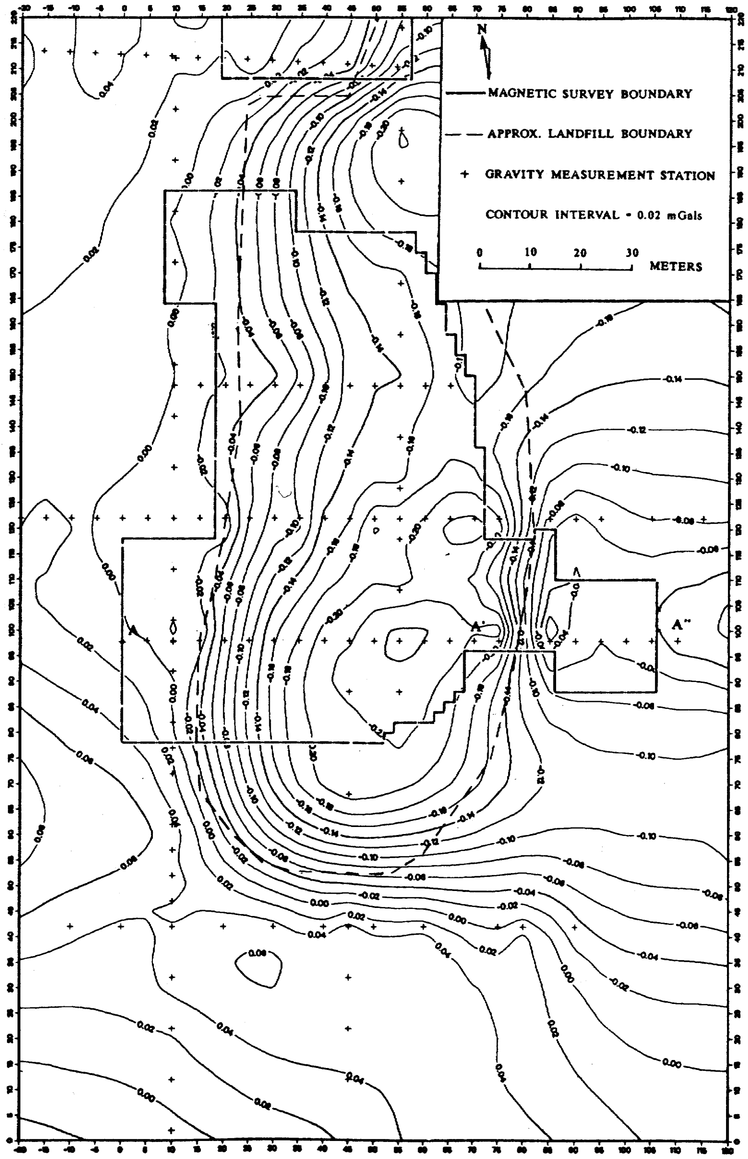


Figure 27 Bouguer Gravity Anomaly Plan of Landfill Site (after Roberts). Contour Interval 20 μGals

Archaeological Studies

An interesting example of the application of very precisely controlled and corrected microgravimetric surveys to archaeological problems is to be found in Lakshmanan 1987 and 1991. Very careful gravity measurements were made in, on and around the pyramid of Cheops, in Egypt, in order to locate possible secret chambers (voids).

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Note: These references marked * are particularly recommended for additional reading

THE CG—3M – A HIGH PRECISION, MICROGAL RESOLUTION, LAND GRAVIMETER, WITH WORLDWIDE RANGE

H.O. Seigel*, I. Brcic* and P. Mistry*

INTRODUCTION

The evolution of metrology in all fields of scientific endeavour has been a progression towards higher precision of measurement, coupled with a reduced dependence on the skill of the operator of the instrument. These, seemingly contradictory trends, have resulted from the incorporation of intelligence imbedded in the instrument. Until recently, however, the field of land gravimeter measurements has been an exception to this progression.

Truly, field portable land gravimeters first became available about 50 years ago (e.g. LaCoste North American), but these early units tended to have serious limitations in respect of their weight, gravity range and fragility.

These were followed, a decade later, by much smaller, quartz element instruments, which greatly facilitated the measurements of the earth's gravitational field (Frost, World-Wide and Worden).

* Scintrex Limited, Concord, Ontario Canada
August 23, 1993

The CG—3M

The introduction, in 1959 of the LaCoste-Romberg G meter established a plateau of technical development which, with some enhancements (D meter in 1967), remained the industry standard for three decades.

These latter instruments were based on the zero-length spring suspension. They were purely mechanical, with manual nulling of the proof-mass position. Their gravity-sensing element is made of Invar, or a similar iron alloy with a low temperature coefficient of expansion. These gravimeters are of the design known as *astatic*, they operate in a state close to unstable equilibrium, and this gives them great mechanical sensitivity. However, their linear range is very small, so that they are usually operated as null-reading instruments. That is, another external force is applied to the proof mass, to counterbalance the force of gravity, thus bringing the mass back into a standard or *null* position. It is then the amount of this restoring or nulling force which is taken as a measure of the difference in the gravity field. In the case of the LaCoste-Romberg meters, as in all other purely mechanical gravimeters up to that time, the restoring force is the torque of the auxiliary or reading spring.

When operated at their optimum, with very careful handling and transport, etc., in the hands of a highly skilled operator, these gravimeters can achieve a precision of measurement (S.D. of an individual measurement) of the order of about 15 microGals for the G meter and 8-10 microGals for the D meter.

Whereas the G and D meters remained the standard for land gravity measurements for so long, they had certain shortcomings, which were all well known, but accepted, because no better alternative was available. Some of these shortcomings include:

1. Non-linear scale factor, requiring the use of a calibration table to convert the dial readings to gravity differences
2. Periodic (circular) error due to micrometer screw imperfections
3. Susceptibility to *sets* due to shocks in transport or reading, necessitating very careful handling at all times (despite being clamped between readings)
4. Possible susceptibility to the influence of strong magnetic fields, despite the metal of the element being demagnetised and a μ-metal shield placed around it

5. Possible susceptibility to the influence of pressure changes, despite the use of a buoyancy compensator and
6. A great deal of subjective judgement is required on the part of the operator, in order to obtain the optimum precision of measurement, thus requiring a long period of training and survey experience in order to qualify

Gravity measurements are of value in respect of many applications of the geosciences, including geological mapping, resource development, hydrogeology, civil engineering, the environment and even archaeology. Some applications require a high precision of measurement, i.e.: a resolution of 1 microGal and a S.D. of 5 microGals or better (e.g. Butler, 1984; Lakshmanan, 1991). These are becoming more common. They include:

- in civil engineering: the search for voids and fissures in karst areas, old mining areas, etc.
- in hydrogeology: karstic zones and alteration zones; mapping all alluvial thickness
- in archaeology: location of small, subsurface voids and man-made structures
- in resource development: mapping of small, near surface structures and deposits
- in tectonic studies and volcanology: mapping of small changes in gravity with time, which reflect tectonic movements and magma changes
- in geothermal production: periodic measurements to determine changes in the level of water in the reservoir

For these applications, gravity differences of the order of 10-20 microGals may be very significant, and precision of measurement of the order of 5 microGals or better is required. For this reason, such measurements are termed *microgravimetry.*

For microgravimetry, the LaCoste D meter has been, until recently, the only instrument available. The D meter has a resolution of 1 microGal and a stated "repeatability of 5 microGals and accuracy better than 10 microGals". Unfortunately, the range of the high resolution measurement, without coarse reset, has been only 200-300 milliGals on the D meter.

The CG—3M

It has been clear, for some years, that there was a need for a high-precision land gravimeter, with worldwide range without resetting, for microgravimetry as well as geodetic measurements of the earth's gravitational field. In addition, such a new-generation gravimeter should be so designed as to avoid the shortcomings, listed above, of the existing gravimeters. It should employ modern techniques of electronic measurement, signal processing and data storage, and be as automatic reading as possible in order to reduce the dependence on the skill and training of the operator. In addition, it should make real-time corrections for the more common sources of gravity variations, such as long term drift, tidal gravity effects, ambient temperature fluctuations and residual tilt errors.

The Scintrex CG-3 and CG-3M Gravimeters

Development Objectives

Starting in 1984, Scintrex embarked on the ambitious task of creating a new generation of land gravimeters which would match or exceed the precision of the LaCoste meters, but which would avoid many of the limitations of all previous meters. The desired characteristics which were targeted include:

1. Straightforward to Manufacture —This meant departing from the astatic principle, with its critical dependence on dimensional precision.

2. Mechanical Simplification —This meant replacing some of the mechanical complexity of the astatic meters with electronic circuitry to achieve the same high sensitivity, with the ease of replication and suitability for routine production inherent in the use of electronics. It also meant eliminating the use of micrometer screws and gears, with their mechanical imperfections.

3. Tolerance of Rough Field Use —This meant utilizing a fused quartz element, with its inherent super-elasticity and greater freedom from sets. A corollary of using a quartz element is also freedom from the effects of external magnetic fields.

4. Freedom From Ambient Temperature Variations—This means a high degree of temperature stabilization, through thermostatting the sensor, and is most effectively accomplished by having no mechanical feedthroughs which would conduct heat into the sensor.

5. Worldwide Range.—With a resolution of 1 microGal, without the need for any mechanical reset mechanisms.

6. High-Precision Measurements —With a S.D. of the order of 5 microGals or better.

7. Electronic and Software Control of the Measurement — This carries with it freedom from the subjective judgement of the operator in making the measurement. It also allows for many novel and useful features such as intelligent signal processing, correction for tilt errors and tidal effects, etc., as we shall see below. It implies the elimination of micrometer screws and gear boxes, with their mechanical imperfections and limitations on linearity, etc.

On commencing this task, Scintrex started with the benefit of 25 years of manufacture of quartz element astatic gravimeters, the CG-2. It also had a solid foundation in microprocessor based electronics and software which could be applied to the problem. In addition, we were able to utilize the talents and experience of Dr. Andrew Hugill, an Australian physicist, who had done his Ph.D thesis in the field of gravimeter development.

Despite all these advantageous beginnings, it still required almost six years of hard work and almost $1 million to produce, the CG-3 (10 microGals resolution) gravimeter. It required an additional two years to produce the CG-3M, the high precision (1 microGal resolution) gravimeter. The main reason why is illustrates by Figure 1, which shows the basic principles of the stable gravimeter. This shows a single, vertically suspended spring, which supports a mass M. Changes in the pull of gravity on the spring causes a proportionate change in the length of the spring. Simplistically, if we could measure such changes with sufficiently high precision, we could measure the changes of the gravitational field.

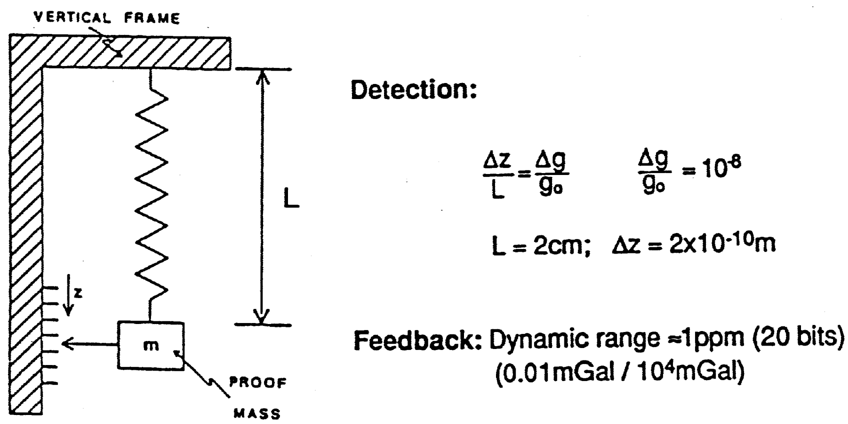

Figure 1 Principle of Operation of a Stable Gravimeter

However, using *Hooke's Law*, we find that to measure gravity changes to 1 microGal, i.e. to about one part in 10^9 of the earth's normal gravity, we must detect a fractional change in the spring length of the same order, i.e. to the order of 10^{-11}m. Until recently, this was simply not feasible in a portable instrument.

We chose to work with fused quartz, rather than using an iron/nickel alloy (invar) for the various reasons given above, and we have had no reason to regret our decision.

Design Features

Figure 2 shows the basic construction of the CG-3 and CG-3M gravimeters. The gravitational force on the proof mass is balanced by a zero-length spring and a relatively small electrostatic restoring force. The position of the mass is sensed by a capacitative displacement transducer. An automatic feedback circuit applies a 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 system, is converted to a digital signal and then transmitted to the instrument's data acquisition system for processing, display and storage in solid state memory.

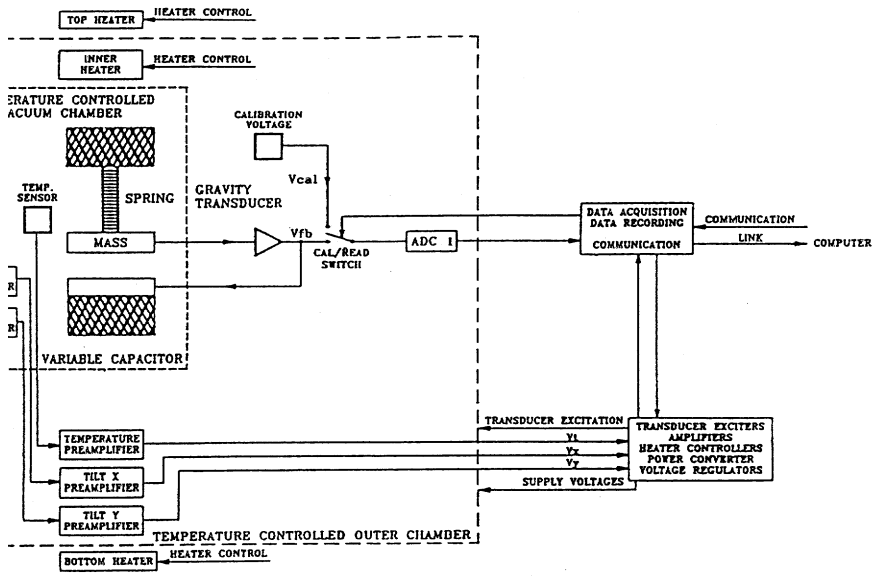

Figure 2 Basic Construction of the CG-3 and CG-3M Gravimeters

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 which supports the sensor within 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 milliGals without resetting. Low noise electronic design, including an auto-calibrating 23 bit analogue to digital converter, results in a resolution as high as 1 microGal, (CG-3M) thus equipping the gravimeter for both detailed field investigations and large scale regional surveys.

The sensor is enclosed in a sealed aluminum chamber to essentially eliminate the effect of external pressure changes. The most critical components, including the gravity and tilt sensors, are in a double oven, which reduces long-term external temperature changes by a factor of 100,000. A temperature sensor is in close proximity to the spring to provide a compensation signal for residual temperature changes. Such residual changes are usually less than 1m°K. Some of the other, less critical electronic components are in the outer oven, thermostatted to a fraction of °K.

The signal from the gravity sensor ADC is sampled once a second and the samples are averaged for sufficient time (depending on the ambient noise conditions) to reduce the random error to the desired level. Noise reduction is assisted by an algorithm which statistically rejects individual high noise readings.

Software corrections are made, in real time, for long term drift of the sensor, for residual sensor temperature variations, for sun and moon tides, and for tilt of the sensor out of the vertical.

For maximum safety and convenience, the entire gravimeter, including sensor and all electronics, is housed in one chassis. There are no dangling cables to endanger the instrument.

Figure 3 shows the CG-3M in operational mode in the field.

Figure 3 The CG-3M in Operation in the field

The CG-3 and CG-3M communicate with the outside world through an RS-232 port. Figure 4 shows a typical data print out, including station number, corrected gravity values; calculated standard deviation of one second samples; tilts out of the vertical (in arc seconds); internal residual sensor temperature variations in m°K; residual tidal correction; the number of one second gravity readings which have been averaged; the number of noisy readings rejected; and the time of the measurement.

```
-------------------------------------------------------------------------------
SCINTREX V4.1       AUTOGRAV / Cycling Mode          R4.4
Cycle Time:     150                                          Ser No:      8267.
Line:      2.  Grid:      0.   Job:      0.  Date: 95/05/08  Operator:       0.

GREF.:                   -4158. mGals          Tilt x sensit.:           296.5
GCAL.1:                 6131.436               Tilt y sensit.:           283.8
GCAL.2:                       0.               Deg.Latitude:              43.7
TEMPCO.:                 -0.1241 mGal/mK       Deg.Longitude:             79.6
Drift const.:               0.18               GMT Difference:            4.hr
Drift Correction Start  Time: 11:57:16         Cal.after x samples:         12
                        Date: 95/04/13         On-Line Tilt Corrected = "*"
-------------------------------------------------------------------------------
```

Station	Grav.	SD.	Tilt x	Tilt y	Temp.	E.T.C.	Dur	# Rej	Time
0.	41.684	0.041	2.	-2.	-0.69	-0.023	120	0	14:03:57
0.	41.685	0.037	1.	-3.	-0.67	-0.023	120	0	14:06:27
0.	41.684	0.044	2.	-3.	-0.65	-0.023	120	1	14:08:57
0.	41.683	0.031	1.	-3.	-0.65	-0.023	120	0	14:11:27
0.	41.682	0.036	1.	-3.	-0.65	-0.024	120	0	14:13:57
0.	41.682	0.034	1.	-3.	-0.64	-0.024	120	0	14:16:27
0.	41.680	0.033	2.	-3.	-0.64	-0.024	120	0	14:18:57
0.	41.682	0.045	2.	-3.	-0.64	-0.024	120	0	14:21:27
0.	41.681	0.036	2.	-3.	-0.64	-0.024	120	1	14:23:57
0.	41.681	0.038	1.	-3.	-0.64	-0.023	120	0	14:26:27
0.	41.683	0.038	1.	-3.	-0.64	-0.023	120	0	14:28:57
0.	41.679	0.042	1.	-4.	-0.63	-0.023	120	0	14:31:27
0.	41.681	0.034	1.	-4.	-0.64	-0.023	120	0	14:33:57
0.	41.682	0.043	2.	-3.	-0.64	-0.023	120	0	14:36:27
0.	41.680	0.035	2.	-3.	-0.64	-0.023	120	0	14:38:57
0.	41.681	0.037	2.	-3.	-0.64	-0.023	120	0	14:41:27
0.	41.679	0.037	2.	-3.	-0.63	-0.023	120	0	14:43:57
0.	41.682	0.032	2.	-3.	-0.63	-0.023	120	0	14:46:27
0.	41.683	0.039	2.	-3.	-0.63	-0.023	120	0	14:48:57
0.	41.681	0.039	2.	-3.	-0.64	-0.023	120	0	14:51:27
0.	41.679	0.049	2.	-3.	-0.64	-0.022	120	0	14:53:57
0.	41.679	0.039	2.	-3.	-0.64	-0.022	120	0	14:56:27
0.	41.678	0.038	2.	-3.	-0.64	-0.022	120	0	14:58:57
0.	41.682	0.040	2.	-3.	-0.63	-0.022	120	0	15:01:27
0.	41.681	0.038	2.	-3.	-0.64	-0.022	120	0	15:03:57
0.	41.680	0.042	2.	-3.	-0.63	-0.022	120	0	15:06:27
0.	41.679	0.044	2.	-3.	-0.63	-0.021	120	0	15:08:57
0.	41.680	0.040	2.	-3.	-0.63	-0.021	120	0	15:11:27
0.	41.684	0.038	2.	-3.	-0.63	-0.021	120	0	15:13:57
0.	41.678	0.039	2.	-3.	-0.63	-0.021	120	0	15:16:27
0.	41.681	0.036	2.	-3.	-0.63	-0.020	120	0	15:18:57
0.	41.681	0.043	2.	-3.	-0.63	-0.020	120	0	15:21:27
0.	41.681	0.041	2.	-3.	-0.63	-0.020	120	0	15:23:57
0.	41.680	0.044	2.	-3.	-0.63	-0.020	120	0	15:26:27
0.	41.682	0.040	2.	-3.	-0.63	-0.019	120	0	15:28:57

Figure 4 Typical CG-3M Data Printout

Extensive field measurements with the CG-3 and CG-3M by users in 25 countries to date have confirmed that the CG-3 Autograv has a standard deviation, for an individual measurement, of 14 microGals, or less, and the CG-

3M of better than 7 microGals, under average earth noise conditions. This ranks them, respectively, essentially on a par, for precision of measurement, with most LaCoste models G and D gravimeters, but with a worldwide range, without resetting, of course.

PERFORMANCE FEATURES

Aside from higher resolution of reading (1 microGal vs. 5 microGals) and greater precision, most of the other performance characteristics of the CG-3M and CG-3 are similar. These are described below.

a) Effect of Ambient Temperature Changes

The fused-quartz element of the CG-3 and CG-3M gravimeters has a coefficient of change of elasticity with temperature, which results in a coefficient of gravity measurement of the order of 100 milliGals per °C. If one wishes to achieve useful measurements of changes in gravity at the microGal level with such an element, it is clear that a high degree of temperature stabilization and/or compensation for temperature changes, is required, effectively down to the order of 10^{-50}C.

This has been accomplished by virtue of a combination of enclosing the element in a double oven, each under thermostat control, with insulation, and inserting a high resolution thermistor, reading to 10^{-50}C, in the heart of the element. The latter determines any residual temperature offset in the sensor, and provides the basis for an on-line correction for the offset.

These gravimeters are normally set to maintain a gravity sensor temperature of about 59°C, which is comfortably above the standard upper limit of operating temperature (45°C), for world-wide use. For exclusive use in colder climates, a lower thermostatic setting may be optionally (factory) installed, with a resultant saving in power consumption and battery lifetime. For really hot countries, an even higher setting is optionally available.

Figure 5 on page 105 shows the effects of abrupt, step-function changes of 23°C in ambient temperature (*Text*) on a CG-3M. Two curves are shown, one being the internal thermistor temperature and the second the observed gravity indication, software corrected for the residual internal temperature change.

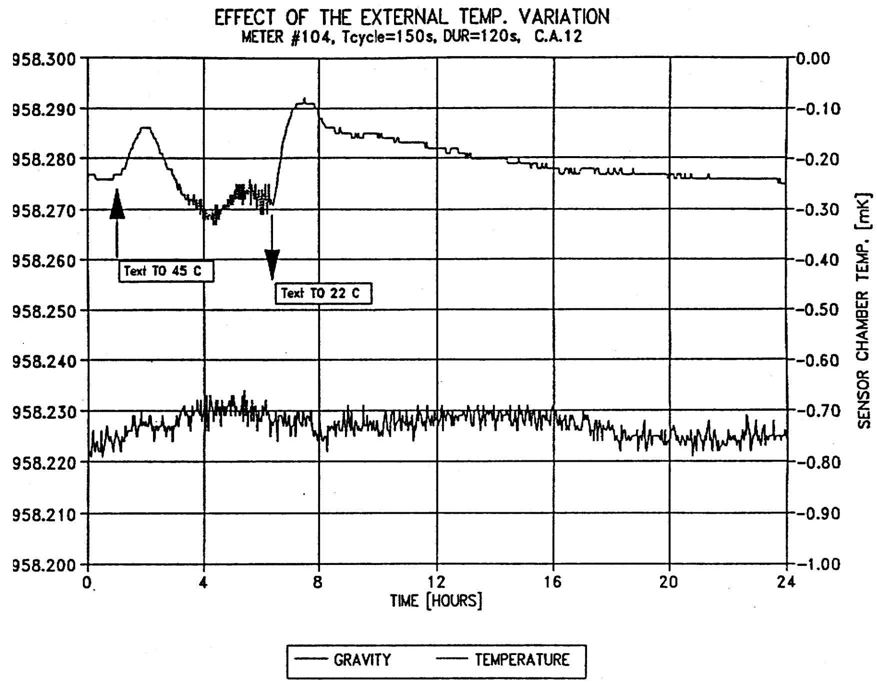

Figure 5 Effect of External Temperature Variations

From the internal thermistor indications, it is clear that the effective temperature stabilization factor is of the order of 10^{-5} even for abrupt changes. After software correction, the residual effect of the temperature shock on the observed gravity values is less than 5 microGals i.e. an effective temperature isolation factor of better than 5×10^5, resulting in a temperature coefficient of less than 0.2 microGals/°C. It should be noted that some of the long period (12–24hr) gravity variations, of the order of about ±3 microGals amplitude, that can be seen on Figure 5 are typical of residual tidal effects, not compensated by the Longman's formula, in the Concord area.

b) Effect of External Pressure Variations

Figure 6 on page 106 shows the results of a laboratory test of a CG-3M where the ambient air pressure was reduced from normal atmospheric pressure (about 103 kiloPascals) to 0.25 atmospheric pressure (about

25 kiloPascals) in four steps, and then brought back to normal in four steps. The lowest pressure in this test is lower than the lowest pressure to be expected on the highest mountains on earth (about 30 kiloPascals). Nevertheless, aside from transients associated with the abrupt pressure shocks, steady-state effects on the observed gravity are less than 10 microGals, resulting in a pressure coefficient of less than 0.15 microGals/kiloPascal. The gravity transients that are observed, which correlate in time and polarity with the abrupt pressure changes, also correlate with sharp temperature transients on the sensor thermistor, associated with the rapid exit or entry of air into the region adjacent to the sensor. In practice, changes in barometric pressure are expected to occur slowly during survey operations, and such transients should not be encountered.

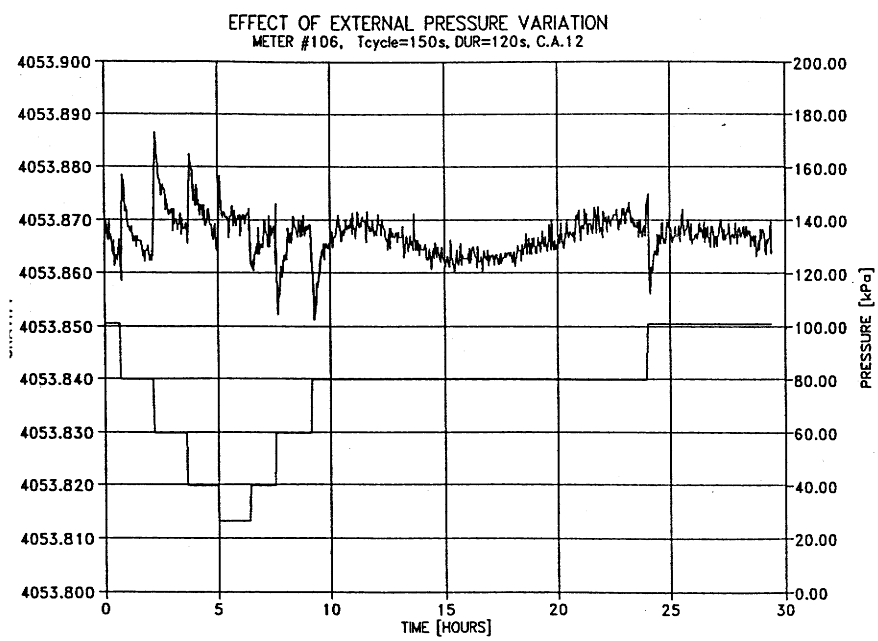

Figure 6 Effect of External Pressure Variations

c) Effect of External Magnetic Fields

Figure 7 on page 107 shows the results of a laboratory test of a CG-3M which was subjected to ambient (vertical) magnetic field changes of ±5 gauss (±5 x 10^5nT), i.e. approximately 10x the earth's magnetic field. The absence of any appreciable change in gravity values is, of course, a natural consequence of the intrinsically non-magnetic properties of the fused-quartz of the element of the CG-3M. Thus, the magnetic field coefficient of the CG-3M is less than 1 microGals/Gauss.

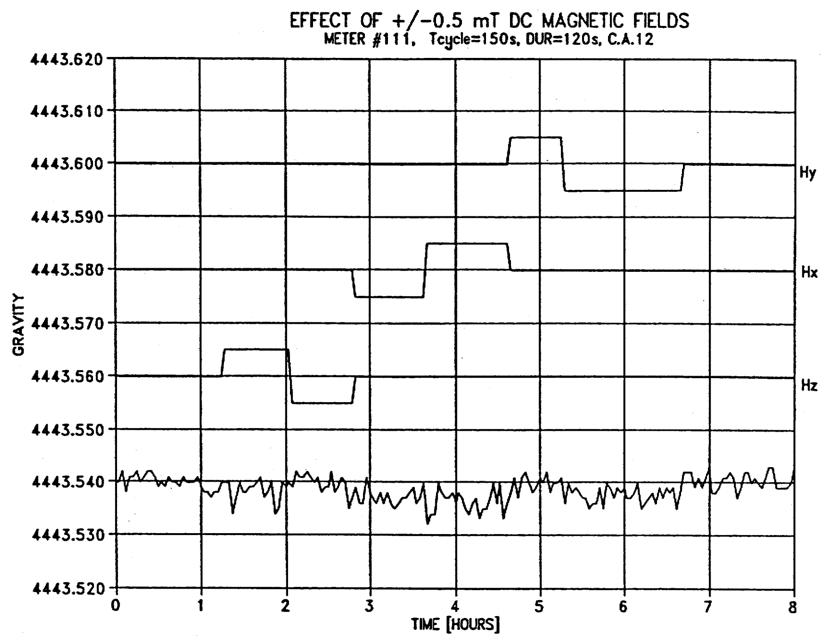

Figure 7 Effect of Magnetic Field Variations

d) Tolerance to Shocks

Figure 8 on page 108 shows the results of the standard drop (shock) test which is part of the acceptance test procedure of each CG-3 and CG-3M. In this test, one side of the gravimeter is raised about 2 cm and dropped onto its (marble) base. This is repeated several times, raising different sides of the gravimeter. An accelerometer attached to the gravimeter indicate that the peak acceleration during the drop was of the order of 25 G. The acceptance criterion applied to all CG-3M, in relation to this shock test, is that the resultant offset of the measured gravity value should be less than 10 microGals.

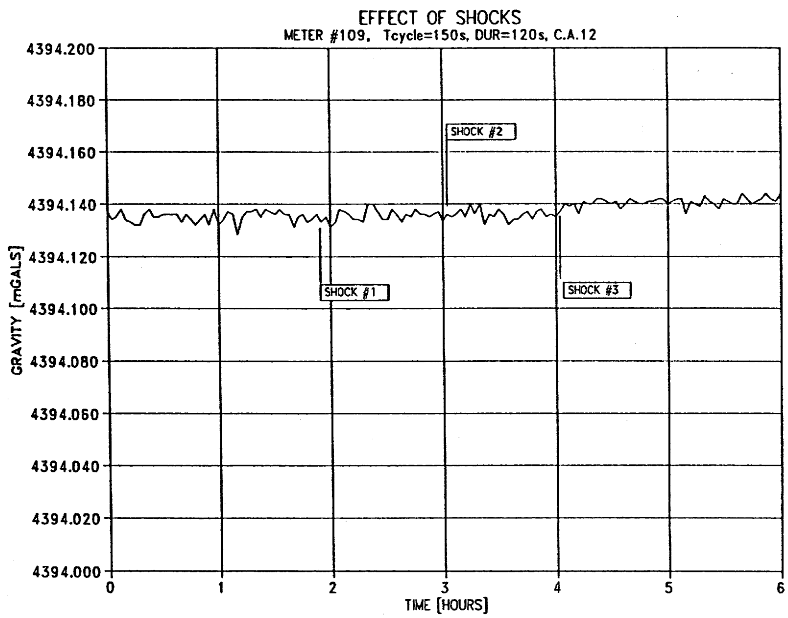

Figure 8 Effect of Shock

It must be recalled that these gravimeters are not clamped at any time, so that their ability to withstand such shocks is a tribute both to their robust construction and the great strength and super-elasticity of pure fused-quartz.

e) Stability of Long Term Drift Rate

Despite the many advantages of pure fused-quartz as the material for a gravimeter sensor, it does exhibit one problem that had to be overcome, viz: long term drift due to creep of material in the spring. When a gravimeter is newly built, its drift rate may be of the order of 0.5 milliGals/day. Over time, the drift rate slowly reduces, typically to the order of 0.2 milliGals/day after several years use.

Over any period of days at the outset of use, or weeks after it has been in use for a year or more, the drift rate of a CG-3 or CG-3M will be remarkably linear and can be accurately compensated, by keying in the currently observed drift rate into the keyboard. The CG-3/3M Operator Manual provides simple instructions for so doing, at periodic intervals. The microprocessor then applies the appropriate correction, on a time basis, for each gravity reading. In this manner the long term drift of a CG-3 or CG-3M is readily reduced to less than 20 microGals/day, in real time, without any further intervention by the operator.

Figure 9 on page 109 shows the output of a stationary CG-3M which was cycled for 100 hours (4 days), with one reading of 300 seconds duration every 900 seconds. A linear drift of 0.61 milliGals/day has been removed, in real time. Of course, on-line corrections have also been applied for internal temperature fluctuations and solar/lunar tides.

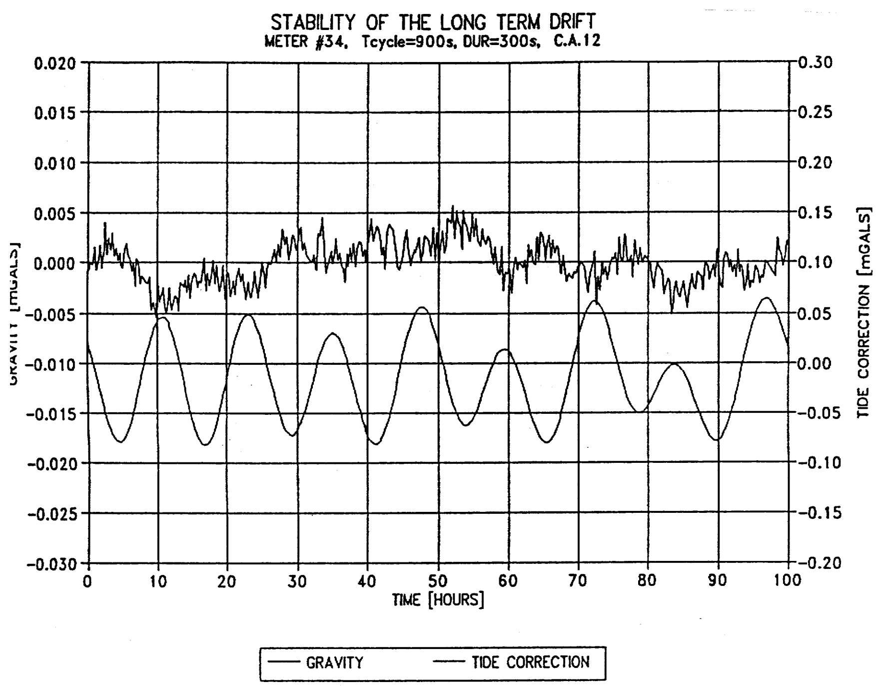

Figure 9 Stability of Long Term Drift

It is clear to see that the residual drift, after internal, linear compensation with time, is less than 5 microGals in 6 days, i.e. is well within the stated specification of 20 microGals/day. It should be noted that there is a residual tidal effect, of about ±3 microGals amplitude, that has not been compensated by the Longman's formula in the Concord area.

f) Considerations of the Calibration Factor

In common with all relative (as distinct from absolute) gravimeters, the CG-3M must be calibrated, by one or other means. This can be done on a tilt-table, using the well-known cosine law of dependence of gravity versus tilt from the vertical. This method, however, is rarely accurate beyond about 1 part in 1000. Better accuracy is achieved by running the gravimeter over a test-calibration range, entailing a number of stations, extending over a distance of many kilometres.

On such a calibration range, an absolute gravity measurement should be made at or near the stations of highest and lowest gravity values. All stations are then tied into the absolute gravity stations by means of multiple ties between the absolute gravity and ordinary stations.

Scintrex tests and calibrates all its production gravimeters over such a calibration range, established by the Geological Survey of Canada. It extends from Orangeville, Ontario to Collingwood, Ontario and includes five stations, fairly evenly spaced over a distance of 80 km. The maximum gravity span within this range is about 105 milliGals.

Each calibration run starts at Station 1 (Orangeville), reads stations 2 to 5 (Collingwood) and then stations 4 to 1, in reverse, on the return run. A computer program, acting to determine the best straight-line fit between all of the observed gravity values, using the GSC station values as the correct values, determines the following factors: calibration scale factor; standard deviation of the observed readings relative to the accepted GSC values, and the residual drift. In order to pass inspection, the gravimeter must conform to its specifications, namely SD less than 14 microGals for CG-3 and less than 7 microGals for CG-3M.

Figure 10 on page 111 shows the results of one such test. The actual observed gravity values corrected for long term drift, tides and residual temperature fluctuations, and their time of measurement are shown. These are then corrected for any residual drift to yield column 5.

IELD TEST PROGRAM VERSION 2.0 (c) SCINTREX LTD.

nter data file name -)
IELD TEST 93 Wed Oct 14 17:43:22.440 1992

(1) STN	(2) TIME	(3) READING	(4) ELAP TIME	(5) DRIFT ADJUSTED	(6) DIFF	(7) DIFF *SCALE	(8) GRAVITY	(9) SQUARED DIFFERENCE
1	10:40:18	8.297	0.00	8.297				
1	15:51:52	8.310	5.19	8.297				
2	11:13:46	34.296	0.56	34.295	025.998	025.993	025.993	0.000000
2	14:48:02	34.308	4.13	34.298	026.001	025.996	025.993	0.000008
3	12:20:25	67.363	1.67	67.359	059.062	059.056	059.059	0.000009
3	14:10:34	67.370	3.50	67.361	059.064	059.058	059.059	0.000000
4	12:43:46	86.889	2.06	86.884	078.587	078.581	078.581	0.000000
4	13:47:05	86.891	3.11	86.883	078.586	078.580	078.581	0.000001
5	13:15:50	114.278	2.59	114.272	105.975	105.967	105.965	0.000006

rift = -0.002503477 **PASSED DRIFT TEST**
D = 0.002014 SUM = 0.000024 **PASSED STANDARD DEVIATION TEST**
CAL1' = GCAL1*SCALE = 5988.226*0.999972 = 5988.061
EAST SQUARES Y-INTERCEPT = 0.004132

Figure 10 Typical Field Calibration Test Results

Differences from Station 1 values are shown on Column 6. A computer program then calculates the calibration value which provides the best fit to the accepted GSC values and applies this to all observed gravimeter readings (Column 7). These are then compared with the GSC values, accepted as being correct.

In the present test (gravimeter #93), the elapsed time was 5 hours and 19 minutes. The SD determined was 2.0 microGals. The scale factor (**GCAL 1**) was determined to be 0.999992 times what had previously been determined for this meter, i.e. 28 ppm lower than last calculated. However, it should be noted that with a **SD** of 2 microGals, in a range of only 105 milliGals, the probable error of the **GCAL1** calculation is larger than the 28 ppm change calculated. A calibration range with a much greater range of gravity values would be required in order to make a more precise measurement of **GCAL1**.

Due to the release of residual stresses that may be established in the gravimeter element during its manufacturing process, there may be a subtle change with time in the geometry of the element. This change may manifest itself in small changes in the gravimeter calibration factor. These changes are largest when the CG-3 or 3M is very new and is undergoing its laboratory and field testing, prior to shipment. After a period of some months of use, any further changes in the **GCAL1** factor become very small.

Figure 11 on page 112 shows the variation of the **GCAL1** calibration factor, with time since production, for several CG-3 and CG-3M's. Typically, after 1-2 months of use, any further changes in **GCAL1** are of the order of 1 ppm/day, and, in fact will lie within the error bars of the **GCAL1** measurement on the 105 mGal calibration range employed.

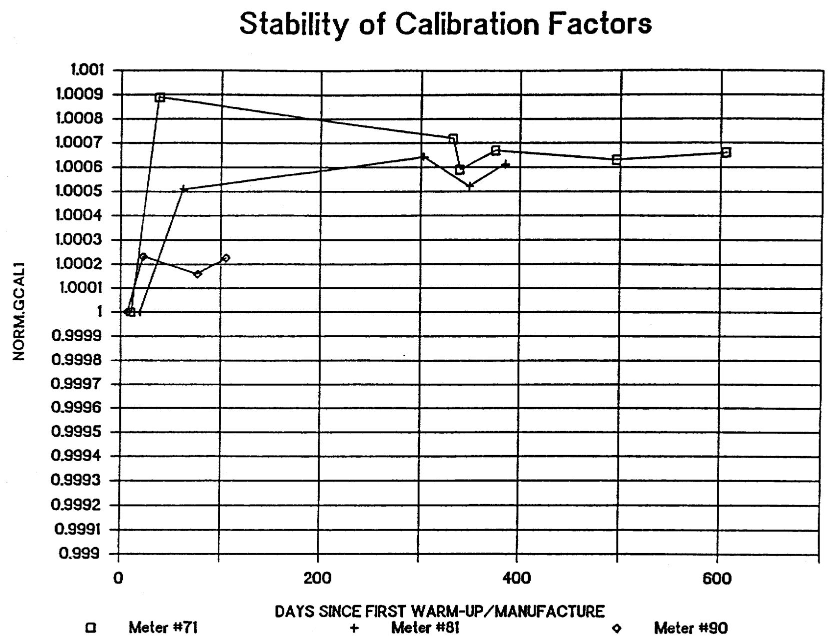

Figure 11 Stability of the Calibration Factor

g) Precision in Field Use

As has been shown ("Tolerance to Shocks" on page 107) the CG-3 and CG-3M are ruggedly built and highly tolerant to shocks, of up to at least 5G, which would normally be expected to give rise to substantial offsets in other makes of gravimeters. Whereas it is good practice to handle all gravimeters with care in the field, some inadvertent shocks are inevitable in the typically rough field environment.

An interesting comparison between the performance of a CG-3 gravimeter and three LaCoste **G** meters may be found in a paper by Andrew Hugill (Hugill, 1990). This paper, in part, reports on the results of experience in establishing an upgraded gravity reference network in the country of Jordan, including 34 stations covering a range of 611 milliGals. The instruments were transported over most of the network in 4 wheel drive vehicles. Approximately half of the distance traversed was on very rough secondary roads or rough tracks. Two of the **G** meters (G74 and G291, GSC owned) were equipped with shock-mounted cradles inside their normal carrying cases. As a further precaution against vibration and shock-induced drift, they were carried in a heavy, specially constructed transit case, mounted on air bag isolators. The third **G** meter, (G880) and the CG-3, had no shock or vibration protection, and were simply strapped into position on the rear seat of the vehicle. Table 1 shows the standard deviation of the station ties for each of these four gravimeters.

Table 7:

Gravimeter	Total Ties	Standard Deviation (mGal)
LCR G 074	91	0.047
LCR G 291	88	0.038
LCR G 880	82	0.076
CG-3 8909126	81	0.018

In terms of **SD** of measurement, under these strenuous field conditions, the CG-3 proved to have twice the precision of measurement of the very carefully handled GSC **G** meters and four time the precision of the **G** meter which was given the same ad-hoc treatment as the CG-3. It may also be noted that the CG-3 employed was an early model, produced in 1989.

As an indication of the level of precision achievable by more recent CG-3M gravimeters, Figure 12 presents a histogram of the standard deviations of 54 recent calibration runs over the GSC calibration (105 milliGal) range. It will be noted that all runs resulted in **SD** of between 1 and 8 microGals, with a mean (and median) at 4.8 microGals.

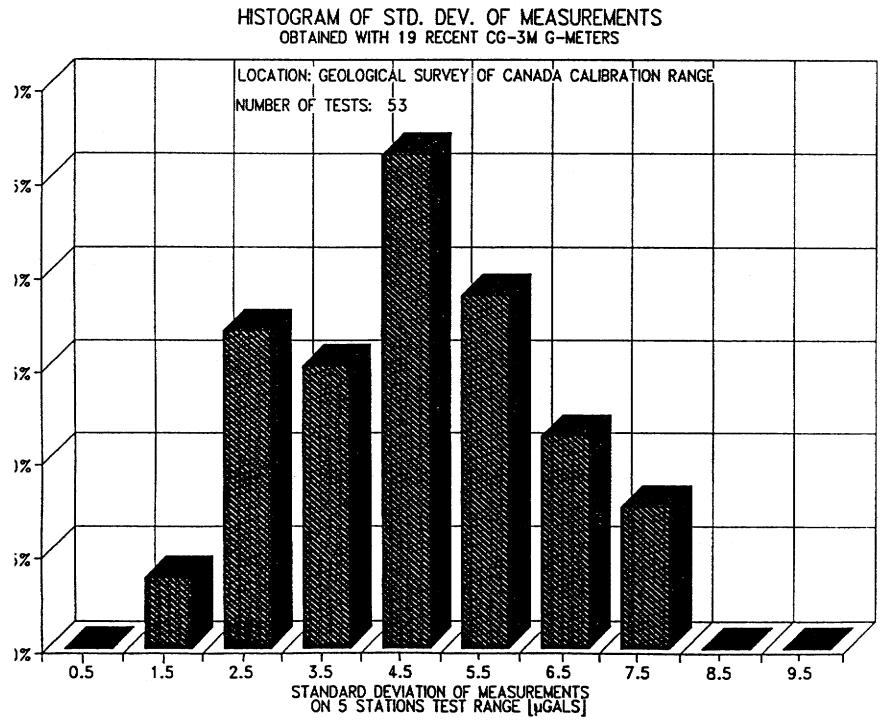

Figure 12 Histogram of the Standard Deviation of Individual Measurements — 54 Recent CG-3M Tests on GSC Calibration Range

Thus, the CG-3M can, properly, claim to provide a **SD** of the order of 5 microGals in normal, field use.

With some gravimeters, vibration due to transporting vehicle can cause large and irregular drift. For example, to quote from Page 3.2 of the LaCoste and Romberg Instruction Manual, Model **G** and **D** Gravity Meter (6-1989):

> "Certain vibration frequencies are worse than others. Snowmobiles and helicopters may cause severe short-term drift".

In their critical evaluation of a CG-3, the Geological Survey of Canada tested the effect of helicopter transport on the data quality. They report as follows (Liard et al, 1993):

> "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 transportation 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, 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."

SUMMARY

A novel gravimeter, suited to the computer and electronic communication age, has been developed and extensively field proven. It incorporates a quartz element, based on a stable rather than astatic design, coupled with microprocessor-based electronics and software.

The CG-3M provides worldwide (7000 milliGal) coverage, with one microGal resolution (without reset) and with a standard deviation which can achieve 5 microGals or better in normal field use. It is rugged, requiring no clamping between measurements. It is highly insensitive to ambient temperature and pressure variations, to strong magnetic fields to vibration during transport and to shocks due to rough handling. It provides automatic, on line correction for tilt errors, tidal gravity variations and residual long term drift. It provides smart digital signal enhancement based on statistical considerations. It records all data in solid state memory. It communicates with microcomputers, modems and other peripheral devices through an RS-232 port.

Clearly, the CG-3M has set a new standard in field portable relative gravimeters, for microgravity as well as general purpose gravity measurements.

LIST OF FIGURES

REFERENCES

Butler, Dwain K., Microgravimetric and Gravity Gradient Techniques for Detection of Subsurface Cavities; Geophysics Vol.49 No.7 p. 1084-1096, July 1984.

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Liard, J., Gagnon, CG., Hearty, D.B., Salib, P., and Flint, T.R., Evaluation of the Scintrex CG-3 Gravity Meter, Geological Survey of Canada, Open File Report October, 1993.

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Appendix II

GRAVIMETER CALIBRATION ON A CALIBRATION RANGE

It is assumed that a calibration line or range is available for this purpose. To be useful, it should consist of five or more stations, fairly evenly spaced in gravity values, over a gravity range of at least 100 mGals. The gravity values for each station must have been determined, with an accuracy of better than 10 μGals. This may have been carried out by repeated loop measurements, with a series of well-calibrated gravimeters. Best of all, the stations at the upper and lower values of gravity will have had their values established using absolute gravimeters.

If we designate the stations as **1** to **5**, then for calibration, the following sequence of steps is performed.

1. Starting with station **1**, read the sequence of stations **1**,**2**,**3**,**4**,**5**,**4**,**3**,**2**,**1**.
2. Apply the residual linear drift correction as per *Instrumental Drift — CD* on page 37
3. Apply the Free-Air correction for the relative elevation of the gravimeter reference level and the station marker, as per *Variation with Elevation — CE* on page 44.
4. Apply the correction for atmospheric pressure changes, or else avoid calibrating on any days when pressure changes greater than 1 kPa are forecast.
5. Perform a linear regression to fit the corrected gravity data to a line of the form

where $\mathbf{g_r}$ is the reference gravity value at each station, **R** is the corrected (*observed*) gravimeter reading, and **b** is a constant.

A reference level equal to the value at station **1** will be subtracted from each of these suite of values.

The value of **k** is the correction factor to be applied to the value of the calibration factor **K** which had been employed (e.g. as provided by the manufacturer) up to the time of the calibration. That is, the updated calibration factor, to be employed for succeeding (or even recently preceding) measurements, becomes

There are two ways of applying the scale correction factor **k**:

1. Post processing — which involves multiplying all recorded measurements by **k**, and
2. Adjusting the calibration constant (in software controlled instruments) according to the last mentioned formula.

Option 1 has advantages in geodetic type work, in that it allows the calibration of the gravimeter to be easily and unambiguously monitored over a long period of time. Option 2 offers more convenience in prospecting-type surveys, as the readings are directly in mGals.

To ensure that your new value of **k** is accurate, obey the following cautions:

a. Only use a calibration range whose gravity values have been carefully and properly established, by a responsible and knowledgable agency, using well calibrated microgravimeters
b. Only use stations which have been well marked and are intact, so that they can be precisely re-occupied
c. Only use stations which are well away from surface waters whose levels may radically change with time
d. Only calibrate on days with low microseismic activity, and even then, discard stations with high seismic noise (e.g. due to frequent vehicle passage, or wind noise) from the linear regression calculation.

Example: The following is a print-out of such a calibration check, on a CG-3 gravimeter, on the Scintrex calibration line with five stations, of about 106 mGal range.

The value of **k** so determined, in this case, 0.999972, is hardly worth incorporating since it differs from unity by only 28 ppm, i.e. within the limits of accuracy of the measurements.

Appendix II