2

GRAVITY METHOD

Differences in rock density produce small changes in the Earth's gravity field that can be measured using portable instruments known as gravity meters or gravimeters.

2.1 Physical Basis of the Gravity Method

The gravitational constant, G, has a value of 6.67×10^{-11} N m^{2}kg^{-2}. Gravity fields are equivalent to accelerations, for which the SI unit is the m s^{-2} (alternatively written as the N kg^{-1}). This is inconveniently large for geophysical work and the gravity unit (g.u. or μm s^{-2}) is generally used. The cgs unit, the milligal, equal to 10 g.u., is still also very popular.

2.1.1 Gravity field of the Earth

The Earth's gravity field is almost the same as that of a sphere having the same average radius and total mass but increases slightly towards the poles. The difference between polar and equatorial fields is about 0.5% or 50 000 g.u. The rate of change is zero at the poles and equator and reaches a maximum of about 8 g.u. per kilometre north or south at 45° latitude (Figure 2.1). The relationship between normal sea-level gravity and latitude (λ) is described by the *International Gravity Formula*, adopted in 1967:

$$g_{\text{norm}} = 9\,780\,318.5 + 51629.27 \sin^2 \lambda + 229.5 \sin^4 \lambda$$

The theoretical sea-level gravity at the equator is thus 9 780 318.5 g.u. This formula replaced an earlier, 1930, version with slightly different constants (including an equatorial sea-level gravity of 9 780 490 g.u.). The change of formula was necessitated by the recognition that the absolute gravity values at the 'Potsdam' system of base stations were in error by some 160 g.u., and that correcting this error, and allowing for an improved knowledge of the shape of the Earth, required a corresponding change in formula. The network of international base stations compatible with the 1967 IGF is known as IGSN71 (see Notes to Bibliography). It is still all too common to find surveys in which the 1930 IGF has been applied to data referenced to IGSN71 bases or that the 1967 IGF has been applied to Potsdam values, leading to errors of up to 160 g.u. in latitude-corrected values.

Recently there has been a move towards using an updated formula that is fully compatible with the World Geodetic System 1984 (WGS84). The equation is more complicated than that defining IGF67, and an additional,

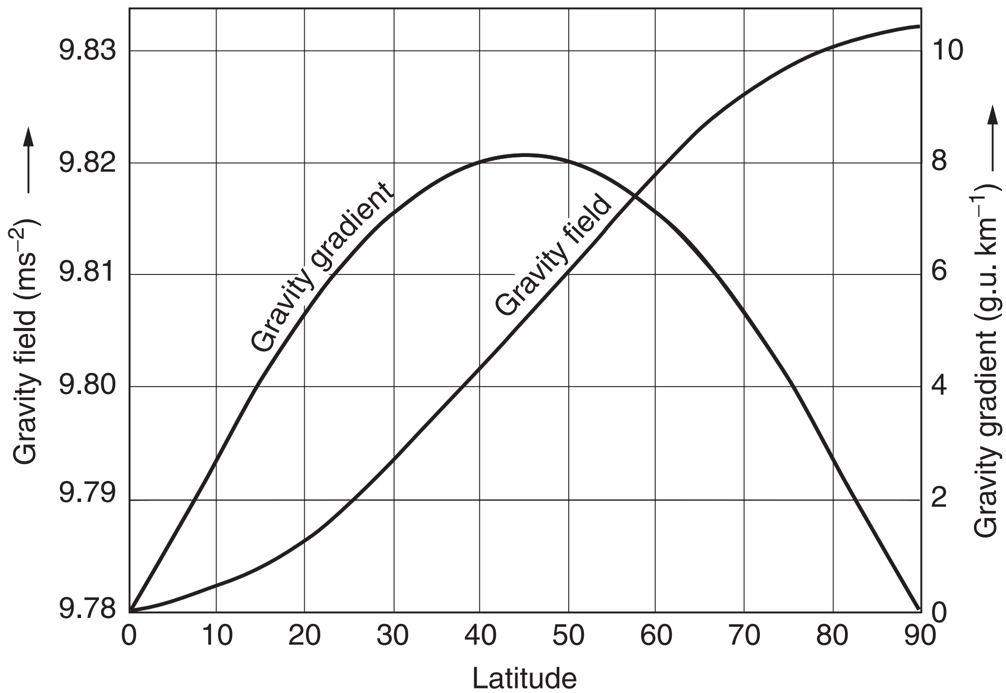


Figure 2.1 *Variation in theoretical sea-level gravity field and in corresponding north–south horizontal gradient with latitude. There is no east–west gradient in the theoretical field.*

elevation dependent, correction is needed for the mass of the atmosphere (see Notes to Bibliography). Since the actual changes implied in theoretical gravity are often smaller than the errors in absolute gravity of individual gravity stations, and no changes in base-station values are required, the changeover is widely regarded as not urgent and is proceeding only slowly.

A major sedimentary basin can reduce the gravity field by more than 1000 g.u., but many other common targets, such as massive ore bodies, produce anomalies of only a few g.u. Caves and artificial cavities such as mine workings usually produce even smaller (and negative) effects, even when very close to the surface. Topographic effects may be much larger. Elevation difference alone produces a gravity difference of nearly 20 000 g.u. between the summit of Mount Everest and sea-level. For engineering and geological purposes, gravity changes must often be measured to an accuracy of 0.1 g.u. (approximately one-hundred millionth of the Earth's field), and this is the sensitivity of virtually all modern gravity meters. The so-called 'microgravity meters' have readout precisions of 0.01 g.u. but not even their manufacturers claim accuracies of better than about 0.03 g.u.

2.1.2 Rock density

The SI unit of density is the $\mathrm{kg\,m^{-3}}$ but the $\mathrm{Mg\,m^{-3}}$ is widely used since the values are, numerically, the same as those in the old cgs system in which water has unit density. Most crustal rocks have densities of between 2.0 and

Table 2.1 *Densities of common rocks and ore minerals (Mg m^{-3})*

Common rocks	
Dry sand	1.4–1.65
Serpentinite	2.5–2.6
Wet sand	1.95–2.05
Gneiss	2.65–2.75
Coal	1.2–1.5
Granite	2.5–2.7
Chalk	1.9–2.1
Dolerite	2.5–3.1
Salt	2.1–2.4
Basalt	2.7–3.1
Limestone	2.6–2.7
Gabbro	2.7–3.3
Quartzite	2.6–2.7
Peridotite	3.1–3.4
Ore minerals	
Sphalerite	3.8–4.2
Galena	7.3–7.7
Chalcopyrite	4.1–4.3
Chromite	4.5–4.8
Pyrrhotite	4.4–4.7
Hematite	5.0–5.2
Pyrite	4.9–5.2
Magnetite	5.1–5.3

2.9 Mg m^{-3}. In the early days of gravity work a density of 2.67 Mg m^{-3} was adopted as standard for the upper crust and is still widely used in modelling and in calculating elevation corrections for standardized gravity maps. Density ranges for some common rocks are shown in Table 2.1.

2.2 Gravity Meters

For the past 50 years the vast majority of gravity measurements have been made using meters with unstable (*astatic*) spring systems, and this seems likely to remain the case for the foreseeable future. Gravity surveys are complicated by the fact that such meters measure gravity differences, not absolute field strengths.

2.2.1 Astatic spring systems

Astatic systems use *zero-length* main springs, in which tension is proportional to actual length. With the geometry shown in Figure 2.2 and for one particular

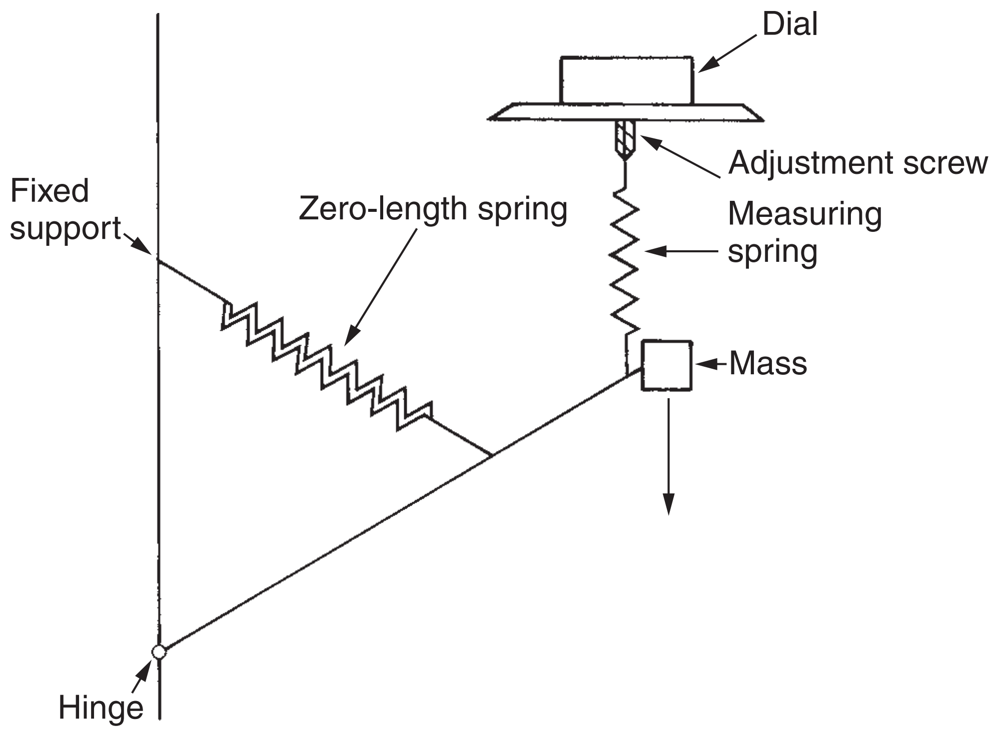


Figure 2.2 *Astatic gravity meter. The tension in the zero-length spring is proportional to its length. Measurements are made by rotating the dial, which raises or lowers the measuring spring to return the mass to a standard position.*

value of gravity field, the spring will support the balance arm in any position. In stronger fields, a much weaker auxiliary spring can be used to support the increase in weight, which will be equal to the product of the total mass and the increase in gravity field. To use an expression common in other geophysical methods, the zero-length spring *backs off* a constant weight so that the measuring spring can respond to small changes in gravity field.

None of the meters described below (and illustrated in Figure 2.3) uses exactly the system of Figure 2.2. The Worden and Sodin have two auxiliary springs, one for fine and one for coarse adjustments, attached to balance arms of more complicated design, while in the later Scintrex meters (CG-3 and CG-5) the restoring force is electrostatic. LaCoste meters have no auxiliary springs and measurements are made by adjusting the point of support of the main spring.

Because spring systems are mechanical, they are subject to drift. Short-period drift is largely due to temperature changes that affect the elastic constants of the springs despite the compensation devices that are usually included. There is also longer term extensional *creep* of springs under continual tension. Repeated readings at base stations are required to monitor drift and to allow the necessary corrections to be calculated.

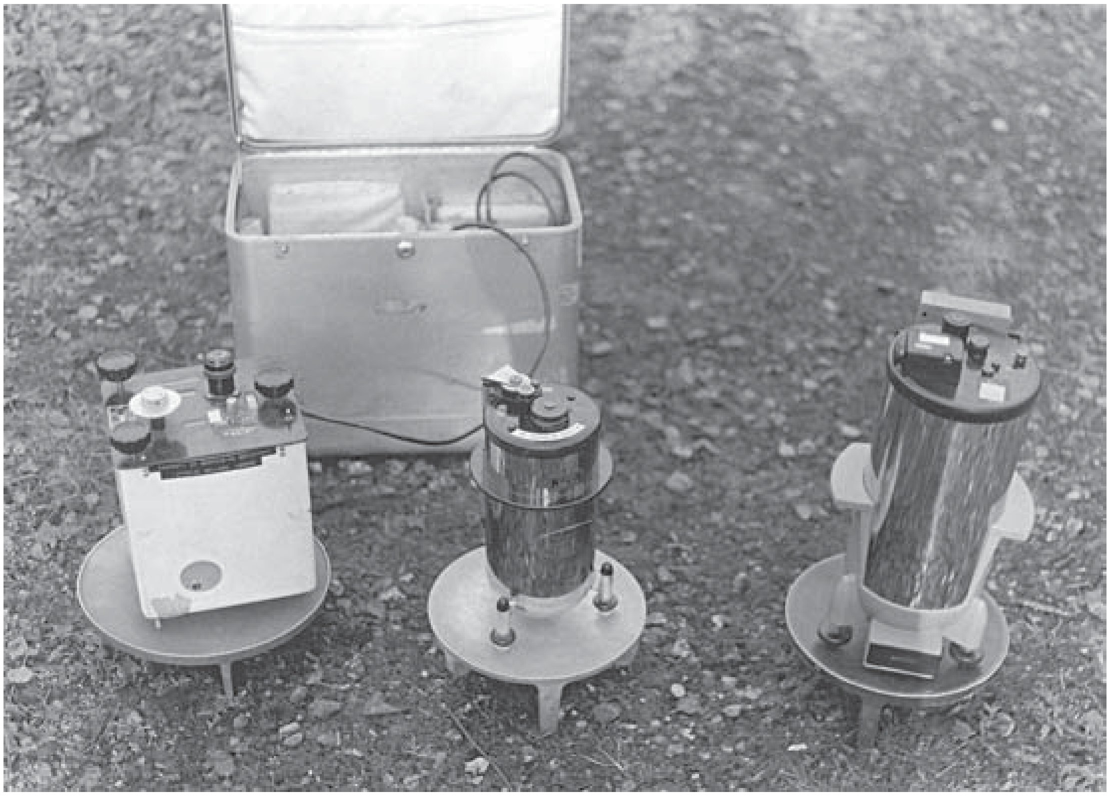


Figure 2.3 *'Manual' gravity meters. From left to right, LaCoste 'G' (geodetic), Worden 'Student' and Sodin.*

Although gravity meters remained essentially unchanged for almost 50 years, major moves were made in the last decade of the twentieth century towards automating readings and reducing the need for skilled operators. The LaCoste G and D meters were fitted with electronic readouts and the Scintrex CG-3 pioneered automated tilt correction and reading. The basic LaCoste meter was then completely redesigned as the fully automatic Graviton-EG, in which actual levelling, rather than merely the levelling correction, is automated. Inevitably, data loggers have also been added and can be directly downloaded to laptop PCs. The Graviton-EG, the CG-3 and its successor, the CG-5 Autograv, are also sufficiently rugged to be transported in the field without additional protective cases. However, despite the advantages of the newer models, the longevity (and, to some extent, the high cost) of gravity meters ensures that the less sophisticated versions will be around for many years to come. Much of the discussion below refers principally to these older meters.

2.2.2 Quartz astatic meters

Worden, Sodin and Scintrex meters have springs of fused quartz, enclosed in vacuum chambers that provide a high degree of thermal insulation. Some also have electrical thermostats, implying a need for heavier batteries, and the Scintrex meters have a temperature sensor that allows corrections for temperature-induced drift to be made by software. Vacuum-chamber meters are pressure sensitive, the effect with older meters amounting to as much as 2 g.u. for a kilometre elevation change, although in the CG-3/CG-5 this has been reduced by a factor of four or five. None of the quartz meters can be clamped, so the spring systems are all to some degree vulnerable when in transit. In some cases, if a meter suffers sharp sideways acceleration or is tilted, even gently, through more than about 45°, the springs may become tangled, and have to be unknotted by the manufacturer.

Worden and Sodin quartz meters have limited ranges on their direct-reading scales, of generally between 500 and 2000 g.u., and must be reset if a limit is reached. Some meters can be reset with a second dial calibrated to a lower degree of accuracy but in others an uncalibrated adjustment screw is used. It is always advisable to allow several hours for the system to settle after reset, and surveys of areas with large elevation changes need to be carefully planned to allow for this.

The level bubbles of Sodin meters are mounted deep within the instrument to shield them from the direct rays of the sun, which in other meters can cause levelling errors due to uneven heating of the fluid. They therefore need to be illuminated and are much less easy to check during reading than are levels on the top of the meter. It seems probable that more readings are taken off-level with Sodins than with other meters. With all the manual quartz meters it takes an experienced and conscientious observer to maintain the theoretical reading accuracy of 0.1 g.u.

2.2.3 Steel astatic meters

LaCoste meters (Figure 2.4) use steel springs. Because steel conducts heat well, these cannot be effectively insulated and thermostatic control is essential. The meter weight, of about 5 kg, is roughly doubled by the necessary rechargeable battery. Some form of charger is needed in the field since a single charge lasts only one or two days, depending on thermostat setting and external temperature. For two or three hours after reaching operating temperature, the drift is so high that the instrument is unusable. Drift is then very low, and can even be extrapolated linearly across intervals during which the meter has been off-heat. However, discontinuous *tares,* of perhaps several g.u., can occur at any time. These are the main form of drift in LaCoste meters and if they happen more than about once a month the instrument should be checked by the manufacturer.

With spring clamped, a LaCoste meter is reputedly able to survive any shock that does not fracture the outer casing. The springs are also less affected by vibration and the optical systems are generally clearer than those of most quartz meters. Even quite inexperienced observers have little difficulty in

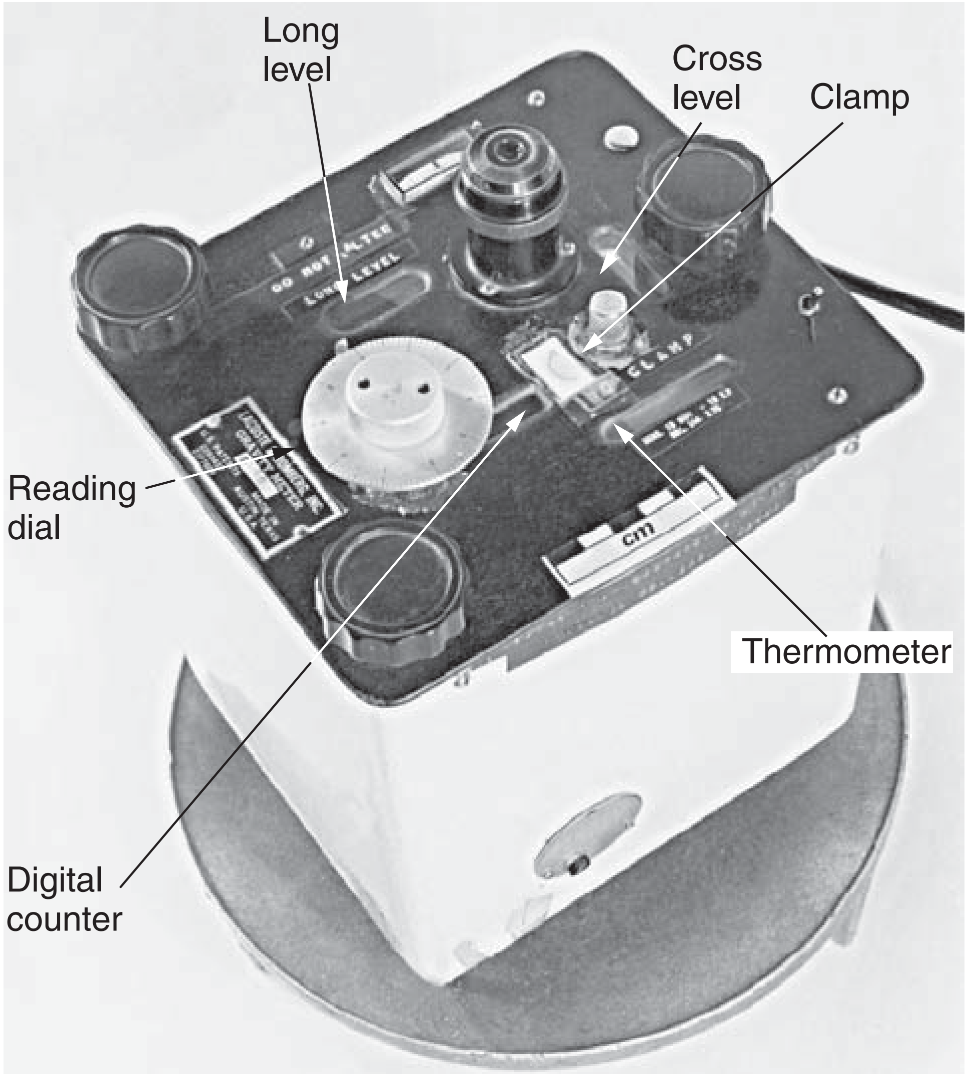


Figure 2.4 *Controls of the LaCoste 'G' meter. Note the two level bubbles at right angles, the clamp and the aluminium reading dial. The digital counter is behind the small window between the clamp and the dial. The thermometer, viewed through a window in front of the clamp, monitors internal temperature and must show the pre-set operating temperature if the instrument is to be usable.*

achieving accuracies of 0.1 g.u., particularly if aided by the optional (and expensive) electronic repeater needle.

A major advantage of the LaCoste G (geodetic) meter over the Worden and Sodin quartz meters is that a single long measuring screw is used to give readings world-wide without resetting (the D-meter, used for microgravity surveys, sacrifices this advantage in the interests of greater reading precision). Calibration factors vary slightly over the range, being tabulated for 1000 g.u. intervals. The G-meter thus has considerable advantages over quartz equivalents, but costs about twice as much.

2.2.4 Setting up a gravity meter

Gravity meters are normally read on concave dishes supported by three short stubs to which longer legs can be attached. The stubs are usually used alone, pressed firmly but not too deeply into the ground. The under surface of the dish must not touch the ground since a fourth support point allows 'rocking' back and forth. Thick grass under the dish may have to be removed before a reading can be taken. Extension legs may also be used but readings will then take longer, the dish itself may have to be levelled (some incorporate a bull's-eye bubble) and the height above ground will have to be measured.

The meters themselves rest on three adjustable, screw-threaded feet and are levelled using two horizontal spirit-levels (see Figure 2.4), initially by being moved around the dish until both level bubbles are 'floating'. The temptation to hurry this stage and use the footscrews almost immediately should be resisted.

Usually one of the levels (probably the *cross-level*, at right angles to the plane of movement of the balance arm) is set parallel to a line joining two of the feet. Adjustments to the third foot then scarcely affect this level. The quickest method of levelling is to centre the cross-level bubble, using one or both of the two footscrews that control it, and then use the third screw to set the *long-level.* Some meters can rotate in their casings and level bubbles and feet may become misaligned, but levelling is very much easier if any such slippage is corrected. Experienced observers often use two screws simultaneously but the ability to do this efficiently comes only with practice.

Once a meter is level, a reading can be obtained. With most gravity meters, this is done by rotating a calibrated dial to bring a pointer linked to the spring system to a fixed point on a graduated scale. Because the alignment is rather subjective if the pointer is viewed directly through an eyepiece, all readings in a single loop should be made by the same observer. The subjective element is then eliminated when the base reading is subtracted. Subjectivity is much reduced when instruments are fitted with electronic repeaters.

It is vital that the level bubbles are checked whilst the dial is being adjusted, and especially immediately after a supposedly satisfactory reading has been taken. Natural surfaces subside slowly under the weight of observers, off-levelling the meter. On snow or ice the levels have to be adjusted almost continuously as the dish melts its way down, unless it is insulated from the surface by being placed on a small piece of plywood.

All mechanical measuring systems suffer from *whiplash* and two readings will differ, even if taken within seconds of each other, if the final adjustments are made by opposite rotations of the reading dial. The only remedy is total consistency in the direction of the final adjustment.

Earthquakes can make the pointer swing slowly from side to side across the field of view and survey work must be stopped until the disturbance is over. Fortunately, this effect is rare in most parts of the world, although very large earthquakes can affect gravity meters at distances of more than 10 000 km. Severe continuous vibration, as from nearby machinery or the roots of trees moved by the wind, can make reading difficult and may even displace the reading point.

2.2.5 Meter checks

A series of checks should be made each day before beginning routine survey work. The meter should first be *shaken down* by tapping the dish gently with a pencil between readings until a constant value is recorded. This method can also be used if, as sometimes happens, the pointer 'sticks' at one side of the scale.

The levelling system should then be checked. Because astatic systems are asymmetric, the effect of a levelling error depends on the direction of tilt. A slight off-levelling at right angles to the balance arm gives a reading of gravity field multiplied by the cosine of the tilt angle (an error of about 0.15 g.u. for a tilt of $0.01°$). If the tilt is in the plane of movement, reading *sensitivity* (the amount the pointer moves for a given rotation of the dial) is also affected.

Off-levelling a correctly adjusted cross-level will reduce the reading, regardless of the direction of offset. To check that this actually happens, the meter should be set up and read normally and the cross-level should then be offset by equal amounts in both directions. The pointer should move roughly the same distance in the same direction in each case. Meters are usually considered usable provided that the movements are at least in the same direction, but otherwise the level must be adjusted.

The long-level affects reading sensitivity, i.e. the distance the pointer moves for a given dial rotation. The recommended sensitivity and instructions for resetting will be found in the manufacturer's handbook. The actual sensitivity can be estimated by moving the dial by a set amount and noting the pointer movement. After adjustment, levels often take a few days to settle in their new positions, during which time they must be rechecked with special care.

2.2.6 Meter calibration

Readings on non-automatic meters are usually combinations of values read from a dial and numbers displayed on a mechanical counter. The sensitivity of most such meters is such that the final figure on the dial corresponds to approximately 0.1 g.u.

Readings are converted to gravity units using calibration factors specific to the individual instrument. These are usually quoted by manufacturers in milligals, not g.u., per scale division and involve the arbitrary insertion of a decimal point somewhere in the reading. The factors are not affected by changes in reading sensitivity but may alter slowly with time and should be checked regularly. This can be done by the manufacturers or by using calibration ranges of known gravity interval. Calibration ranges usually involve gravity changes of about 500 g.u., which is within the range of even the most limited-range meters, and almost always make use of the rapid change of gravity field with elevation. A height change of about 250 metres is generally necessary, although in some cases local gravity gradients can also play a part. Travel times between top and bottom stations should normally be less than 15 minutes and the two stations should be well marked and described. A *run* should consist of at least an ABAB tie (Section 1.4.2), giving two estimates of gravity difference. If these differ by more than 0.1 g.u., more links should be added.

Meters with separate fine and coarse adjustments can be checked over different sections of their fine ranges by slightly altering the coarse setting. Most meters need a little time to stabilize after coarse adjustment, but if this is allowed it may be possible to identify minor irregularities in a calibration curve. This cannot be done with LaCoste G-meters, since only one part of the curve can be monitored on any one calibration range. Because of slight irregularities in the pitch of the adjustment screws, different meters may give results on the same range which differ consistently by a few tenths of a g.u.

2.3 Gravity Reductions

In gravity work, more than in any other branch of geophysics, large and (in principle) calculable effects are produced by sources which are not of direct geological interest. These effects are removed by *reductions* involving sequential calculation of a number of recognized quantities. In each case the sign of the reduction is opposite to that of the effect it is designed to remove. A positive effect is one that increases the magnitude of the measured field.

2.3.1 Latitude correction

Latitude corrections are usually made by subtracting the *normal* gravity, calculated from the International Gravity Formula, from the *observed* or absolute gravity. For surveys not tied to the absolute reference system, local latitude corrections may be made by selecting an arbitrary base and using the theoretical north–south gradient of $8.12 \sin 2\lambda$ g.u./km.

2.3.2 Free-air correction

The remainder left after subtracting the normal from the observed gravity will be due in part to the height of the gravity station above the sea-level reference surface. An increase in height implies an increase in distance from the Earth's centre of mass and the effect is negative for stations above sea level. The *free-air correction* is thus positive, and for all practical purposes is equal to

3.086 g.u./metre. The quantity obtained after applying both the latitude and free-air corrections is termed the *free-air anomaly* or *free-air gravity*.

2.3.3 Bouguer correction

Since topographic masses are irregularly distributed, their effects are difficult to calculate precisely and approximation is necessary. The simplest approach assumes that topography can be represented by a flat plate extending to infinity in all directions, with constant density and a thickness equal to the height of the gravity station above the reference surface. This *Bouguer plate* produces a gravity field equal to $2\pi\rho Gh$, where h is the plate thickness and ρ the density (1.1119 g.u./metre for the standard 2.67 $\text{Mg}\,\text{m}^{-3}$ density).

The Bouguer effect is positive and the correction is therefore negative. Since it is only about one-third of the size of the free-air correction, the net effect of an increase in height is a reduction in field. The combined correction is positive and equal to about 2 g.u. per metre, so elevations must be known to 5 cm to make full use of meter sensitivity.

Because Bouguer corrections depend on assumed densities as well as measured heights, they are fundamentally different from free-air corrections, and combining the two into unified elevation corrections can be misleading. It is also sometimes stated that the combined corrections reduce gravity values to those that would be obtained were the reading made on the reference surface, with all the topography removed. This is not true. In Figure 2.5, the

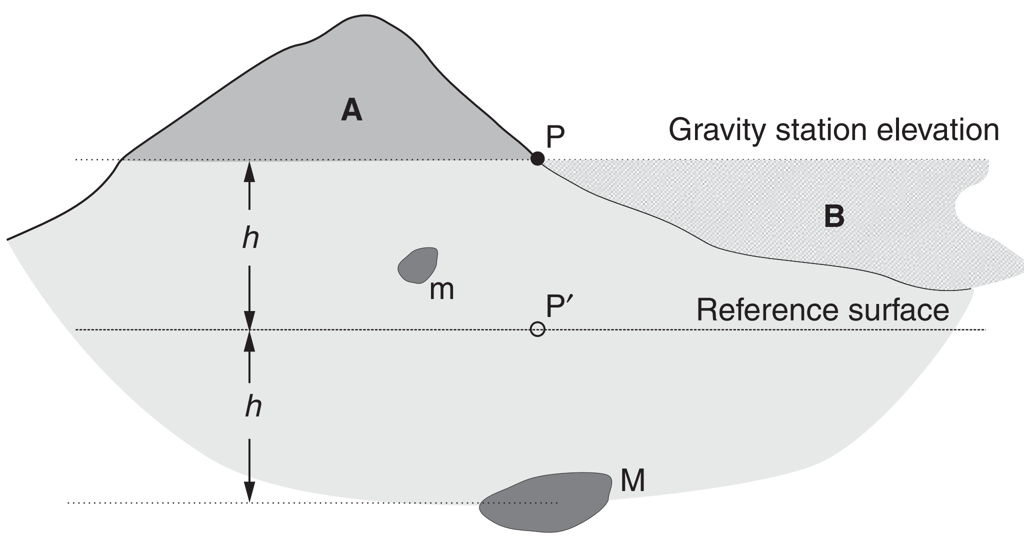


Figure 2.5 *Terrain corrections. The corrections are for the deviations of the topography from a surface parallel to sea level through the gravity station, and not from sea level itself, and are always positive (see discussion in text). Even after application of the Bouguer and free-air corrections, the gravity effects of the masses M and m will appear on the maps as they are measured at the station point P, and not as they would be measured at the point P′ on the reference surface.*

effect of the mass M recorded at the observation point P is unaltered by these corrections. It remains the effect of a body a distance $2h$ below P, not at the point P′ a distance h below it. Still more obviously, the corrections do not mysteriously eliminate the effect of the mass m, above the reference surface, since the Bouguer correction assumes constant density. Bouguer gravity is determined at the points where measurements are made, a fact that has to be taken into account in interpretation.

2.3.4 Terrain corrections

In areas of high relief, detailed topographic corrections must be made. Although it would be possible to correct directly for the entire topography above the reference surface in one pass without first making the Bouguer correction, it is simpler to calculate the *Bouguer gravity* and then correct for deviations from the Bouguer plate.

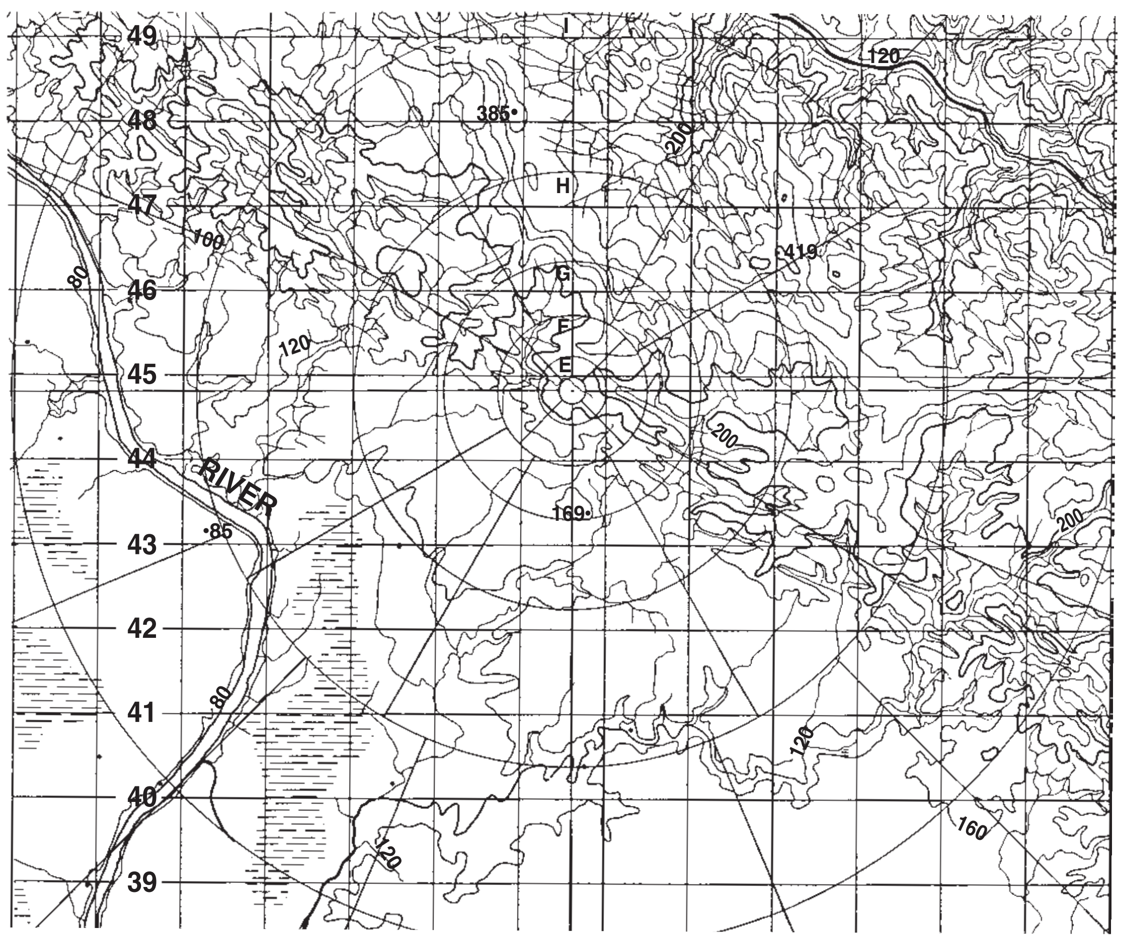


Figure 2.6 *Hammer chart (Zones E to I) overlaid on a topographic map. The difficulties in estimating average heights in the larger compartments are easily appreciated. The letters identifying the zones are difficult to see in this example but are clear when the overlay is removed from the map and viewed on its own.*

A peculiarity of the two-stage approach is that the second-stage corrections are always positive. In Figure 2.5, the topographic mass (A) above the gravity station exerts an upward pull on the gravity meter, the effect is negative and the correction is positive. The valley (B), on the other hand, occupies a region that the Bouguer correction assumed to be filled with rock that would exert a downwards gravitational pull. This rock does not exist. The terrain correction must compensate for an over-correction by the Bouguer plate and is again positive.

Terrain corrections can be extremely tedious. To make them manually, a transparent *Hammer chart* is centred on the gravity station on the topographic map (Figure 2.6) and the difference between the average height of the terrain and the height of the station is estimated for each compartment. The corresponding corrections are then obtained from tables (see Appendix). Computers can simplify this process but require terrain data in digital form and may be equally time consuming unless a digital terrain model (DTM) already exists.

Adding terrain corrections to the simple Bouguer gravity produces a quantity often known as the *extended* or *complete Bouguer gravity*. Topographic densities are sometimes varied with geology in attempts to still further reduce terrain dependence.

2.4 Gravity Surveys

A gravity survey is a basically simple operation but few are completed wholly without problems, and in some cases the outcomes can only be described as disastrous. Most of the difficulties arise because gravity meters measure only differences in gravity field and readings have to be interrelated by links to a common reference system.

2.4.1 Survey principles

A gravity survey consists of a number of *loops*, each of which begins and ends with readings at the same point, the *drift base* (Section 1.4). The size of the loop is usually dictated by the need to monitor drift and will vary with the mode of transport being used; two-hour loops are common in detailed work. At least one station of the reference network must be occupied in the course of each loop and operations are simplified if this is also the drift base for that loop. In principle, a base network can be allowed to emerge gradually as the work proceeds but if it is completed and adjusted early, absolute values can be calculated as soon as each field station has been occupied, allowing possible errors to be identified while there is still time for checks to be made. There is also much to be gained from the early overview of the whole survey area that can be obtained while the network is being set up, and practical advantages in establishing bases while not under the pressure to maximize the daily total of new stations that characterizes the routine production phase of most surveys.

A small survey may use an arbitrary base without any tie to an absolute system. Problems will arise only if such a survey has later to be linked to others or added to a national database. This nearly always happens eventually and the use of a purely local reference is often a false economy.

2.4.2 Base stations

The criteria used in siting reference bases differ from those for normal stations. Provided that exact reoccupation is possible, large terrain effects can be tolerated. These may make it inadvisable to use the gravity value in interpretation, in which case the elevation is not needed either. On the other hand, since the overall survey accuracy depends on repeated base readings, quiet environments and easy access are important. Traffic noise and other strong vibrations can invalidate base (or any other) readings. Also, the general principles outlined in Section 1.4 apply to gravity bases, and descriptions should be provided in the form of sketch plans permitting reoccupation exactly in elevation and to within a few centimetres in position (Figure 2.7).

2.4.3 Station positioning

The sites of field stations must also be chosen with care. Except in detailed surveys where stations are at fixed intervals along traverses, observers in the field have some, and often considerable, freedom of choice. They also have the responsibility for estimating terrain corrections within the area, up to

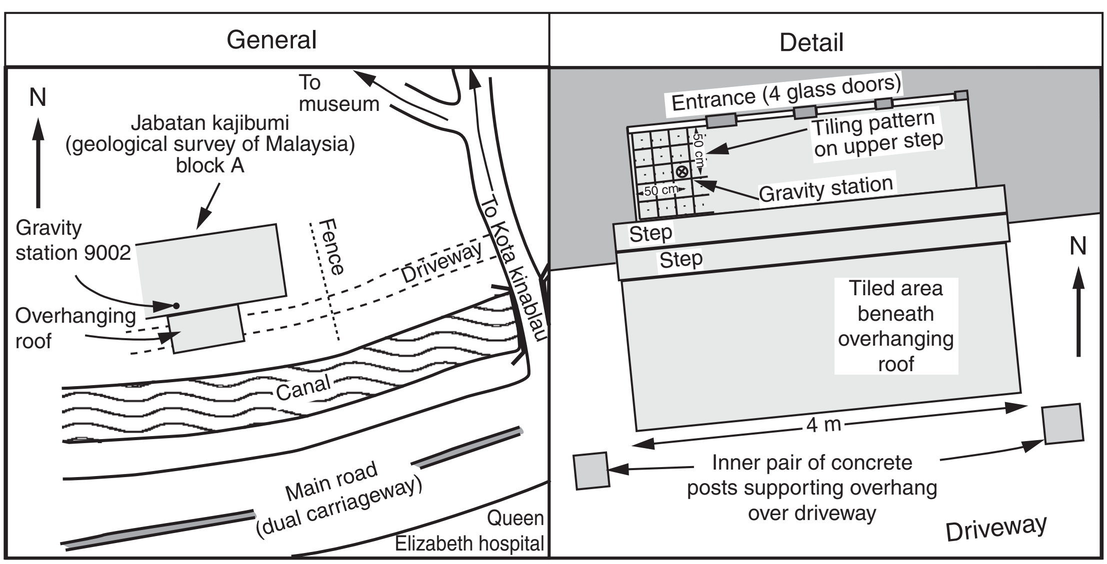
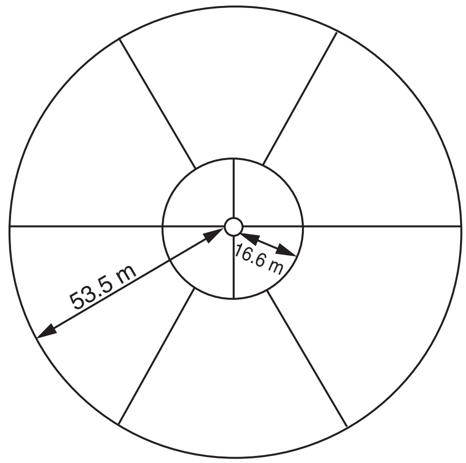


Figure 2.7 *Gravity base-station sketches. Two sketches, at different scales, together with a short written description, are usually needed to ensure the station can be reoccupied quickly and accurately.*



Area ------------------

Date ------------------

Station ----------------

Observer ---------------

Note: Terrain should be flat in central zone A (radius 2 m)

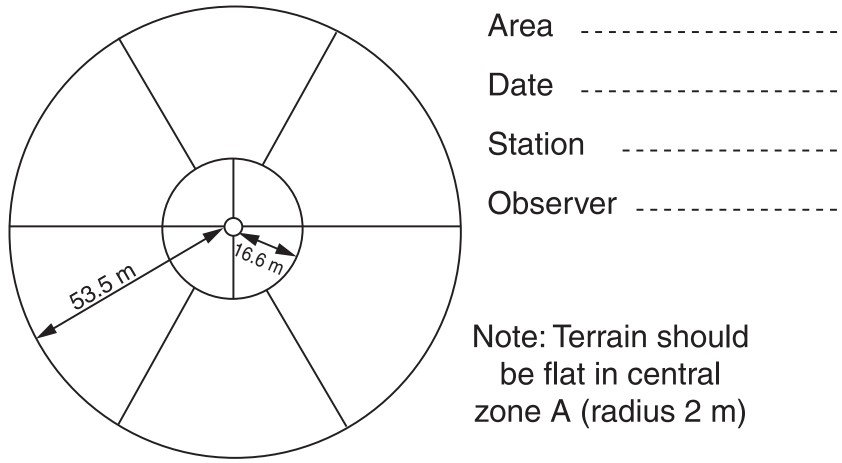
Zone B (2.0–16.6 m)	
Terrain correction (g.u.)	Height difference (metres)
0.01	0.3–0.6
0.02	0.6–0.8
0.03	0.8–0.9
0.04	0.9–1.0
0.05	1.0–1.1
0.1	1.1–2.1
0.2	2.1–2.7
0.3	2.7–3.6
0.4	3.6–4.3
0.5	4.3–4.9

Zone C (16.6–53.5 m)	
Terrain correction (g.u.)	Height difference (metres)
0.01	1.3–2.3
0.02	2.3–3.0
0.03	3.0–3.5
0.04	3.5–4.0
0.05	4.0–4.4
0.1	4.4–7.3
0.2	7.3–9.7
0.3	9.7–11.9
0.4	11.9–13.7
0.5	13.7–15.5

Figure 2.8 *Field observer's Hammer chart, for Zones B and C.*

about 50 metres from the reading point, where features too small to be shown on any topographic map can be gravitationally significant. Corrections can be estimated in the field using a truncated graticule such as that in Figure 2.8, which covers the Hammer zones B and C only. Height differences of less than 30 cm in Zone B and 130 cm in Zone C can be ignored since they produce effects of less than 0.01 g.u. per compartment. The charts can also be used qualitatively, to select reading points where overall terrain corrections will be small.

The effect of a normal survey vehicle is detectable only if the observer actually crawls underneath it, and most modern buildings produce similarly small effects. Old, thick-walled structures may need to be treated with more respect (Figure 2.9). Subsurface cavities, whether cellars, mine-workings or natural caverns, can produce anomalies amounting to several g.u. The gravity method is sometimes used in cavity detection but where this is not the object



Zone B (2.0–16.6 m)	
Terrain correction (g.u.)	Height difference (metres)
0.01	0.3–0.6
0.02	0.6–0.8
0.03	0.8–0.9
0.04	0.9–1.0
0.05	1.0–1.1
0.1	1.1–2.1
0.2	2.1–2.7
0.3	2.7–3.6
0.4	3.6–4.3
0.5	4.3–4.9

Zone C (16.6–53.5 m)	
Terrain correction (g.u.)	Height difference (metres)
0.01	1.3–2.3
0.02	2.3–3.0
0.03	3.0–3.5
0.04	3.5–4.0
0.05	4.0–4.4
0.1	4.4–7.3
0.2	7.3–9.7
0.3	9.7–11.9
0.4	11.9–13.7
0.5	13.7–15.5

Figure 2.8 *Field observer's Hammer chart, for Zones B and C.*

about 50 metres from the reading point, where features too small to be shown on any topographic map can be gravitationally significant. Corrections can be estimated in the field using a truncated graticule such as that in Figure 2.8, which covers the Hammer zones B and C only. Height differences of less than 30 cm in Zone B and 130 cm in Zone C can be ignored since they produce effects of less than 0.01 g.u. per compartment. The charts can also be used qualitatively, to select reading points where overall terrain corrections will be small.

The effect of a normal survey vehicle is detectable only if the observer actually crawls underneath it, and most modern buildings produce similarly small effects. Old, thick-walled structures may need to be treated with more respect (Figure 2.9). Subsurface cavities, whether cellars, mine-workings or natural caverns, can produce anomalies amounting to several g.u. The gravity method is sometimes used in cavity detection but where this is not the object

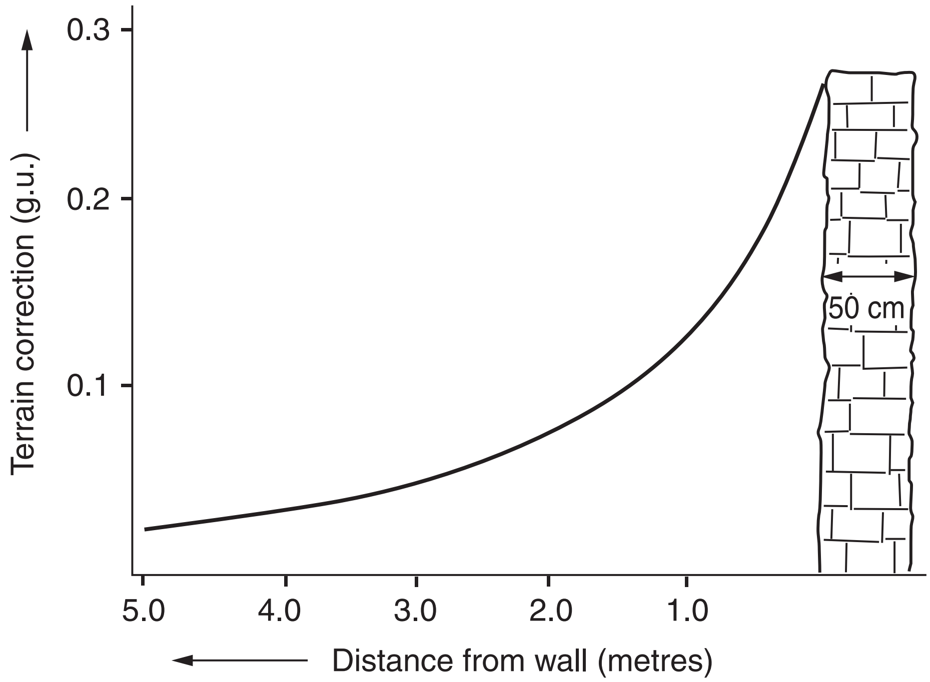


Figure 2.9 *Effect of a half-metre thick stone wall on the gravity field.*

of the survey it is obviously important that stations are not sited where such effects may occur.

2.4.4 Tidal effects

Before meter drift can be estimated, allowance must be made for *Earth tides.* These are background variations due to changes in the relative positions of the Earth, moon and sun, and follow linked 12- and 24-hour cycles superimposed on a cycle related to the lunar month (Figure 2.10). Swings are largest at new and full moons, when the Earth, moon and sun are in line. Changes of more than 0.5 g.u. may then occur within an hour and total changes may exceed

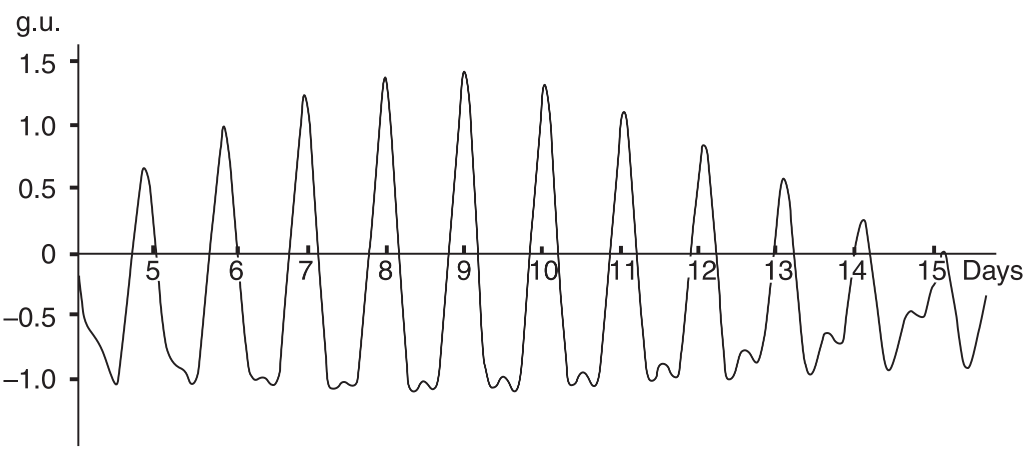


Figure 2.10 *Tidal variations, 5 to 15 January 1986, in g.u.*

2.5 g.u. The assumption of linearity made in correcting for drift may fail if tidal effects are not first removed.

Earth tides are predictable, at least at the 0.1 g.u. level required for gravity survey, and corrections can be calculated using widely available computer programs. Meter readings must be converted to gravity units before corrections are applied.

2.4.5 Drift corrections

The assumption that instrument drift has been linear in the time between two base readings is unlikely to be true if drift is dependent mainly on external temperature and large changes in temperature have been wholly or partly reversed during that time. However, it is difficult to make any other assumptions, except with modern instruments such as the CG-5 where internal temperature is recorded and compensated for automatically.

To correct manually for drift using the linear assumption, readings are first tidally corrected and the corrected initial reading at the drift base is then subtracted from every other reading in turn. The result of doing this to the final reading at the drift base gives the total drift. The *pro rata* corrections to the other stations must be calculated or estimated graphically to a final accuracy of 0.1 g.u. The sign of the correction is dictated by the requirement that, after correction, all drift base relative values should be zero.

Absolute observed gravities are obtained by adding the absolute value at the drift base to the drift-corrected gravity differences.

2.4.6 Elevation control

The elevations of gravity survey points can be determined in many different ways. If 1 g.u. contours are required, high-accuracy optical, radio-wave or DGPS techniques are essential, while barometric levelling or direct reference to sea-level and tide tables may be adequate for the 50 or 100 g.u. contours common in regional surveys. Measuring elevations is often the most expensive part of a gravity survey and advantage should be taken of any 'free' levelling that has been done for other purposes, e.g. surveyed seismic lines.

2.4.7 Field notebooks

At each station, the number, time and reading must be recorded. The most modern meters incorporate data loggers that do this at a key stroke, but all other information must be recorded in field notebooks. This may include positional information from GPS receivers and elevation data from barometers.

Any factors that might affect readings, such as heavy vibrations from machinery, traffic, livestock or people, unstable ground or the possible presence of underground cavities, should be noted in a *Remarks* column. Comments on weather conditions may also be useful, even if only as indicating the observer's state of mind. Where local terrain corrections are only occasionally significant, estimates may also be entered as 'Remarks', but individual terrain-correction sheets may be needed for each station in rugged areas. Additional columns may be reserved for tidal and drift corrections, since drift should be calculated each day, but such calculations are now usually made on laptop PCs or programmable calculators and not manually in field notebooks.

Each loop should be annotated with the observer's name or initials, the gravity-meter serial number and calibration factor and the base-station number and gravity value. It is useful also to record the difference between local and 'Universal' time (GMT) on each sheet, since this will be needed when tidal corrections are calculated.

Gravity data are expensive to acquire and deserve to be treated with respect. The general rules of Section 1.4.2 should be scrupulously observed.

2.5 Field Interpretation

Gravity results are usually interpreted by calculating the fields produced by geological models and comparing these with the actual data. This requires a computer and until recently was only rarely done in the field. Even now, an appreciation of the effects associated with a few simple bodies can help an observer temporarily severed from his laptop to assess the validity and significance of the data being collected. This can sometimes lead to a vital decision to infill with additional stations being taken at a time when this can be done quickly and economically.

2.5.1 The Bouguer plate

The Bouguer plate provides the simplest possible interpretational model. An easily memorized rule of thumb is that the gravity effect of a slab of material 1 km thick and 1 Mg m^{-3} denser than its surroundings is about 400 g.u. This is true even when the upper surface of the slab is some distance below the reading points (as in the case of the second layer in Figure 2.11), provided that the distance of the station from the nearest edge of the slab is large compared with the distance to the lower surface. The effect varies in direct proportion to both thickness and density contrast.

Example 2.1

In Figure 2.12, if the standard crustal density is taken to be 2.67 Mg m^{-3}, the effect of the upper sediment layer, 1.5 km thick, would be approximately $1.5 \times 0.37 \times 400 = 220$ g.u. at the centre of the basin.

The effect of the deeper sediments, 1.6 km thick, would be approximately $1.6 \times 0.27 \times 400 = 170$ g.u.

The total (negative) anomaly would thus be about 390 g.u.

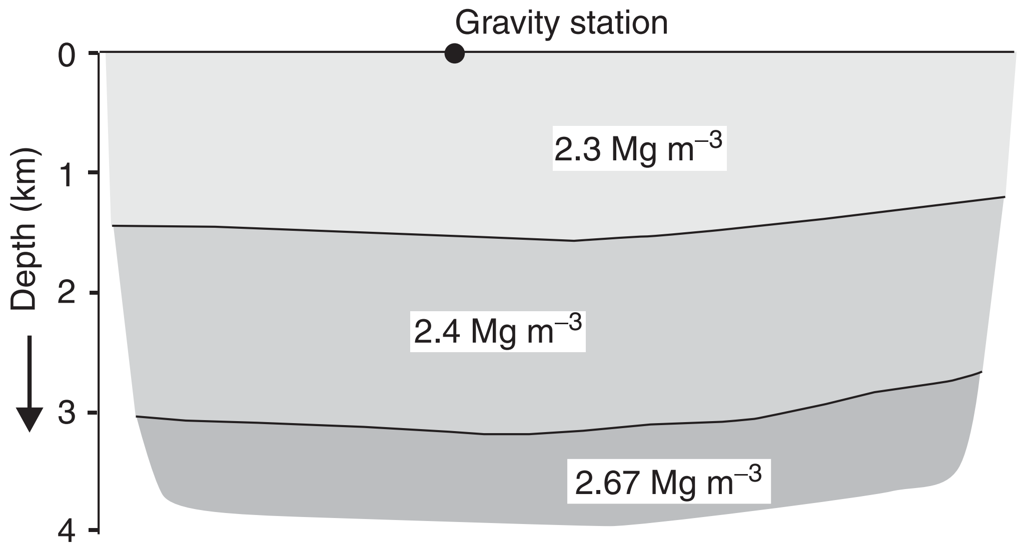


Figure 2.11 *Sedimentary basin model suitable for Bouguer plate methods of approximate interpretation. Basement is assigned the standard 2.67 Mg m^{-3} crustal density.*

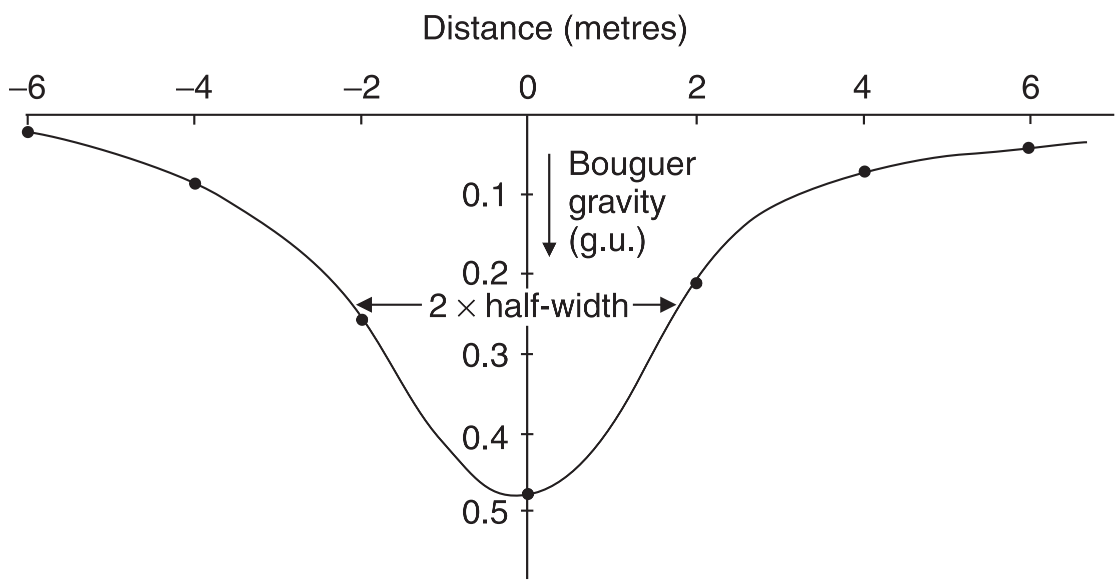


Figure 2.12 *Detailed Bouguer anomaly profile over a subsurface cavity.*

2.5.2 Spheres and cylinders

Less-extensive bodies that produce anomalies similar to that in Figure 2.12 (or its inverse) can be modelled by homogeneous spheres or by homogeneous cylinders with circular cross-sections and horizontal axes. The field due to a sphere, radius r measured at a point immediately above its centre, is:

$$g = 4\pi\rho G r^3/3h^2$$

The factor $4\pi\rho G/3$ is about 280 g.u. for a density contrast of 1 $Mg\,m^{-3}$ and lengths measured in kilometres, or 0.28 g.u. if lengths are measured in metres. The depth, h, of the centre of the sphere is roughly equal to four-thirds of the half-width of the anomaly.

For an infinite horizontal cylinder of circular cross-section (an example of a 2D source), the maximum field is:

$$g = 2\pi\rho G r^2/h$$

The factor $2\pi\rho G$ is about 400 g.u. for a density contrast of 1 $Mg\,m^{-3}$ and lengths measured in kilometres, or 0.4 g.u. if lengths are measured in metres. The depth, h, of the axis of the cylinder is equal to the half-width of the anomaly.

Example 2.2

Interpreting the anomaly of Figure 2.13 as due to a roughly spherical air-filled cavity in rock of density 2.5 $Mg\,m^{-3}$ and working in metres:

$$\text{Half-width of anomaly} = 2\text{ m}$$

$$\text{Therefore depth to sphere centre} = 2 \times 4/3 = 2.7\text{ m}$$

$$\text{Amplitude of anomaly} = 0.45\text{ g.u.}$$

$$\frac{(\text{gravity anomaly}) \times h^2}{0.28 \times (\text{density contrast})} = \frac{0.45 \times 2.7^2}{0.28 \times 2.5} \quad \text{i.e.} \qquad r = 1.7\text{ m}$$

Example 2.3

Interpreting the anomaly in Figure 2.13 as due to a roughly cylindrical air-filled cavity in rock of density 2.5 $Mg\,m^{-3}$ and working in metres.

$$\text{Half-width of anomaly} = 2\text{ m}$$

$$\text{Therefore depth to cylinder centre} = 2\text{ m}$$

$$\text{Amplitude of anomaly} = 0.45\text{ g.u.}$$

$$\frac{(\text{gravity anomaly}) \times h}{0.4 \times (\text{density contrast})} = \frac{0.45 \times 2.0}{0.4 \times 2.5}$$

$$\text{i.e.} \qquad r = 0.8\text{ m}$$

2.5.3 Nettleton's method for direct determination of density

Density information is clearly crucial to understanding gravity anomalies, but is not easily obtained. Samples collected in the field may be more weathered, and so less dense, than the bulk of the rock mass they are assumed to represent, and the density reduction may be accentuated by the loss of some of the pore water. Estimates may also be obtained, rarely and expensively, from borehole gravity or from radiometric well logging, but such data will normally only be available where the work is being done in support of exploration for hydrocarbons.

There is, however, a method, due to Nettleton (1976) by which density estimates can be made directly from the gravity data. The bulk density of topography may be estimated by assuming that the correct value is the one which removes the effect of topography from the gravity map when corrections are made. This is true only if there is no real gravity anomaly associated with the topography and the method will fail if, for example, a hill is the surface expression of a dense igneous plug or a dipping limestone bed (Figure 2.13). The method may be applied to a profile or to all the gravity stations in an area. In the latter case, a computer may be used to determine the density value that produces the least correlation between topography and the corrected anomaly map. Even though the calculations are normally done by the interpreters, field observers should understand the technique since they may have opportunities to take additional readings for density control.

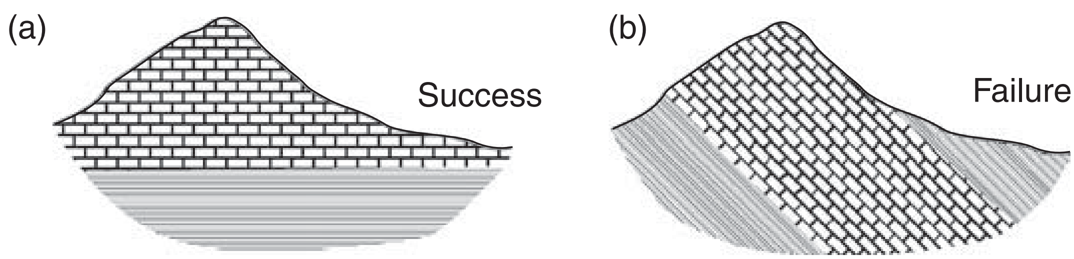


Figure 2.13 *Examples of cases in which the Nettleton (1976) method of density determination could be expected to (a) succeed and (b) fail.*