BEST PRACTICE IN GRAVITY SURVEYING

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Introduction

What does gravity measure?

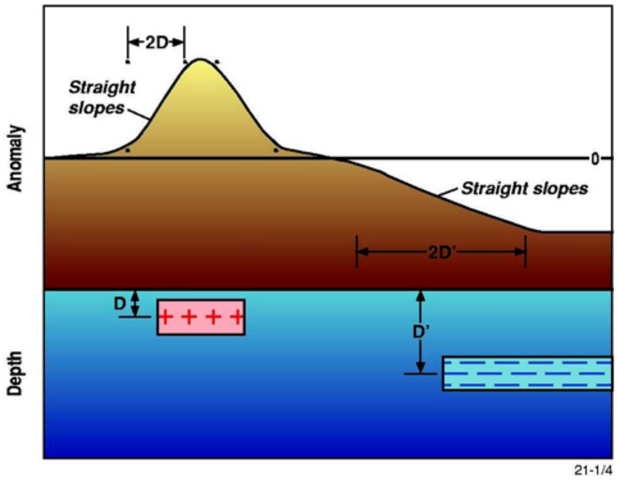
Gravity is the force of attraction between masses. In geophysical terms it is the force due to the integrated mass of the whole Earth, which acts on the mechanism of a measuring instrument. Measurements are usually made at the surface of the Earth, in aircraft or on ships. They may also be made in mines or on man-made structures. The gravity field in space may be inferred from the orbit of a satellite. The measuring instrument may be a very precise spring balance, a pendulum or a small body falling in a vacuum.

If the Earth were a perfect homogeneous sphere the gravity field would only depend on the distance from the centre of the Earth. In fact the Earth is a slightly irregular oblate ellipsoid which means that the gravity field at its surface is stronger at the poles than at the equator. The mass (density) distribution is also uneven, particularly in the rigid crust, which causes gravity to vary from the expected value as the measurement position changes. These variations are expressed as gravity anomalies, the mapping of which gives us an insight into the structure of the Earth.

Gravity varies as the inverse square of the distance of the observer from a mass so that nearby mass variations will have a more pronounced (higher frequency) effect than more distant masses whose effect will be integrated over a larger area (lower frequency). The force is proportional to the mass so that, per unit volume, higher density bodies will cause a more positive gravity anomaly than lower density bodies.

The general rules of gravity interpretation are:

- Higher than average density bodies will cause a positive gravity anomaly with the amplitude being in proportion to the density excess.
- Lower than average density bodies will cause a negative gravity anomaly.
- The areal extent of the anomaly will reflect the dimensions of the body causing it
- A sharp high frequency anomaly will generally indicate a shallow body
- A broad low frequency anomaly will generally indicate a deep body
- The edges of a body will tend to lie under inflection points on the gravity profile
- The depth of a body can be estimated by half the width of the straight slope (between the points of maximum curvature) of the anomaly in its profile as shown in Figure 1.



Definitions

Measurements of gravity are usually expressed in a mass independent term, such as acceleration. The range of gravitational acceleration at the Earth's surface ranges from approximately 9.83 metres per second squared (ms^{-2}) at the poles to 9.77 ms^{-2} at the Equator. Gravity variations within countries and particularly within mineral prospects are much smaller and more appropriate units are used. These units are:

- ◊ Micrometre per second squared (μms^{-2}) = 10^{-6} ms^{-2} (the SI unit)
- ◊ Milligal (mgal) = $10^{-3}cm.s^{-2}$ = 10^{-5} ms^{-2} = 10 μms^{-2} (the traditional cgs unit)
- ◊ Gravity unit (gu) = 1 μms^{-2} (the old American measure = 1 meter scale division)
- ◊ Microgal (μgal) = 10^{-8} ms^{-2} = 0.01 μms^{-2} (often used for absolute measurements)
- ◊ Newton metre per kilogram ($Nm.kg^{-1}$) = 1 ms^{-2} (an alternative form of units)

In this document gravity surveying refers to the field measurement of gravity and the accompanying measurement of position and elevation; surveying used alone has its common meaning of measuring positions and elevations.

What are we looking for?

Gravity operates measurably over the whole range of distances we deal with in geological interpretations and is not shielded, as may be the case with electromagnetic fields. The gravity fields of high and low density distributions may, however, interact to mask their individual signatures.

Gravity is just as useful a tool for investigating deep tectonic structures as part of regional syntheses as it is for finding buried streambeds or caves in urban engineering studies; it is just that the survey parameters and precision required will be quite different. In between these extremes we may be interested in outlining sedimentary basins, rifts, faults, dykes or sills, granitic plutons, regolith drainage patterns or kimberlite pipes. An effective gravity survey can be designed to solve many of the pertinent physical geological questions. We should first decide what we are looking for, and then design the gravity survey accordingly.

How can gravity help us?

Gravity anomalies only occur when there are density contrasts in the Earth, so gravity surveying is only useful if the structure we are investigating involves bodies of different density. The density contrast between the bodies must be high enough to give an anomaly that rises above the background noise recorded in the survey. If the differences in magnetisation or susceptibility are more characteristic of the bodies than density changes then gravity is not the best tool for the job.

The structures we are looking for must vary in density in the direction of the measurements; a series of flat lying strata of constant thickness will not give any change in the anomaly at the Earth's surface. The only deduction we can make is that the mean density of the whole suite is more or less than the crustal average based on the sign of the anomaly. A complicated geological structure at depth may not give a signal at the surface that can be resolved into separate anomalies. In these cases seismic surveys may be more effective.

The size and depth of the bodies we are looking for will determine the optimum observation spacing for the gravity survey. Sampling theory indicates that the observation spacing should be closer than half the wavelength of the anomaly we are seeking. For shallow bodies an observation spacing equal to the dimension (in the measurement direction) of the body or twice the dimension for deeper bodies will detect the existence of a body but not define its shape. Four observations across a body, two just off each edge and two on top of the body (ie spacing about a third of the body dimension) will give a reasonable idea of the shape.

The amplitude of the anomaly we are expecting will determine the survey technique that may be used. Obviously, if we are looking for a 10μms^{-2} anomaly barometer heighting with an accuracy of 5 metres (which equates to approximately 15μms^{-2} in the anomaly) or an airborne gravity survey (with an accuracy of 50μms^{-2}) would not be effective. The introduction of GPS height determination to better than 0.1 m has enabled gravity surveying to become effective for regolith modelling.

If the existing gravity coverage in an area is spaced at 11 kilometres and we are interested in structures of 10 km dimensions we should see some evidence for these bodies in the existing anomaly pattern. If the anomaly pattern is basically featureless it indicates that no 10km bodies with significant density contrast are present in the area. When considering doing a gravity survey it is essential to look at the existing data and use that in the decision process and survey planning.

The environment may have a bearing on the type of survey that can be done or if one can be done at all. For example, it may be impossible to do a ground survey in a heavily rainforested area without cutting access lines. The landscape may be so rugged that even though a land survey can be done, the terrain corrections (described below) are the main part of the measured anomalies and accurate calculation of these corrections is very difficult. The area may be covered by shifting sand or swamp, making the stabilisation of a meter very difficult, even if you could place one on the surface. In these areas a lower resolution airborne survey may be the only possibility.

The gravity anomaly pattern is ambiguous in that the same pattern can be produced by an infinite number of structures, however, most of these are physically impossible or highly unlikely and a skilled interpreter can usually narrow the range of solutions to a fairly well defined class. Problems can arise when the effect of one body largely cancels out the effect of another body. Subtle high frequency perturbations on the anomaly profile can indicate that this is occurring.

Gravity Surveying

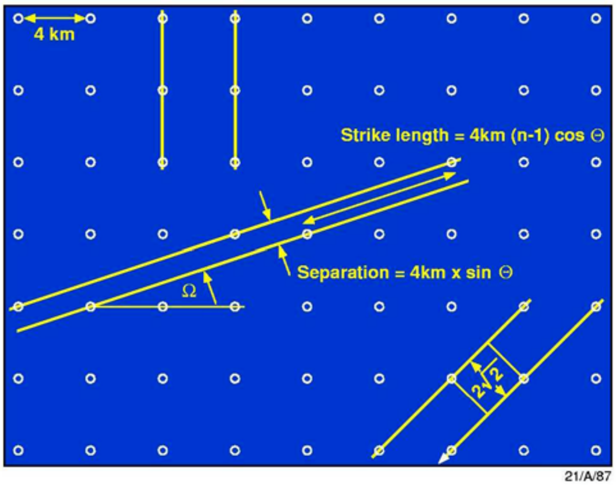
Gravity Survey design

Choosing survey parameters for the target

The scientific design of gravity surveys can make the difference between a highly successful interpretation tool and a waste of resources. The broad scale surveying of the continent with an observation spacing of 11 kilometres could be justified by the need to define the tectonic structure of the continent and to determine the size and extent of the major tectonic units. Surveys designed to solve geological problems should contain sections of various station spacing.

- ***Orientation***

Designing a gravity survey at an angle of about 30/60 degrees to the strike direction of the geology can often provide more information than one oriented at right angles, as illustrated in Figure 2. If a 4km grid runs parallel to a dyke 500m wide it is possible to miss the full effect of the body. If the grid is aligned at 30˚ the effective grid spacing is 2km (4km sin30˚) across the dyke and its position and size would be much better defined. If we were looking for small circular features such as kimberlite pipes the station spacing would be critical but not the orientation.



- ***Density / spacing***

In regional surveys, observation density or station spacing is often calculated from the area to be covered divided by the number of stations that can be afforded within the budget. When planning the station spacing consideration should be given to the existing anomaly pattern (which areas show high frequency effects and which seem to be smoothly varying) in conjunction with the known geology (where are the dense bodies and where are the sedimentary rocks or granites). Using this information and, if available, the aeromagnetic anomalies a series of polygons can be constructed to delimit areas of higher and lower desired station density. In areas of long linear features it is worth considering anisotropic spacing (eg 2 x 1km) with the closer spacing aligned across the features. If no previous or indicative gravity data is available an evenly spaced coverage should be surveyed first, followed by targeted in-fill based on the results of this even coverage.

- ***Regular grid or opportunity (along roads)***

In most parts of the country a regular grid of observations will necessitate the use of a helicopter for transport; this will increase the cost by 50 to 100% compared with road vehicle gravity surveys. In urban areas and farming areas with smallholdings fairly regular grids of 1, 2 or 4km can be achieved by utilising road transport.

Access may be influenced by the geology, so when conducting gravity surveys on roads it is necessary to check that the roads are not located preferentially along the geology if that is going to adversely bias the results. For example, roads are often positioned along ridgelines or river valleys for convenience of construction. In some cases this bias is an advantage; such as the greenstone belts of the Eastern Goldfields of Western Australia where the land is more fertile on the greenstones and hence roads and sheep or cattle stations tend to be located on them.

- ***Effectiveness of detailed traverses***

Detailed traverses provide useful information for interpreting extensive linear features but are of limited use in constructing a reliable gridded surface of an area. When planning a regional gravity survey of an area the coverage should be as regularly spaced as possible in all directions. If, for example, the survey is along roads spaced at 20km apart, reading stations at less than 5km spacing along the roads may not be cost effective. If minimal extra cost is involved closer stations may be read to give greater reliability to the data.

Station Selection

The position of gravity stations should be chosen carefully. The aim is to avoid the reading being influenced by physical effects that are difficult to quantify. The requirements for stations that need to be re-occupied are described in a later section.

- ***In rugged country***

The standard formulae for the calculation of simple gravity anomalies assume a flat earth surface at the observation point. Any deviation from a flat surface needs to be compensated by a terrain correction (see below). As terrain corrections are difficult to compute accurately for features near the station it is better to choose a station position that minimises this problem (Leaman 1998). If possible the gravity station should be sited on a flat area with at least 200m clearance from any sharp change in ground elevation.

- ***What to avoid - moving locations***

In addition to avoidance of large changes in elevation nearby, the gravity station may need to be moved from its predesignated location because:

◊ Dense vegetation prevents a helicopter landing or would interfere with the GPS
◊ Boggy, swampy or snow covered ground prevents access to the site
◊ Soft sand, loose rock or mud does not provide a stable footing for the meter
◊ The site is exposed to strong winds
◊ The site is in a river or lake
◊ The site has an important cultural significance
◊ Access to the site has not been granted or the site is dangerous

When the station location needs to be moved it should not be moved more than 10% of the station spacing unless absolutely essential so as to maintain regular coverage.

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- ***City gravity surveys***

Constructions in cities, towns, airports or mines, for example, can introduce many terrain effects that are not immediately obvious. Noise and vibration may also be a cause of concern in these locations. The following points need to be considered:

◊ Measurements near excavations (pits, tunnels, underground car parks) will need to be corrected for terrain effects
◊ Dams, drains, sumps and (underground) tanks that have variable fluid levels should be avoided.
◊ Measurements in or near tall buildings or towers will be affected by terrain and are susceptible to noise from wind shear. GPS reception may also be poor.
◊ Sites near major roads, railways, factories or heavy equipment will be subject to intermittent vibration

Urban measurements should be made in parks, outside low-rise public buildings or at benchmarks (for quick position and height control).

Combining different disciplines

Broad scale geophysical surveying is a costly exercise whichever scientific technique is being employed. It is sensible to consider employing two or more techniques when this can be done at a marginal cost increase over the primary technique and without undue compromise to the efficiency and scientific validity of either technique.

- ***Gravity and geology - competing requirements***

Joint gravity and geochemical sampling has been done successfully in Western Australia with a reasonably regular 4 km gravity grid being established. The demands of the geological sampling may bias the positions to streambeds, outcrops or particular soil types. These positions may also pose terrain effect problems. The combined methods can best be accommodated in regional in-fill using 4 or 5 km station spacing.

- ***Gravity bases at geodetic or magnetic sites - synergies***

Siting gravity stations at geodetic or magnetic primary reference points has several advantages. The total number of sites may be reduced. Measurements can be made concurrently thus reducing the operational costs. Deflections of the vertical and defining of the local slope of the geoid may be important in very precise measurements. Precise measurements at exactly the same point over time can be correlated to define crustal movement.

Assessment of different platforms

Gravity meters measure gravity acceleration so any other acceleration acting on the meter, such as occurs in a moving platform (aircraft, ship, etc.), will distort the measurement. If the platform is moving at a constant speed or the instantaneous accelerations can be calculated, a correction can be applied to the gravity reading to give a meaningful result, however, the value will not be as accurate as a measurement made on the ground.

- ***Aircraft - airborne gravity & gradiometry surveys***

Airborne gravity contractors quote an accuracy of 10μms^{-2} for their work The absolute accuracy is more like 50μms^{-2}. The former figure may reflect the relative precision along a flight line but the values are subject to instrument drift and air movements that cannot be adequately adjusted out by using crossover ties. Airborne readings are usually filtered by a moving average 5 or 10 point filter so the effective wavelength is longer than the sample spacing would imply. These methods are quite expensive compared with conventional ground readings and do not compete on price or quality. They are only effective in areas which are very remote, forested, water covered, swampy or dangerous (pollution, mines or animals). They are ineffective in areas of rugged terrain due to terrain effects and the extreme difficulty in maintaining a perfectly steady flight path.

Airborne gradiometry promises to be a much more useful exploration tool. It relies on the simultaneous measurement of gravity at two or more closely separated locations. The apparatus is constructed in such a way that nearly all the extraneous forces will cancel out in the comparison of the two (or more) observations and the output will be a gravity gradient tensor (gradient vector). The gradients are useful by themselves as high frequency response sensors of the geology, but for quantitative modelling a good ground gravity survey of the area is required to provide the ground constraint.

- ***Ship - submarine***

Seaborne gravity surveys are subject to similar stability problems as airborne gravity surveys but to a lesser degree. The movements of the sea in deep water tend to be slower and more predictable than air currents and a large ship will not be greatly affected by chop and swell on a calm day. Obviously gravity surveying in rough weather will give poor results. The elevation of the observation, which is critical in calculating the gravity anomaly, is reasonably well defined for sea surface measurements. Before GPS positioning became the standard the accuracy of marine gravity surveys was 5-10μms^{-2} or worse. New gravity surveys appear to have an accuracy of 1-5μms^{-2} which is an order of magnitude less accurate than land gravity surveys. Submarine gravity surveys are less accurate still and have been only a curiosity. Submarine or sea bottom gravity surveys may be useful in the future for pinpointing high-grade mineral deposits on the sea floor. Underwater gravity meters have been used in shallow water and can give similar accuracy to terrestrial readings.

- ***Vehicle - car, 4WD, quadbike, motorbike***

Conventional gravity surveys are often carried out using a wheeled vehicle to transport the operator and equipment between the observation sites. At the observation site the gravity meter is lifted out of its box or cradle and placed on the ground or a base-plate and the meter is levelled and read (optically or digitally)
Standard vehicles are used in built up areas or closely settled farmland with good roads. 4WD vehicles are used on rough tracks, along fence lines or across paddocks, quadbikes (4WD agricultural motorbikes are useful in densely timbered or scrubby areas where turning ability and vehicle weight are important. Two wheel motorbikes may be convenient along traverse lines. Care must be taken that gravity meters are protected from bumps and vibration as much as possible.

- ***Helicopter - heligrav***

Helicopter transport may be used for conventional gravity surveys where large distances are travelled between the observation sites and where a regular grid is required. They are the most effective (though more expensive) method of transport in remote areas. Heavily forested and very rugged terrain may be problematic.
The Scintrex Heligrav system is a self-levelling digital reading gravity meter, with attached tripod, which is suspended by cable from a helicopter. The system is carefully lowered onto the ground and the helicopter backs off to remove the down-draft from the meter and slacken the cable and then hovers while the reading is made. The data flows between the helicopter and the meter via an umbilical cord attached to the cable.

Precision & Accuracy

What can we aim for?

The most precise absolute gravity measurements are pushing towards 0.001 μms^{-2} or 0.1 μgal. Relative gravity meters can now be read to 0.01μms^{-2}. Gravity anomalies, described later, are the most useful representation of the gravity field for interpreters; they can be calculated from gravity survey data to an accuracy of about 0.3 μms^{-2}.

What are the constraints?

The accuracy and effectiveness of gravity surveys depends on several independent variables as described below. The techniques for measuring these parameters improve over time and at any stage one or other of the techniques may be the limiting factor in attaining the ultimate precision.

- ***Positions***

Positions were originally obtained by graphical methods - plotted on topographic maps or pin pricked on air photos and transferred to base maps. The precision of these methods was about 0.1 minute of arc (~200m). Detailed gravity surveys were surveyed with theodolites and are accurate to about 10 m. Hand held GPS receivers with selective availability (SA) give positions to 100m and without SA to 7m. Differential GPS can give positions to ±1 cm.

- ***Heights***

Heights for regional gravity surveys were originally measured using aneroid barometers with accuracy of 10+m, then micro-barometers (5m) and then digital barometers (1m). In practice the accuracy achieved depended on the variability of the weather pattern. Detailed gravity survey heights were surveyed using theodolites and stadia to a precision of 0.1m but the accuracy of these measurements could drift by several metres along traverses away from height control. Hand held GPS are not suitable for heighting but dual frequency receivers with base control can give heights to a few centimetres. The local model of the geoid must be known to correct geocentric heights to local elevations or a local correction determined from benchmarks. The correction (n values) from the geocentric height to the local geoid (AHD) can be found on the Internet. Airborne elevations were measured by altimeters (pressure gauges) or radar but now GPS receivers are used. Marine water depths are measured by sonar.

- ***Gravity***

Gravity surveyors originally used quartz spring meters with a scale range of as little as 1400μms^{-2}. Measurements could only be made over larger intervals by resetting the scale range with a coarse reset screw or dial that required precise manual dexterity to achieve any repeatability of readings. Resetting the scale range also causes stresses in the mechanism, which relax slowly (over hours or days); this is manifested by irregular meter drift. The precision of these quartz meters was about 0.1 μms^{-2} but the achieved accuracy was often only 1 μms^{-2} or more if a reset had been made. The new electronic quartz meters, such as the Scintrex CG-3, have a worldwide range and incorporate software to compensate for meter tilt and to remove tidal effects and drift; they have a precision of 0.01μms^{-2}.
La Coste and Romberg (LC&R) steel spring gravimeters have a worldwide range and a precision of 0.01μms^{-2}. The scale factor varies with dial reading and is tabulated by the manufacturer. The drift rate of LC&R meters decreases as they age and is generally less than the drift of quartz meters.

What accuracy do we really need for the job?

The accuracy required of the three components in gravity surveying (gravity value, position and height) is determined by the object of the measurements. Control stations for one of the components will obviously need to have the greatest accuracy in that component, values for the other components may not even be necessary. Observations for anomaly mapping will generally be dependent on height accuracy for the overall accuracy.

- ***Base network***

Gravity base stations are points where the gravity value is well defined and which value can be used as a reference for gravity surveys being done in that area. The Fundamental Gravity Network (FGN) of base stations is used as the primary gravity control points for Australia. Only the gravity value is necessary at these points although the position is useful for locating the station and the height may be useful for geodetic purposes. The gravity value should be accurate to at least 0.05 μms^{-2}. Many of the older network stations may have much worse accuracy than this.

- ***Bases within a general gravity survey***

Base stations for gravity should be accurate to 0.1 μms^{-2} and for height to 0.05 metre.

- ***Reconnaissance coverage***

An adequate accuracy for 11 kilometre and 7 kilometre spaced stations is 1 μms^{-2} and 1 metre. These figures will give an anomaly accurate to ~ 3.2 μms^{-2}. Much of the historic reconnaissance data has height accuracy of only 5 metres.

- ***In-fill***

The desired accuracy for 4 kilometre and 2 km spaced stations is 0.3 μms^{-2} in gravity and 0.1 metre in height. These figures will give an anomaly accurate to ~ 0.42 μms^{-2}.

- ***Mineral prospect***

The accuracy of mineral prospect gravity surveys is dictated by the expected amplitude of the anomalies. An anomaly of 0.1 μms^{-2} may be quite significant in the delineation of an ore body. This will require an accuracy of 0.05 μms^{-2} and 0.1 metre. The gravity values do not have to have FGN control, as relative anomalies will serve the purpose, however a tie to the FGN will allow the survey to be integrated into the regional context.

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- ***Engineering***

Engineering gravity surveys are usually extremely detailed and of limited extent. The height precision may be relatively more important than for the mineral prospect case. The required accuracy is 0.05 μms^{-2} and 0.05 metre. For some engineering gravity surveys a gravity value tied to absolute datum is required. Repeated measurements at the same points over time, to detect crustal movements, need to be of the highest possible accuracy.

- ***Detailed traverse - cross-section***

Detailed traverses require a high accuracy relative anomaly for modelling. Relative gravity and height values to an accuracy between 0.1 and 0.05 μms^{-2}, and 0.1 and 0.05 metre depending on the station spacing (eg 250 m and 50 m). The absolute values are not essential for modelling the traverse in isolation but are necessary when integrating the traverse into the regional field. The absolute accuracy is less critical.

Equipment

Gravity Equipment

There are three main classes of gravity measuring instruments:

◊ Pendulums - where the period of the pendulum is inversely proportional to g

◊ Sensitive spring balances - where the spring extension is proportional to g

◊ Falling bodies timed over a fixed distance of fall in a vacuum tube

Within each class there are several variants; the types which have been used for geophysics in Australia are described below. The spring balances are relative instruments, which means that they can only be used to measure the difference in gravity between two or more points. Pendulums can be used for relative and absolute measurements by calculating the ratio of periods measured at two points or the exact period at a particular point. The falling body class measures the absolute gravity.

- ***Pendulums***

The pendulum method of measuring gravity was used all over the world up to the middle of the 20th Century and was the basis for the 1930 Potsdam Gravity Datum. By the time pendulum measurements were phased out in the 1950s the instruments had become quite sophisticated with vacuum chambers, knife edge quartz pivots and precision chronometers. Mechanical imperfections and wear of the pivot were the limiting factors in the accuracy of this class of apparatus.

- ***Quartz spring gravimeters***

The technique of crafting a 'zero-length' spring out of fused quartz lies at the heart of quartz spring gravimeters. The 'zero-length' quartz coil (spring), in theory, exerts the same force regardless of the extension; this implies that the meter has a constant scale factor over the dial range (play of the spring).

The extension of the spring must be related to the gravitational force in a predictable, well-behaved way (preferably linear) in order that the meter can be properly calibrated. The size and play of the quartz springs is limited to ranges between 1400 and 2000 μms^{-2} and hence these meters require a mechanical range resetting screw to enable them to cover the worldwide range of 50000 μms^{-2}. Quartz meters first appeared on the market in the 1930s and were soon generally used for gravity surveying. The early quartz meters were not thermostatically controlled and tended to exhibit a diurnal drift curve. Examples of the quartz spring meters are the Worden, Sharpe and Sodin meters. Scintrex have developed an automatic gravimeter CG-3 (and higher accuracy variant CG-3M) in which tilt compensation, resetting and drift correction is handled electronically; these meters have a worldwide range. Scintrex has also developed the Heligrav system in which a CG-3 is mounted on a tripod and suspended from a helicopter by a winch. The meter communicates with the operator via an umbilical cord. Manoeuvring the helicopter with the meter dangling below is a highly skilled and risk-prone operation.

- ***Steel spring gravimeters***

Lucien LaCoste developed a gravimeter, known as the LaCoste & Romberg (LCR), with a steel mechanism in the 1950s. This meter has a worldwide range and is less prone to drift than the quartz meters. It is thermostatically controlled to about 50°C. The steel spring has a slowly varying parabolic scale factor which is represented by a table of scale factors for given dial readings. There is some evidence that these scale factors do vary slightly in a non-linear way with age and depending on the way the meters are transported. There are three main variants of the LCR meters, all of which are powered by a battery or plugged into a 12 volt power source. The original G meter had hand levelling screws, a mechanism locking screw, an eyepice focussing on a graduated scale and a graduated reading dial and revolution counter display. Later G meters were fitted with electronic readout but the nulling feedback was not always reliable and optical reading still gave the best results. A high precision model, the D meter, was developed in the 1980s. This had a fine and a coarse dial and was capable of positive precision to 0.01μms^{-2} rather than the eyeball interpolation with the G meter. The fully electronic E meter was introduced in the 1990s.

- ***Absolute meters***

After failing to perfect a highly accurate pendulum and with the development of lasers and atomic clocks, researchers in absolute gravimetry turned to the falling corner-cube method. The corner cube is raised and dropped in a vacuum chamber. Mirrors on the corner cube reflect laser light at particular points on the cube's fall, the distance is calculated by counting interference fringes The corner cube is then raised by a mechanical cradle ready for the next drop. A set of 10 drops gives an average acceleration value. Several sets may be executed to obtain the desired accuracy.
There have been various designs for this type of instrument; some prominent examples are the JILAG, FG5 and A10 'portable' meter.

Positioning equipment

The dramatic improvement in the accuracy of gravity surveying over the last 20 years has been due to the revolution in positioning technology. Positions and particularly heights had been the limiting factors in calculating accurate gravity anomalies. Positioning for the first reconnaissance gravity surveys was done without any equipment, it relied on the observer marking a spot on a map or aerial photograph. Theodolites were used for positioning the more detailed gravity surveys.

- ***Pressure based height instruments***

Atmospheric pressure decreases with altitude, so pressure measurements can be used to calculate elevation. A rough estimate of the pressure decrease is 1 millibar for each 8.7 metre increase in altitude. Theoretically it is possible to calculate an absolute height above sea level if one assumes a standard atmosphere, however atmospheric conditions are constantly changing due to movement of pressure systems and daily heating cycles (diurnals). Reasonably accurate height differences can be measured in a local area (within the same pressure regime as the base) if base pressure variations are recorded, the weather pattern is stable and repeat readings are made at the base and selected field stations during the loop. A detailed description of the method is given by Leaman (1984). The height difference network can then be tied into the Australian Height Datum at one or more benchmarks. Particular problems occur if a pressure front travels through the area during a gravity survey as the base pressure may be out of step with the field pressure during the transit. Pressure measuring apparatus that have been used in gravity surveys are altimeters, precision micro-barometers and digital barometers. The micro-barometers were usually read in banks of three to improve the height statistics and the digital barometers could be directly logged by computers.

- ***Global positioning system receivers***

The introduction of the Global Positioning System (GPS) in the late 1980s enabled gravity to take its place as a precision tool in mapping the fine detail of crustal structure. The GPS receiver monitors time encoded signals being broadcast by a constellation of GPS satellites orbiting the Earth, from 3 or more of these signals the position of the receiver can be calculated in reference to the centre of the Geoid. The position values are referred to as the geocentric coordinates. The geocentric geoid differs from the local geoid so local coordinates have to be obtained by applying a geoid transformation and/or by tying the network to local spatial control points.

GPS positioning

The NAVSTAR Global Positioning System (GPS) provides a method of determining a position based on measurements to orbiting satellites. It is an all weather system that provides position accuracies from tens of metres to millimetres, depending upon the equipment and configuration used. It can be used anywhere on the globe, 24 hours of the day and with no user charge.

GPS technology is used extensively in gravity surveying these days where it has greatly reduced the cost of providing accurate positions and heights. In particular, for surveys where the error in station height is required to be less than 10cm, GPS is considerably cheaper than other methods such as optical levelling.

The basic theory and operation of GPS is described in texts such as Hoffman-Wellenhof et al, 1994 or Leick, 1995. Commercial GPS receivers can be single frequency or dual frequency. The accuracy of a position obtained with a single frequency receiver is about 7m horizontal and 12m vertical compared with about 5m horizontal and 8m vertical accuracy for a dual frequency receiver. These accuracies are possible since Selective Availability, a deliberate degradation of the GPS positions, was turned off on 1 May 2000.

Clearly this vertical accuracy is not sufficient for gravity surveying but it can be improved by employing differential or relative techniques using two or more receivers. In the simplest case of differential GPS, one receiver is set up over a known point, *the base*, while another receiver, *the rover*, occupies unknown points. The corrections that need to be applied to the GPS position for the base to obtain its true position are also applied to the GPS position obtained at the same time by the rover at an unknown point. These corrections can be applied in near real-time by utilising a data link, such as radio-modems, to transmit the corrections to the roving receiver or they can be applied during post-processing of the recorded data from both receivers. This form of differential GPS, or DGPS, can be employed using both single and dual frequency receivers. The differential corrections can be obtained by using your own receiver or can be obtained from a variety of commercial systems that make the corrections available either in real-time or for post-processing. The accuracy of this form of differential GPS can approach sub-metre horizontal and near-metre vertical depending on the quality of receiver used, whether it is single or dual frequency, and the type of corrections applied. The vertical accuracy obtained with these systems, at least one metre, would introduce an error of about 3 μms^{-2} in the gravity value. Clearly the vertical accuracy obtained with this type of differential GPS is not sufficient for most gravity surveys.

Carrier-phase differential GPS provides the highest accuracy and is best suited for gravity surveying. This technique uses the phase differences in the carrier wave of the signals transmitted from the GPS satellites that are received simultaneously at the rover and the base to compute a position for the rover relative to the base. Sub-centimetre accuracy in horizontal and vertical position is achievable using this method of differential GPS. Carrier-phase differential GPS can be either post-processed or computed in real-time. The distance between the base and roving receivers is limited in carrier-phase DGPS owing to differences in the effect of the ionosphere on the satellite signals received at the base and the rover if they are too distant. This distance, known as the baseline, is generally limited to about 20km. The baseline distance may be extended to up to 80km or more in situations where there is no interruption in the satellite signals received by the rover, such as when the roving receiver is installed in a helicopter.

The level of accuracy required in the determination of gravity station positions is dependent to a large degree on the type of gravity survey and the size of the anomalies that are expected to be detected. An error of 10cm in the height of a station would result in an error of about 0.3 μms^{-2}. Errors of this magnitude are acceptable in regional gravity surveys with station spacings in the order of one or more kilometres, however for more detailed surveys the height of the gravity station needs to be determined more accurately. To obtain these greater accuracies, shorter baselines and a more rigorous approach to minimising errors needs to be employed. This more rigorous method increases the cost of the survey by increasing the number of GPS base stations needed and the number of measurements required.

The accuracy of the horizontal position of a gravity station is much less critical with latitude errors producing the most effect. An error of 100 metres in the north-south position will result in about 0.5 μms^{-2} error in the gravity value.

Gravity survey logistic planning and preparation

Survey numbering

Most survey numbering schemes involve the year, or last two digits of the year, in the survey number as a quick and easily recognisable guide to the age of the survey. The original AGSO numbering scheme, developed in the late 1950s, was a four digit number with the last two digits of the year as the first two digits of the survey number. The last two digits of the survey number originally signified the type of survey according to the following rules:

- 00-29: surveys done by or for AGSO/BMR (00 sometimes for control work)
- 30-89: surveys done by other organisations (state governments, private companies, universities or international bodies). At some times certain numbers were reserved for particular states (eg 50-59 for Tasmania) or for marine surveys (60-89), but no consistent pattern was set.
- 90-98: control surveys for the Fundamental Gravity Network
- 99: absolute gravity measurements

In the late 1980s the numbering system was changed to indicate the state as follows:

00-19: AGSO or national surveys
20-29: New South Wales
30-39 Victoria
40-49: Queensland
50-59: South Australia
60-69: Western Australia
70-79: Tasmania
80-89: Northern Territory
90-99: Base and absolute stations as above

Within each state series the government surveys are numbered 0,1,2,etc. and the private company surveys as 9,8,7,etc. If more than ten surveys are done in a state in one year, general numbers from 00-19 may be used. Related small surveys should be given the same number, as should surveys carrying over from one year to the next.

The new AGSO survey numbers, for year 2000 and onwards, are six digits with the first four being the year of commencement of the survey. All the old surveys have had 19 added as a prefix to bring them into line with the new scheme.

Plotting proposed points on the base maps

It is good practice to plot the proposed observation locations on a topographic map before starting the gravity survey. Areas of difficult terrain and cultural features will require the re-positioning of some stations. Private landholders may need to be informed and permission sought for working on their property.

Native title clearances

A large part of Australia is now under Native Title or has been claimed. It is necessary to negotiate access to the land with the leaders of the community. Maps of the proposed station locations will be necessary to help identify areas of exclusion and sacred sites. Negotiation with the titleholders normally takes several months and this time should be allowed for in planning the gravity survey.

Station sequencing

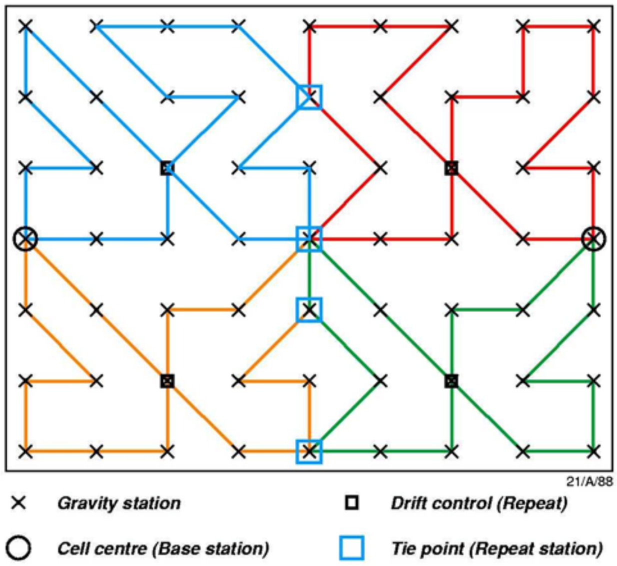
The order in which stations are read may have a significant effect on the cost of transport for the gravity survey and the efficiency of operation. Keeping the time taken for each loop and the distance travelled to a minimum also reduces the risk of error propagation and the loss of data through equipment problems. The position of repeat and tie stations in each loop has a bearing on the strength of the network; for best results these stations should be evenly spaced in the reading order of the loop.

Leapfrogging

In difficult terrain, areas of limited access, or when transport is limited it may be impracticable to control loops from a single base station. One crew may start working from a base station, travel out to the limit of baseline reliability and set up a new base. The old base crew then travels past the new base crew and works until they set up a further base. This leapfrogging procedure continues until a loop closure can be achieved. With limited transport, two crews may set out from base on the helicopter or vehicle, one crew is dropped off at the first station and the second crew is carried to and dropped off at the second station. The transport then returns to the first station and transports the first crew to the third station, then the second crew to the fourth station and so on. This method of leapfrogging is particularly efficient when each crew needs to spend a significant length of time at each station, as for example in a joint geochemical and gravity survey.

Designing a robust network

A gravity survey network is a series of interlocking closed loops of gravity observations. A robust network will generally allow two or more independent paths between any one observation and any other. The design of the gravity survey loop structure, the bases, the repeat and tie stations is critical in enabling accurate station values to be computed with confidence. Repeat and tie stations should not be located at primary position or gravity control stations as this will unduly constrain the network. An example of a gravity loop network is shown in Figure 3.



- ***Minimum number of ties required***

Gravity survey ties to FGN bases, position control stations and where possible other existing gravity surveys are essential for the data to be made compatible with other data in the National Gravity Database (NGD). Ties between gravity surveys will improve the reliability of both and will allow some micro levelling of the data in the NGD in future.

- ***Ties to gravity datum***

All gravity surveys should be tied to the FGN for absolute gravity control. Gravity surveys covering more than two 1:250 000 sheets or extending more than 200 kilometres should tie into 2 or more FGN stations. Ties to older gravity surveys for gravity control should only be made in the absence of a suitable FGN station. Ties should not be made to stations that have only had one previous gravity reading; they should only be made to bases.

- ***Ties to position control and benchmarks***

Ties to height control points (benchmarks) should be made more frequently than to gravity control points. Firstly there are usually many more height control points in the gravity survey area and secondly the geoid has local undulations and the global model used by the GPS processing software does not take these into account. Position control should only be taken from a point that is a recognised geodetic point or, in the case of heights, from a benchmark. Note that geodetic points have an accurate x and y but not necessarily a good z and benchmarks have a good z and poor x and y.

- ***Gravity survey bases***

Gravity survey base stations and cell-centres should be located in flat easily accessible locations and be marked as permanently as practicable. Certainly reoccupations of the point during the current gravity survey should be exact; reading on alternate sides of a point in an area of high local gradient or terrain effect may introduce errors. For primary base stations, photographs should be taken from two directions and a sketch made to facilitate relocation of the station in future.

- ***Control points should not be cell centres***

As mentioned above, cell-centres and other repeat stations should not be located at position or gravity control points. A control point may be used for the primary base station of the gravity survey but this point should not be used as a cell centre as this would have the effect of splitting the network in the matrix inversion process, as described later. The cell centre may be an arbitrary distance from the control point and must have a different station number. For the same reason ties between loops should not be made at control points. To derive reliable statistics about a gravity survey the network nodes should be as freely adjustable as possible.

- ***Repeat and tie stations***

With gravity surveying where each observation is a sample of a physical parameter that is subject to errors from various sources (human or equipment), the more repeats to verify the data, the better. Operationally, however, the less repeats the quicker the gravity survey can be completed. A balance must be struck between achieving reliable results and keeping the cost per new station affordable.

Repeat stations are stations where a reading is made two or more times within the loop, but not as consecutive readings. Tie stations are stations read in two or more loops or two or more gravity surveys. Repeat stations are used to check equipment and processing performance and usually do not play a part in the network adjustment.

In a loop of 23 stations there should be two repeat or tie stations in addition to the cell-centre. For a standard cloverleaf pattern of four loops radiating from a cell centre, if each has 23 stations and the cell-centre is common, there are 89 distinct stations. If there are two repeats or ties in each loop and one cell-centre there will be nine repeats; which is close to 10% of the total

- ***As an insurance against equipment failures***

Many problems can arise during a gravity survey but sound survey design can help to minimise the effects. Problems may be due to equipment; battery failure, transport problems or faulty data logging; or external sources; earthquakes or lack of satellites. When a problem does occur it usually means the loss of the most recently measured data. Data loss can be kept to a minimum by designing repeat or tie stations no more than ten stations apart, data loss is then limited to the stations after the last repeat station.

Marine gravity surveys

Ties to land network - no repeat stations

There are no ties or repeat stations in a marine gravity survey as it is practically impossible to reposition a ship exactly and the tide level would be different anyway. Marine gravity surveys have to be tied to the absolute datum by using a portable land gravimeter to measure the interval between the ship-borne meter and an FGN or known gravity base station at the port of call. Often the ship traverse will not be a closed loop and the control will be two different bases, one at each end. Standard network adjustment does not work in these cases and interpolation or error spreading must be used.

Many marine gravity surveys are designed with crossover lines so an interpolated tie or repeat value can be calculated and used for network adjustment.

Airborne, satellite and gradiometry measurements

Limitations

Direct control of airborne gravity surveys is even more difficult than marine gravity surveys. The best solution is good ground gravity control in strategic places so that an upward continuation to the flying height can be used to check the airborne data.

Ground control is even more important for gradiometry surveys. Conventional gravity survey interpretation can be ambiguous and gradiometry is even more obscure. Using the ground survey as a quantitative constraint, the qualitative value of the gradiometry can be fully exploited.

Field Technique

Calibrating the meters

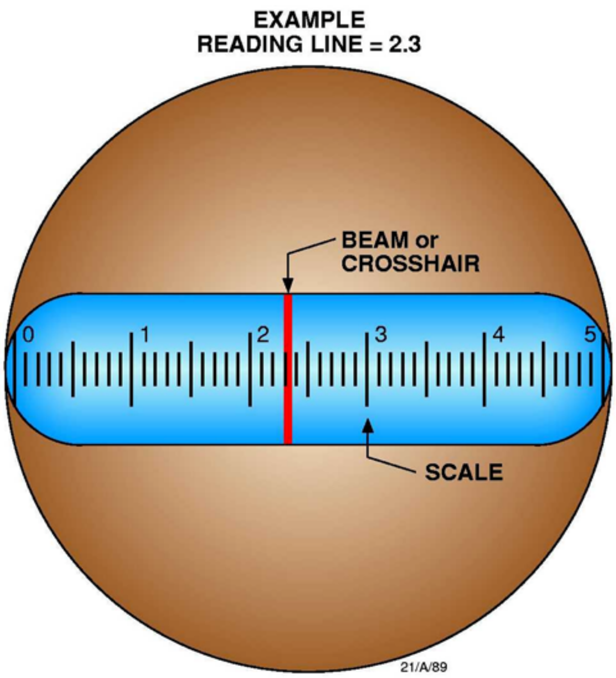
All spring type gravity meters have a scale factor. Quartz meters have a 'constant' scale factor that is often marked on the top of the meter. LCR meters come with a maker's table of scale factors versus dial readings. Scale factors tend to vary slightly as the meter ages, they may also be changed if the meter is overhauled or rebuilt. The scale factor will also change if the level adjustment is off centre, the sensitivity has been adjusted, the vacuum is not tight enough or the thermostat is not working properly. There is also evidence of non-linear effects, which have been documented (Murray, 1995), when several meters are used to measure the same differences between points. For all the above reasons it is recommended that all gravity meters are calibrated before and after each gravity survey. Calibration involves reading the meter at two points of known gravity; the gravity interval between them should be at least 500 μms^{-2}. LCR meters should also be calibrated, even though they have a variable scale factor, as this will detect deviations from the maker's table and help to statistically define each meter's behaviour. Inconsistent calibration results are a good indicator of a faulty meter.
Descriptions and values of suitable calibration points are available from AGSO.

How to read the meter

The secret of consistent and accurate meter reading is following a routine. If the same procedure is followed for each reading the sources of difference are reduced Some tips for a good reading technique with optical meters are:

◊ Level the meter before unclamping
◊ Do not turn the dial while the meter is clamped
◊ Be familiar with the reading line on the graticule and where the beam should be placed as shown in Figure 4 (eg just touching the left of the line)
◊ Always turn the dial in the same direction when approaching the reading line - you may need to wind the dial back past the reading line to do this
◊ Always use the same eye for reading

For electronic meters, keep the recording time the same for each reading



View as seen in eyepiece

Keeping the meters on heat

Observers must be alert to the power status of meters at all times. The temperature of the meter should be regularly checked, any variation would indicate low power or an intermittent power fault. Care should be taken when lifting the meter in or out of the case or cradle that the power leads are not snagged or pulled. At night when the batteries are being charged, the charging controller should be checked for correct cycling. Spare power leads should be available in case of breakages.

Keep an eye on the readings

Check the readings mentally as they are made and compare them with the previous readings in the loop. Is the difference realistic taking into account any appreciable height difference. You should have looked at the existing gravity anomaly map for the area and noted where there are any high gradients. When the loop is closed the final reading should be very close to the initial reading. The maximum tidal difference should only be 3 μms^{-2}. If a reading has an unexpected value and there is no sign of equipment error the point should be repeated later in the loop or tied to by an adjoining loop. If the anomalous reading is verified a few extra step out stations should be read to define the extent of the anomaly.

Limiting the loop times

All gravity meters drift, and the drift is not always linear, so measurements should be made in the form of a closed loop, in which the first and last measurements are made at the same point. The duration of the loop should be restricted to less than six hours wherever possible for the following reasons:

- To keep the risk of equipment failure or earthquake interference manageable
- To keep diurnal effects to monotonically increasing or decreasing functions that can be eliminated with the meter drift
- To reduce the chance of severe weather changes during the loop
- To reduce the effect of any non-linearity in the meter drift
- So that the GPS baseline does not become too long for the required accuracy

Unfavourable conditions

Gravity surveying can be adversely affected by environmental or cultural conditions at individual station sites or applying to the whole gravity survey. The remedy for these problems is to wait for them to abate or to move the station to a better site. In particular, base stations should not be placed in exposed or noisy positions.

- ***Earthquake noise***

Gravity meters are extremely sensitive instruments, they can be affected by large earthquakes anywhere in the world. The effect is manifested by an unstable reading, which tends to oscillate with a period of a few seconds. The beam on an optically read meter will swing from side to side on the scale, the amount of movement will depend on the sensitivity of the meter. On some less sensitive meters the mid-point of the oscillation can be accurately judged and a reading recorded. Electronic meters may show an increased error value and take longer to stabilise.

The intensity and duration of the earthquake effect will depend on the geology of the area, with the greatest effect being on a poorly consolidated sedimentary basin and least effect on cratonic outcrop. Large earthquakes in distant parts can cause disruption to readings over many hours, whereas small local earthquakes have only a few minutes effect.

- ***Windy or stormy weather***

Gravity meters buffeted by the wind will give noisy readings and barometric heights will be distorted by large pressure changes in storms. Close to coastlines ground noise may be generated by large long period waves. Bad weather can also distract the observer making the likelihood of errors greater.

- ***Ambient temperature too high***

Thermostat controls on gravity meters are usually set at about 50°C, obviously if the ambient temperature rises above this the meter temperature may fluctuate, causing errors in the readings. The meter is usually read just above the ground where radiated heat may drive the temperature well above the prevailing air temperature. If the meter is exposed to direct sunlight the, usually black, top plate will heat up and adversely affect level bubbles and cause temperature gradients inside the meter. Meters transported in vehicles without air-conditioning may also be exposed to excessive temperatures. As far as possible meters should not be subject to temperature shocks, for example, taking the meter from an air-conditioned vehicle to a high external temperature.

- ***Unstable footings***

Care must be taken when placing a gravimeter on unstable ground as the meter may move off level during the measurement. Examples of unstable ground are mud, sand, shale, scree, floating ice, salt crust and loose pavement. The meter base-plate may need to be pushed in until the bottom of the flat plate is resting on the surface. A large board may be placed on mud, sand or salt crust to give stability to the meter. The operator should be careful not to dislodge the meter when kneeling or walking beside it.

- ***Cultural artefacts***

Some parts of Australia are under Native Title and negotiation is necessary with the title-holders to gain access to the land under their control. There will probably be some places on this land which are sacred sites or restricted areas and the positions of stations and travel routes will need to be moved to avoid them.

War memorials and churches are often good stable and permanent sites for gravity base stations but sensitivity should be shown and permission sought when a permanent mark is to be placed on the site.

Open-ended loops

All gravity loops should be closed for normal land gravity surveys. Closing a loop means reading the gravimeter at the same place at the beginning and end of the loop. The only way reliable results can be obtained from a loop that is not closed is when the first and last points read are well-defined base stations. Examples of open loops are ship traverses across an ocean or around a coastline, which start at one port and end at another. Another non-conventional loop structure is the ladder sequence, such as A-B-A-B-C-B-C-D-C-D-etc. Although this sequence starts and finishes at different points it can be seen that the series is made up of intersecting closed loops.

- ***Recovering from disasters***

Sometimes a gravity loop can not be completed as planned. This may be due to a vehicle breakdown, bad weather or equipment failure. In this case the last read station should be clearly marked for a follow-up tie. If the last point read in the incomplete loop can not be exactly located the next last should be located and so on until a sure relocation is made. All stations read in the original loop after the sure relocation will be lost. A follow-up tie should be made by reading at this relocated point, then at the original base of the loop and then back at the relocated point if possible, or a tie from base to relocated point to base.

GPS methods

The most common field method used when GPS surveying for gravity surveys is called kinematic surveying. In this method data is recorded continuously by both the base and roving receivers during the gravity loop. In the early days of kinematic survey it was necessary to start recording by occupying a known baseline to initialise the system. This is no longer necessary, due to advances in receiver technology and data processing algorithms and techniques. The kinematic method produces a trajectory of the GPS antenna’s position for the duration of recording. The data can be post-processed or precise positions can be obtained in real-time using a data link.

Real-time kinematic, known as RTK, saves time as there is no need to post-process the data, however it is limited in its use by the reliability of the data link. Most RTK systems use UHF radio modems as the data link between the base and roving receivers. These systems can not be used in rough terrain or over long distances without the use of radio repeaters because the UHF link is generally limited to line of sight operation. Satellite telephones and cellular telephones have been used successfully for RTK surveying where UHF is not suitable, but this is a costly alternative.

Marking base stations

Gravity loop and network adjustment depends on exact reoccupation of a reading station at a repeat, tie or loop-base station. These points are nodes in the adjustment network and any mis-location and consequent differential in gravity value will be propagated through the network, thus reducing its accuracy. The required type and permanence of station marking depends upon the significance of the station in the gravity survey and its use or future use.

- **Repeat stations** are those that are read twice or more within the loop and not in any other loop; a colour tape or spray of paint will suffice for these. This mark only needs to survive for the duration of the loop.

- **Tie stations** are those read in more than one loop, the permanence needed will depend on the likely time between returns. The time span may be several months. A short stake with colour tape and a station number label should suffice.

- **Loop-base stations or cell centres** are the start and end point of loops. Usually these points will be used for a number of loops. Exact reoccupation is very important at these points and a flat stable surface is recommended. The reading point should be marked with paint and a star picket with labelled tape or tag should be driven into the ground beside (within 0.5 m) the reading point.

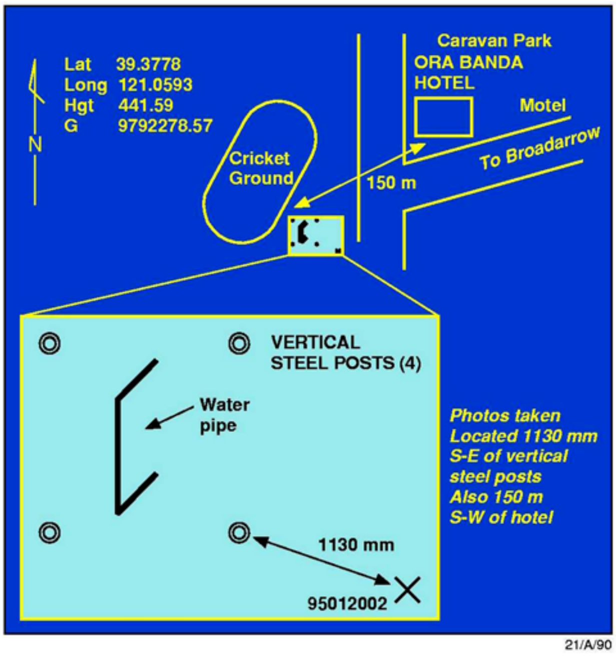
- **Permanent base stations** should be established during the gravity survey to become reference points to which other gravity surveys may tie, All base stations (gravity and elevation) should be permanently marked, for example with a 1.5 metre star picket with approximately 1 metre above the ground. The reading position and station number should be marked on a flat-topped concrete monument of at least 30 centimetre diameter. All base stations should be sketched and photographed for identification and permanently marked with the station number.

Site descriptions for bases or terrain corrections

Some stations need to or should be described so that they can be re-located in future gravity surveys, be used as a reference point or have a terrain correction calculated. General stations located at a named feature, town, bore or homestead &c should be annotated.

- ***Photographs***

Photographs are very useful for providing the geographical context of a station. At least two panoramic shots showing the station and surroundings from opposite directions are needed. Photographs should be on colour film or digital. Some sense of scale and distance should be framed, for example the meter and observer or a vehicle. A photograph of any local topographic features with scale and distance cues would be useful for estimating the near zone terrain correction.



- ***Sketch map***

Diagrams, as illustrated in Figure 5, are useful for the precise location of the observation site, particularly in relation to a building or cultural structure. Exact distances and angles can be annotated and, if necessary, a side elevation can be drawn. Sketch maps of the surrounding area and the district may be included to make the re-location of the station easier. Sketch maps are always made for FGN stations.

- ***What is needed for estimating terrain corrections***

In order to calculate the near zone effect of terrain corrections an approximate model of mass distributions around the station needs to be created. Distances, bearings and elevations need to be estimated for any topographic variation from a flat plain at the elevation of the observation point. If the observation point is on sloping ground the slope and the extent of the sloping ground needs to be estimated. Note that hills and valleys do not cancel each other out in the calculations.

- ***Identifying marks/features, serial numbers of old points***

All stations read on the site of an existing station should be annotated with the name or number of the existing station. Stations located at a named place, in a town, at a point which has a number (benchmark or geodetic station) or at a road junction, for example, should have these details annotated in the description.

Field logging and pre-processing

Data logging

Recording of gravity survey readings up to the 1980s was done manually in field notebooks. Some of these notebooks were designed for data entry to mainframe computer processing and had the fields and columns delimited, but many gravity surveys were recorded free hand. There was always the risk of transcription errors or dyslexia between the dial reading, notebook and keyboard.

Hand held computers and data loggers were introduced in the 1980s. The more sophisticated systems had a basic capacity for prompting and data validation.

In the 1990s digitally recording equipment with direct data logging to disc or computer became the standard.

Processing in the field - checking, verification, instant follow-up

Daily processing of each day's data is very important to check that equipment is functioning normally, satellite lock is maintained, the meter drift is reasonable, and the station readings are sensible. If real time position values have been recorded these can be used for the daily checking. Simple gravity anomalies should be calculated and plotted on a map or imaged to build up a progressive picture of the survey results. Unexpected anomalies should be checked for gravity, position or height irregularity and any obvious errors flagged for re-measurement the next day. If the station values are plausible the station should be re-read, and if unchanged several step-out stations should be read to scope the anomaly.

Processing

Meter drift

Causes of drift

All gravity meters drift. Meter drift is caused by mechanical stresses and stains in the mechanism as the meter is moved, subjected to vibration, knocked, unclamped, reset, subjected to heat stresses or has the dial turned etc, Meter drift does tend to moderate with age as the mechanism creeps to a lower stress level. Meter drift is effectively a temporary and variable change in scale factor.

Drift removal

Removal of meter drift plays a significant part in the accuracy of gravity surveys. Meter drift can only be sampled at points of known gravity or at repeated stations that only account for about 10% of readings in a normal gravity survey. In between these sample points we have to make assumptions about how the drift behaves.

- ***Piecewise linear drift***

The simplest assumption is that drift is linear and, in the absence of documented drift behaviour of each meter, this is probably the logical thing to do. This assumption is the basis of the piecewise linear method of drift removal.

- ***Long term drift***

The long-term drift of a meter can be documented by recording the readings at repeated base stations over a number of weeks or months. From these readings, a long-term drift curve can be constructed. The long-term drift curve is of limited use in modelling the drift performance of a meter over the time scale of a gravity loop but may be useful for ties that take several days to complete.

- ***Drift curves from experience***

The short-term drift performance of meters should be tested more regularly. It is worthwhile running meters over a series of known base stations under operational conditions to see how the meter drift performs. If this is done regularly, a characteristic drift curve may be developed and applied to real gravity survey results.

- ***Automatic drift removal***

Some electronic gravimeters, such as the Scintrex CG-3, have in-built automatic drift removal based on linear drift between loop-base station readings. It is important to check from time to time that the automatic drift correction is working properly, by reading at points with a known or previously read value between the loop-base station readings. Many processing programs will apply a linear drift correction to the loops before network adjustment.

- ***Tares***

Gravimeters are prone to have steps in their drift curves. Some mechanical hitch or stick catches or releases and causes the subsequent readings to be higher or lower than before. These jumps are called tares and may be several μms^{-2} in magnitude. It is often difficult to determine where in the loop a tare has occurred unless it is large enough to be obvious. Tares are detected by the difference in reading at base stations or repeat points being much more than expected from normal drift. If a tare occurs in a loop it should be isolated to a segment between two repeated points and that segment will have to be re-measured. The before and after parts of the loop may need to be separated for processing.

- ***Resetting the range***

Resetting the range on older quartz instruments is an imprecise process and is likely to radically change the drift characteristics for some time after the change. Reliable results will not be achieved if a meter is reset while measuring a loop. A reset could be considered to be a large tare.

- ***Bumps and bangs***

Gravimeters are delicate instruments that can be adversely affected by rough handling. Sudden accelerations may cause tares or changes to the drift behaviour. A meter should be thoroughly checked and re-calibrated after a serious shock such as being knocked over.

- ***Travel sickness***

Prolonged or rough travel may change the drift behaviour of a meter. There is some evidence that meters transported by helicopter exhibit different drift behaviour from those transported by road or on foot.

- ***Morning sickness***

For the first few readings each morning a gravimeter often appears to have an elevated drift. This may be due to prolonged inactivity during the night. There is often a saw-tooth pattern when the readings at a base station, that is read over several days, are plotted. Making one or two dummy readings at the base camp, before starting to make measurements from the loop-base, may alleviate this effect.

Scale factors and calibration

Variability of scale factors

All gravimeters come from the manufacturer with a scale factor or table of factors. However this (these) factor(s) may change over time as the meter becomes worn and the stresses in the materials dissipate. Quartz meters, with a single calibration factor, can be calibrated before and after a gravity survey and the average calibration factor used in the processing of the data. LCR meters, with varying scale factor, should be calibrated between points of known value across a wide range of the dial to detect any variation from the maker's table.

- ***Variation over time***

A table of scale factors versus time should be established so that the appropriate factor can be chosen when reprocessing a gravity survey. For LCR meters a scale factor adjustment factor may be stored. Scale factors may change significantly if the meter is overhauled or upgraded and new sets of factors and dates need to be stored.

- ***Variation with reading***

It is possible that the LCR scale factor adjustment factor is also a function of the dial reading which would require a non-linear adjustment to the non-linear scale factor. A similar problem with the quartz meters is less likely if they are calibrated properly.

Processing of calibration results

Calibration results should be processed before the gravity survey begins to check for any gross difference from the expected value, which could indicate a malfunction in the meter. The average of the pre- and post-survey calibration results can be used to define the scale factor to be used in reducing the gravity survey data.

Post processing and network adjustment

Definition of the network adjustment

The gravity survey network is the set of interconnected loops and the attached control stations. When the scale factor has been determined and the Earth tide correction and meter drift have been removed from the readings in a loop as described above, we are left with a series of gravity differences at each station relative to the loop-base. These differences need to be adjusted to fit any control stations or tie points in the loop. The repeat points may have been adjusted to the same value as part of the drift removal but may be left as measured and adjusted here. The network adjustment is the process of fitting the loops together and using the control points as the datum level. In a simple network where one control value can be propagated throughout, loop by loop, there is no ambiguity in the values. In the case of two or more control values and loops which interconnect each other via different paths a more complex adjustment is required. Commonly, a least square adjustment solution is obtained via a matrix inversion.

Is the network well conditioned?
For a network to be well conditioned all loops must be connected together and the connection point must not be a control station. Adjustments can not be propagated through a control station so a set of non-intersecting loops, which are only connected at a control station, is a fragmented network. Incorrect station identification may also cause a fragmented network.

Processing each meter separately
Results from each meter should initially be processed separately to check that the meter performance is satisfactory. Comparing the tie point values between the meters may also show systematic variations indicating the need for scale factor adjustment. Errors that are detected should be corrected or deleted at this stage.

Choosing the nodes
A node in the network is a tie-point or base station whose several measurements will be adjusted to a single value in the network adjustment. The choice of nodes determines how adjustments are spread through the network. At a minimum the loop-bases and tie points must be specified as free nodes and at least one control point must be specified as a fixed node. Every point that has more than one reading may be specified as a node and every point that has an external value can be used as a fixed node.

- ***Minimal constraint solution***

An adjustment should be made using one control point and the minimum number of nodes needed to link the network. This adjustment will show the internal consistency of the data and highlight station number errors and mis-occupations. Adjustments will be distributed throughout the network with minimal constraint

- ***Using control values to isolate the errors***

Adding more than one control value to the adjustment will introduce constraints on the node adjustments. This will tend to isolate problem areas. Errors in the meter scale factors will be indicated by an increase in the error statistics compared with the single meter adjustments.

Marine and satellite processing

EOTVOS corrections
These corrections are applied to compensate for changes in heading and velocity (change in angular momentum).

Network adjustment - using crossovers
Network adjustment for marine (and airborne) gravity surveys uses interpolated values where the ship tracks cross as the tie points.

Earth Tide corrections

Reason for tidal correction
The Earth is subject to the gravitational attraction of the Sun and Moon. If the Earth were a homogeneous rigid sphere the effects of the Sun and Moon could just be added to the Earth's gravity to obtain a resultant acceleration at the surface; this case would be easy to model and predict. However, the Earth is not homogeneous, rigid or a perfect sphere so the problem of prediction becomes much more complicated.

EAEG tables
For many years the European Association of Exploration Geophysicists (EAEG) published tables of predicted tidal gravity corrections which could be used to estimate the tidal correction at any point at any time in the prospective year. These tables were useful in the days of hand calculation

The Longman formula
With the advent of computer processing in the 1960s an automatic calculation of tidal gravity corrections was required. Longman (1959) developed a Fortran program to compute the tidal effect of the Sun and Moon at the Earth's surface. This code became the basis for the AGSO tidal gravity correction program, which could produce listings of predicted corrections or apply corrections directly to gravity meter readings.

Uncertainties in computation
The above tidal correction formula gives values that are accurate for the ideal Earth modelled but it does not allow for the variable crustal elasticity and the effect of ocean loading. The Earth takes time to respond, by deformation, to the forces exerted by the sun and moon. This response time is manifested as a phase lag. The Earth will deform to a different extent in different places, depending on the elasticity of the crust and the effect of tidal slop in the oceans; this can be represented as an amplification factor. The phase lag and amplification factor are variables peculiar to each point on the Earth's surface. These variations are small but significant for very precise work and may be determined by recording tides for several days at each site.

Automatic corrections
The Scintrex CG-3 gravimeter has tidal correction built in to its software. Most commercial processing software has tidal correction built into its data reduction tool.

Lumping it in with the drift
If the duration of the gravity loop is less than 6 hours it is usually safe, for preliminary results, to assume a linear tide and remove it with the drift. There are times when the tide is large and the maximum or minimum lie in the middle of the loop; in this case the errors may be noticeable.

Gravity anomalies

What are gravity anomalies?
Gravity anomalies are the difference between what is measured and what is expected assuming the reading is made on an homogeneous spheroid. The observed reading is corrected for the expected gravity value at that latitude and height, calculated from the reference spheroid. Other correction terms, which may be applied, are for any masses above the geoid or lack of mass below the geoid, the curvature of the Earth, the weight of the atmosphere, isostatic balance, etc.

- ***Normal gravity***

The normal or theoretical gravity value at a geographic location is calculated using the assumption that the Earth is a regular homogeneous ellipsoid of rotation (the reference ellipsoid). The following equation gives a closed form approximation to the normal gravity based on the 1967 geodetic reference system:

$$g_N = 9780318.5\ [1.0 + 0.005278895 \sin^2\varphi + 0.000023462 \sin^4\varphi]\ \mu ms^{-2}$$

Where: φ is the geographic latitude of the point
A rough rule of thumb is that normal gravity decreases or increases by about one milligal per mile (1 μms^{-2} per 160 metres) at 30° latitude in a north or south direction

- ***Free-air anomaly***

The simple free-air gravity anomaly is calculated using the following formula:

$$FA = g_{Obs} - g_N + 3.086H \ \mu ms^{-2}$$

Where: g_{Obs} is the observed gravity
g_N is the normal gravity on the ellipsoid at that latitude
H is the height of the meter above the geoid (AHD)

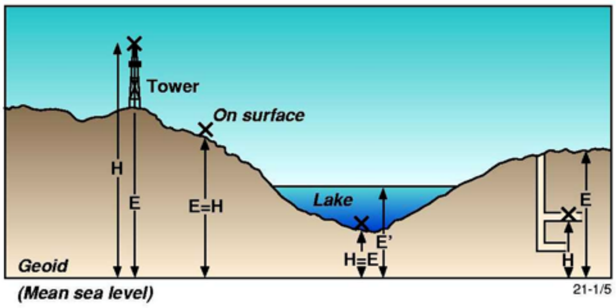
- ***Bouguer anomaly***

The simple Bouguer gravity anomaly is calculated using the following formula:

$$BA = FA - 0.419\rho E \ \mu ms^{-2}$$

Where: FA is the free-air gravity anomaly in μms^{-2}
ρ is the density assumed for the crustal mass around the geoid
E is the elevation of the ground surface above the geoid (AHD)

More complex anomalies may be calculated with extra corrections and for various environments (eg at the bottom of a mountain lake) as set out in the International Gravimetric Bureau (BGI) Bulletin. Several examples are shown in Figure 6.

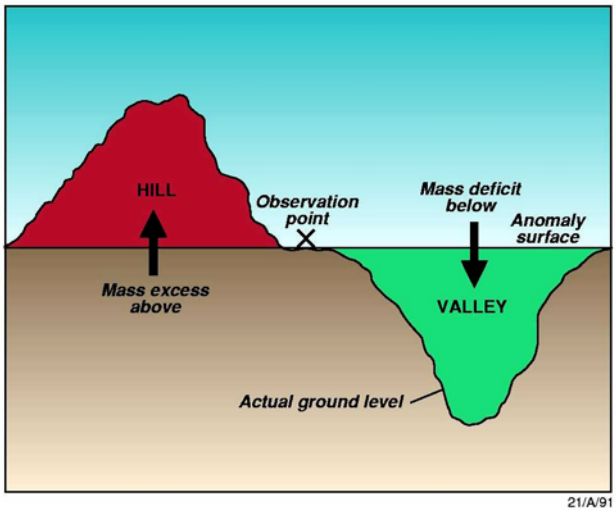


E' = *elevation of lake or ice surface* E = *elevation of ground surface*
H = *elevation of observation point*

Terrain corrections

Definition

Gravity anomalies are calculated on the assumption that the gravity station is sitting on a horizontal plane. If the topography differs from a plane this assumption is incorrect and a terrain correction must be applied to compensate. Any ground above the observation point (hills) tends to attract a mass upwards and any lack of ground below the observation point (valley) reduces the downward attraction as shown in Figure 7. In both cases a positive terrain correction needs to be added to the observed anomaly to normalise its value. The correction is an integral of the gravitational effect of the mass above or the mass deficit below. The correction depends on the density of the surface strata (Leaman 1998).



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Automatic corrections - what do we need?

Many geophysical processing packages now include automatic terrain correction tools. These tools require a file of the regional DTM and the near area DTM and an estimate of the ground slope at the observation point. Both DTMs must be derived from the same topographic base. Australia is now covered by a 9 second (~250m) grid of elevation values. For the near area a 25m DTM is required but is not available in most cases. Satellite radar/laser altimetry promises to provide a micro grid of elevation in the near future.

What size effect is involved?

Terrain corrections are much larger than you think, and extend for much further from a topographic feature. The maximum terrain correction for stations in the NGD is about 250 μms^{-2} even with sensible site selection. The effect of terrain in Australia can extend for up to 50 kilometres.

Some quantitative examples

The following table shows the gravity terrain effect, at various distances, of an escarpment of various heights (using 2.5D modelling). Terrain corrections are shown in μms^{-2}.

Escarpment height	Distance= 200m	1 km	5 km	10 km	20 km	50 km
100 m	6.6	1.8	0.3	0.1	0	0
200 m	24.9	7.1	1.0	0.6	0.3	0
500 m	123.4	43.4	8.0	3.7	1.6	0.5
1000 m	344.6	157.7	32.4	14.8	6.4	1.8

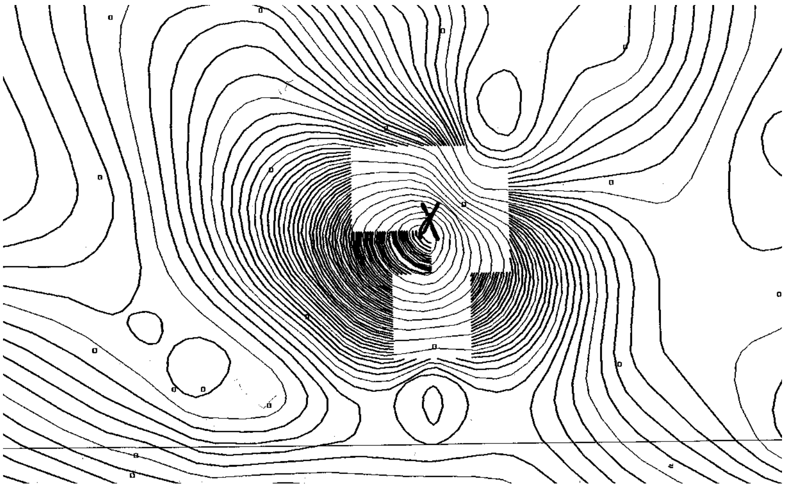
Error detection and quality control

What do errors look like in lists or on maps and images?

Any unexpected break in the pattern of a list or image may indicate an error. Errors come in several forms; single station spikes, loop drift, station mis-tie, positional shift, etc. Any significant single station anomaly is a candidate for error checking. Generally any gravity anomaly which seems to be an artefact of the data distribution should be checked for being a systematic error.

Station	Latitude	Longitude	Height	Gravity	Anomaly
6942.3314	30.65050	139.67033	-0.09	9793556.93	-194.84
6942.3315	30.65033	139.67633	-0.09	9793554.62	-197.01
6942.3316	30.65050	139.68217	-0.03	9793554.12	-197.52
6942.3317	30.65033	139.68783	0.00	9793553.42	-198.03
6942.3318	30.65033	139.69250	-0.03	9793551.72	-199.79
6942.3319	30.65033	139.69850	-0.06	9793549.32	-202.25
6942.3320	30.65067	139.70417	-0.03	9793496.59*	-255.18
6942.3321	30.65050	139.70983	-0.06	9793545.42	-206.28
6942.3322	30.65067	139.71517	-0.09	9793545.22	-206.68

*station 6942.3320 has an error in the gravity value.



X marks an error

Automated detection methods

Automatic error detection relies on statistical analysis or finding data that is out of context. Station values along a line traverse may be checked for sudden jumps or discontinuities in position, height or gravity. Outlier values can be detected during the gridding process when values are boxed into grid cells.

Is it an error or could it be an interesting anomaly?

Reconnaissance gravity surveys with wide station spacing are likely to have quite a few stations with values significantly higher or lower than surrounding values whereas detailed gravity surveys should not have individual outlying values. The size of bodies and realistic density variations set a limit to the amount of variation between stations.

- ***Trend analysis***

Anomalies that do not follow the surrounding trends are suspicious.

- ***Pattern correlation***

Anomalies over particular terrains have a distinctive pattern, anything that does not conform to the pattern should be checked. In some areas the pattern is high frequency and reconnaissance station spacing may not pick up the pattern.

- ***Geological expectation***

The geology of an area will generally predict the trend direction for anomalies and whether long linear features or small high frequency anomalies can be expected.

QC checklist

A reliable data set should have the following characteristics:

◊ Data should be smoothly varying and coherent across the area

◊ Significant anomalies should be supported by more than one station

- ◊ Anomalies should not follow the boundaries of gravity surveys or traverses
- ◊ Trends and lineaments should pass seamlessly across different gravity surveys
- ◊ Anomaly patterns should not conflict with the mapped geology

How to rectify errors in a gravity survey

Check for gravity survey self-consistency

Each survey should be individually checked before being added to a database. Any single station anomalies and pieces of the survey that are inconsistent should be checked. The problem variable should be identified as position, height or gravity by comparing the station with its neighbours in sequence and in position.

Identifying tie points and comparing values

The control and tie points in the problem survey must be identified and their values checked against the current values for those points. In order to do this checking, the control and tie points in a survey must be given the correct original number and be included in the data.

Statistical comparison and grid differencing

Two or more overlapping surveys may be checked by gridding the overlap area of each survey or group of surveys separately and comparing the statistics for the grids. A difference in average values may indicate a datum problem and a difference in standard error a scale problem. The grids may also be subtracted and the pattern of the difference inspected for systematic errors.

Is the projection of coordinates compatible

If the incompatibility between surveys appears to be spatially based, the projections and positional datum should be checked. This may mean going back to the original easting and northing and checking the conversion to geographical.

Changing datum, stretching and tilting

If a datum error has been found and corrected, care should be taken that any change to the survey in question is also reflected in all dependent surveys. A new grid and image should be generated for any area in which changes have been made to check that these changes were effective, were done properly and have not introduced any consequent problems. Where surveys need to be stretched or tilted to fit in with surrounding data or because of a specific problem within the survey, great care needs to be taken to check that the result is satisfactory and to ensure that dependent surveys are not put out of alignment. Usually the control and tie points will be fixed nodes in the transformation and this should quarantine the changes to one survey.

The Australian Fundamental Gravity Network

The development of the AFGN

The Australian Fundamental Gravity Network (AFGN) defines the scale and datum for gravity surveys in Australia and the surrounding oceans. The scale is used to change differences in gravity meter readings to differences in gravity acceleration and the datum is used to convert those differences in acceleration to actual acceleration at each observation point (Wellman et al, 1985a).

The Australian Fundamental Gravity Network was established in the early 1950s using Cambridge pendulum apparatus (Dooley et al, 1961). Ties were made between 59 sites with the observations relative to the station Melbourne A (AGSO station number 5099.9901). Between 1964 and 1967, this network was expanded to a grid of 200 sites consisting of primary stations and excentres on 14 east-west traverses and 3 north-south traverses (McCracken, 1978). The east-west traverses were planned to join places of equal gravity and, for this reason, the network was referred to as the Isogal Network. As the variations in gravity along these traverses were limited to 50-100 μms^{-2}, any calibration errors in the gravity meters were minimised. The north-south traverse along the east coast, known as the Australian Calibration Line (Wellman et al, 1974 and Wellman and McCracken, 1975), was used to define the scale of the network while the other two north-south traverse were used to detect any large errors in the network.

In 1980 a survey was conducted (Wellman et al, 1985a) to strengthen this network and increase its accuracy by taking precise measurements at 67 airports throughout Australia using seven LaCoste & Romberg gravity meters. Ties were also made to six absolute gravity sites that were established in 1979 (Arnautov et al, 1979). These absolute sites became the new datum for the network and for the Isogal84 values (Wellman, 1985b). Further densification of the network has taken place in later years as needed, such as the re-establishment of the Victorian part of the network in 1995 (Murray and Wynne, 1995).

The Australian Fundamental Gravity Network currently consists of about 900 stations at or near over 250 localities throughout Australia. Figure 1 shows the distribution of these stations.

Site selection

Fundamental Gravity Network Stations are preferably placed in a vibration free site that is sheltered from the weather and has an existing concrete base on which a gravity meter can be placed. The actual reading position is marked with either a 6cm brass disc glued to the concrete or, in more recent years, a 2.5cm blue aluminium plug embedded in the concrete flush with the surface. Both markers are stamped with the AGSO station number for identification.

Generally, at least two stations are established at each location. The primary station is located at the most suitable easily accessible site and at least one secondary station, or excentre, is located at another site as a backup in case the primary station is destroyed. Historically, most of these stations have been sited at airports because aircraft were used as transport when the stations were established. Redevelopment of airport buildings over the years has resulted in many stations being destroyed.

Documentation

Station descriptions are available for all Fundamental Gravity Network Stations. These consist of one or more diagrams showing the location of the station and generally two photographs, one distant and one close-up. Information such as the gravity value and, if available, latitude, longitude and elevation are included on the station description. These descriptions, an example of which is shown in Figure 2, are available on request from AGSO and will soon be available on the web.

Calibration Ranges

A calibration range consists of two gravity stations that can be used to calibrate relative gravity meters. The Australian calibration ranges were initially established during 1960 and 1961 primarily for the calibration of quartz type gravity meters (Barlow, 1967). Sites were chosen in Melbourne, Adelaide, Perth, Brisbane, Sydney, Hobart, Alice Springs and Townsville. Since then ranges have been established in Canberra, Darwin and Port Moresby. Some of the original sites have been destroyed and new sites have been established to replace them.

Most calibration ranges have a gravity interval of about 500 μms^{-2} because this approached the largest useable range for some quartz type meters. Barlow (1967) lists the following criteria that were used when selecting suitable sites for calibration ranges:

1. The range should be within reasonable driving time to the area it serves.
2. The gravity interval should be between 500μms^{-2} and 600μms^{-2}.
3. Driving time between stations should be as short as possible.
4. The sites should be accessible at all times.
5. The sites should be permanent.
6. The sites should be easily located and obvious to a new observer.
7. The sites should be free from vibration due to heavy traffic and other causes.
8. The sites should preferably be sheltered from the wind and rain.

In order to obtain the required gravity interval within a short driving distance, most ranges have been located on hills, using the elevation difference to provide the difference in gravity.

LaCoste and Romberg gravity meters are provided with a table of calibration factors covering the full range of the instrument so it is therefore not necessary to calibrate them over the reading range that they will be operating in for a particular survey. However calibration ranges are useful to check the operation and repeatability of these instruments before and after a survey. Accurate calibration of these instruments relative to the Australian Fundamental Gravity Network can be obtained by using a north-south line such as the Australian Calibration Line (Wellman et al, 1985b).

International ties

The AFGN has been tied to the world network by numerous international ties with relative meters and by absolute measurements. A summary of international gravity measurements is given in Murray (1997). In the last four years a number of Japanese, French and Australian absolute measurements have been made at Mount Stromlo near Canberra.

Geodesy

Geodesists use the gravity field to determine the shape of the Geoid throughout the Australian region. The deflection of the vertical is calculated at each gravity station to give an indication of the slope of the geoid around that point. Accurate gravity measurements at primary geodetic points will help to anchor these calculations. It is suggested that the primary geodetic points be included in the AFGN

Future Directions

Absolute Measurements

A systematic network of absolute gravity measurements will be made throughout Australia at selected AFGN stations. These measurements will be used as the reference standard for readjusting the AFGN network to an absolute datum. Future absolute measurements are planned on geodetic points and state survey control marks.

Gradiometry

Gradiometry is a new geophysical tool that provides a different view of crustal density variations. If measured as a full tensor, it contains more information than the vertical component of gravity, but in a qualitative rather than quantitative form. One component of the gradient tensor is the derivative of the observed gravity profile but the gradients have no absolute gravity information so need good ground coverage to provide the reference level.

Multi-disciplinary work

Logistics are the principal costs in doing geophysical surveys. It is sensible to combine several disciplines into one platform. This has been done for marine surveys with seismic, gravity, magnetic and depth measurements being made simultaneously. Airborne surveys have combined magnetic, radiometric and elevation measurements. In future it should be possible to add EM and gravity gradiometry to airborne surveys. Land surveys have combined gravity with geochemical sampling and gravity work has been done using the infrastructure from seismic surveys.

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Appendix A: Gravity Point Located Data Interchange Standard

INTRODUCTION

At a gravity workshop organised by the Australian Geological Survey Organisation (AGSO) in Canberra on the 9th December 1999 a representative group of geoscientists responsible for managing Australian gravity data decided that a standard should be established for the interchange of digital gravity data, based on the ASEG-GDF2 standard. All States (except Western Australia), the Northern Territory and the Commonwealth Government (AGSO and AUSLIG) were represented at the meeting. Des Fitzgerald of DFA (developer of the Intrepid geophysical processing system) and two exploration industry representatives also attended the meeting. A decision was made at the conference of the Chief Government Geologists in 2000 to adopt the ASEG-GDF2 standard for point located data as a minimum requirement.

AGSO is currently moving its geo-scientific databases from divers in-house and unsupported processing packages onto a corporate Oracle system. As part of this process the National Gravity Database is being moved from an in-house database and processing system, which has been running for over 20 years, into an Oracle database with Intrepid as the main data-processing system. This changeover provided an opportunity to consider the format in which we exchange data with the States, Territories, industry and other clients.

In the move towards networked personal computers as the prime data-processing equipment, a standardised form of data exchange is becoming very important. We do not have the skill and facility to write small reformatting programs in the point-and-click environment of Windows NT as we may have had in the command line environment of a mainframe or Unix machine. We just want to be able to suck the data directly into a processing system or a database table with the minimum of effort.

The design of an Oracle point located database requires careful consideration of the required fields, their format and how look-up tables and acronyms are used. When dealing with a database of a million or more records the amount of duplication is important. Some parameters can be logically inferred from others and some can be stored in the survey meta-data table. The same philosophy and much of the structure can be carried across to the data interchange format. Some fields in a point located gravity database or data interchange file are critical and are common while others are more of a housekeeping concern and will be different. Most data interchange involves current or new data and will tend to be a unitary file where all measuring units, gravity control points and positioning parameters, for example, apply to every point value. These parameters can be specified in the meta-data file or the definition file as defined in the ASEG-GDF2 standard (Pratt, 1994). Data may also be exchanged in projected form using northing and easting rather than latitude and longitude, and gravity anomalies rather than observed gravity values. The standard format for gravity data interchange should be broad enough to be convenient and attractive for all types of user while retaining the rigour of a fully self-defining system. The software for packing and unpacking the data should be, ideally, included on the media being exchanged.

RATIONALE

What are the benefits of adopting a national standard for gravity data interchange and why choose ASEG-GDF2? Apart from the aforementioned problem of having to keep writing reformatting code there are a number of important reasons for adopting this standard:

- Discipline – having a standard that is widely publicised on the web, in literature and in tender specifications will make creators and users of gravity data think more clearly about the significance of their data. The specification of mandatory fields will hopefully overcome sloppy reporting practices in which key data fields or base-tie information are omitted. Some parameters that a field operator may not consider as important, such as the base map projection, become critical when divers data sets are assembled into a national database. Writing a standard into government tender specifications will ensure that contracting companies become familiar with the standard and that full value can be extracted from the work performed. We can also encourage the standard being carried over to private contracts by including it in exploration lease reporting requirements.

- Compatibility – having a commonly used standard will not only facilitate the seamless transfer of data between governments, industry and clients but will also encourage the software developers to write the standard into the import/export tools of their processing packages. Australia is fortunate to have several of the big geophysical or GIS software companies based in the country. The data exchange standard must also be independent of equipment and media.
- Integrity – standard specification of field definition, measurement units, base control, survey methods, equipment and accuracy will avoid mistakes and false assumptions and ensure that the data are self contained and recoverable in the future. A standard that includes the survey meta-data will ensure that the information about timing, instruments, contractors, base control, etc. are transmitted digitally with the point data rather than being filed as hard copy in one organisation's archives.

CHOICE OF RECORDED PARAMETERS

The basic parameters or fields for an individual gravity station are those that are actually measured/recorded, or derived from such, at the observation point, these are:

- Stationid – a unique station identifier usually including a survey identifier. If reading at an existing station the original number should be used (if known)
- Latitude or northing – may be result of GPS post-processing
- Longitude or easting - may be result of GPS post-processing
- Elevation of measurement point – often taken to be the ground elevation – may be result of GPS post-processing or pressure measurements, surveying, etc.
- Gravity reading – usually reduced to an (absolute) observed gravity
- Elevation of ground surface or sea bottom if different from above elevation
- Terrain correction – or the topographic information needed to calculate it
- Station type – cell centre, repeat or tie point or normal (survey type) for example
- Comments on location (eg town name), observation conditions (eg windy), marked point (eg benchmark) or particular feature (gate, fence corner, etc.)
- Gravity meter – may be put in the survey meta-data
- Observer – may be put in the survey meta-data
- Date and time – recorded with the field data, usually omitted for reduced data

The first five or six parameters above are mandatory for useful point data, the rest are desirable and should be automatically included as digital data logging becomes the norm. Other information applies to the whole survey or data parcel and should be included in the survey meta-data or DEFN file. These parameters are:

- Survey number
- Survey name
- Time span of survey – start and end dates
- State or country code
- Position units
- Estimated or actual position accuracy
- Base map or projection details
- Positioning method
- Elevation units
- Estimated or actual elevation accuracy
- Elevation datum

- Elevation method
- Gravity units
- Estimated or actual gravity accuracy
- Gravity reference point(s)
- Gravity method
- Date of processing the gravity field measurements to obtain reduced value
- Terrain correction method
- Contractor
- Originating organisation

Many of the above parameters have traditionally been recorded in the report on the survey but have not been stored in digital form. We should aim to capture this information digitally. Other parameters are usually not transmitted with the digital data but are stored in central or national databases to provide a history trail of station records and access controls.

THE PROPOSED STANDARD

The proposed Point Located Gravity Data Interchange Standard allows for all the above parameters and gives guidelines for their definition. While complete information is desirable and will be required in future contract specifications we must accept that much of the existing data in the National Gravity Database and other organisations' data holdings does not contain all this information, or it may be too time-consuming or cost-ineffective to recover it. The standard must be flexible enough to accept as much or as little information as can be provided.

The GDF2 standard permits three types of file for a parcel of data:

- The main point located data file – one text record per observation (station). The records may or may not have a record type label on each record.
- Supporting descriptive information – the survey meta-data file (SMD). COMM type.
- The GDF2 format definition file (DEFN) – may also include units and projection detail.

The gravity data interchange standard defines fields as mandatory, important and useful. In the descriptions that follow the standard fieldname is given in parentheses.

Definition of the mandatory fields:

- Station number (stationno) – a unique gravity station or observation number applying to the point in space where a measurement is made. This number should be used when repeat measurements are made at the same point at later times. The number will change if there is a change in the environment of the point leading to a measurable change in gravity, eg: building changes, excavations or burial. The number is used as a reference to the observation in databases and digital files. For the standard a 10 or 12 character format is adopted. The station identifier is composed of a 6-character survey label preceding a four or six digit station number. The survey label is formed from the year and two additional characters
- Latitude or Northing (latitude) – the latitude of the station in decimal degrees or the northing of the station in metres (projection, origin and zone details to be supplied in the survey meta-data file). Southern Hemisphere latitudes are negative.
- Longitude or Easting (longitude) – the longitude of the station in decimal degrees or the easting of the station in metres. Eastern Hemisphere longitudes are positive.
- Elevation (elevation) – of ground surface in metres (feet) at the position of observation point. The observation may be above (airborne or tower) or below (mine, tunnel, borehole) the ground surface. In marine areas this value is the water depth.

- Observed gravity (obsgrav) – the gravity value tide and drift corrected and network adjusted to the acceleration due to gravity at observation point in micrometres.sec² or milligals. The gravity value may be specified as a free-air or Bouguer anomaly but the method and density should be specified in the survey meta-data (SMD).
- Observation elevation (obselevation) – of the gravimeter or measuring apparatus in metres (feet) at observation point. This parameter is not mandatory if observation is made on the ground surface and the precise difference in height between the ground surface and the measurement sensor position has not been measured.

Definition of the important fields:

- Survey number (surveyno) – the survey in which this (these) observations were made. For repeat readings at a pre-existing station the survey number may differ from the survey part of the station number. If all the data in the transmitted file applies to one survey this number or label should be recorded in the SMD file.
- Position units (posunits) – define the units in which the locations are recorded (eg feet, metres). This value is defined on the position DEFN records set out below.
- Coordinate frame (coordframe) – the description of the coordinate frame of reference used for the positions (eg AMG, WGS84) recorded in the DEFN file. (see App. B)
- Reference ellipsoid (georeference) – the spheroid or geoid used for defining the frame of reference (eg Clarke 1858 Spheroid, Ausgeoid98) recorded in the SMD file.
- Positioning method (posmethod) – defines the method in which the positions were measured or determined (eg GPS, photographs). Put in SMD file (see App. B).
- Elevation units (elevunits) – define the units used for the elevations (eg feet, metres). This value is defined on the elevation DEFN records set out in Appendix C.
- Elevation datum (elevdatum) – defines the datum level for the elevations (eg AHD). This parameter is specified in the SMD file but could be put on a DEFN record.
- Elevation method (elevmethod) – defines the method used to measure the elevation of the ground surface (eg GPS, barometer or survey) in SMD file (see App. B).
- Elevation type (elevtype) – describes the elevation environment of the observation (eg underground, submarine, etc.). It is mandatory if the situation is unusual and cannot be inferred from the elevation and obselevation or it is ambiguous. If all observations are of same type this value can be put in SMD file (see App. B).
- Station type (stationtype) – classifies the station by importance based on method and quality. This important indicator of the reliability should be defined for each station if this is feasible. A value for the survey should be put in the SMD file
- Gravity units (obsgunits) – define the units used for the gravity values (eg milligals, micrometres). This value is defined on the obsgrav DEFN record (see App. C).
- Gravity datum (obsgdatum) – defines the datum on which the gravity values are based. This parameter is specified in the SMD file but could be on the DEFN record.
- Gravity measuring method (obsgmethod) – defines the type of apparatus used for the gravity measurement (eg pendulum, Worden). Specified in SMD file (App. B).
- Gravimeter number (obsgmeterno) – specifies the number of the instrument used for this measurement. Should be on data records where more than one meter was used on a survey. Can be put in the SMD file if only one meter was used.
- Terrain correction (terraincorr) – is the terrain correction computed for the observation point specified in the same units as the gravity value (obsgunits). The terrain correction may be calculated by hand using topographic information recorded at the point or computed from DTM heights or by statistical methods.

- Terrain correction density (TCdensity) – defines the density used in the terrain correction calculations. This parameter is specified in SMD file if it is constant.
- Security classification (restriction) – is a key used to define who has access to these data. For most data transfers this code may be specified in the SMD file.

Definition of the useful fields:

- Position error (poserror) – specifies standard deviation of the position computations in the units used to specify the positions. For most data transfers this code may be specified in the SMD file. This value may be estimated from the method of determining positions (posmethod) but should be included when a value is known.
- Elevation error (eleverror) – specifies standard deviation of the elevation computations in the units used to specify the elevation. For most data transfers this code may be specified in the SMD file. This value may be estimated from the method of determining elevation (elevmethod) but should be included when value is known.
- Observation date (observedate) – is the date on which the observation was made. This information is more important for base and control stations.
- Station description (stationname) – is a concise comment on location, conditions or survey design as exampled on page 3. It is very useful to identify tie points.
- Country or State of survey (countrycode) – indicates the country or State in which the measurement was made. Put in the SMD if it applies to all observation points.
- Gravity error (obsgerror) – specifies standard deviation of the gravity computations in the units used to specify the gravity. For most data transfers this code may be specified in the SMD file. This value may be estimated from the method of determining gravity (obsgmethod) but should be included when a value is known.
- Gravity calculation date (obsgcalcdate) – is of minor importance in most data tranfers but is useful in the National Database. It may be put in the SMD file when known.
- Observation elevation error (eleverror) – is only necessary when the computation of the observation and ground elevations are done independently. There may be an additional error if the difference in heights is estimated.
- Terrain correction error (TCerror) – specifies standard deviation of the terrain correction computations in the units used to specify the gravity. For most data transfers this code may be specified in the SMD file. This value may be estimated from the method of determining terrain corrections (TCmethod) but should be included when a value is known.
- Terrain Correction method (TCmethod) – defines the method used to calculate the terrain corrections. Specified in the SMD file (App. B).
- Comments – useful information or particularities of the processing history.

The standard GDF2 definition records (DEFN) for the above fields are set out in Table 1.

CONCLUSION

The Standard is reasonably straightforward and should not present much difficulty to meet, provided that it is well documented and publicised and is written into government exploration lease regulations and tender specifications. I recommend this Standard to the Federal, State and Territory governments, gravity survey contractors, private mineral and petroleum exploration companies and universities as a positive step in assuring integrity and facilitating exchange of gravity data.

REFERENCES

Pratt, D.A. (1994) ASEG-GDF2 – A data exchange standard for all computer users. ASEG Preview, Issue 50, 46-48.

Table 1. The GDF2 Data Definition File

The first record describes the format of the records in the Survey meta-data file (SMD). The COMM record type allows free format text. The RT:A4 allows for the COMM in the first four characters, the COMMENTS:A76 specifies a length of 76 characters for comments filling up an arbitrary 80 character record. Semicolons separate the fields. The main data file is assumed to be composed of uniformly formatted single observation records with no headers. These records need have no record type code as indicated by the RT=; in the following DEFN lines, however a four character record code may be used.

```
DEFN   ST=RECD,RT=COMM;RT:A4;COMMENTS:A76:  NAME=Description
DEFN 1 ST=RECD,RT=;Surveyno:A6:  NAME=Survey number
DEFN 2 ST=RECD,RT=;Stationno:A12:  NAME=Station number
DEFN 3 ST=RECD,RT=;Latitude:F10.6:  NAME=Latitude
DEFN 4 ST=RECD,RT=;Longitude:F11.6:  NAME=Longitude
DEFN 5 ST=RECD,RT=;Posunits:A3:  NAME=Position units
DEFN 6 ST=RECD,RT=;Poserror:F6.2:  NAME=Position error SD
DEFN 7 ST=RECD,RT=;Coordframe:A10:  NAME=Coordinate reference
DEFN 8 ST=RECD,RT=;Georeference:A10:  NAME=Ellipsoid name
DEFN 9 ST=RECD,RT=;Posmethod:A3:  NAME=Positioning Method
DEFN 10 ST=RECD,RT=;Elevation:F10.3:  NAME=Ground elevation
DEFN 11 ST=RECD,RT=;Elevunits:A1:  NAME=elevation units
DEFN 12 ST=RECD,RT=;Eleverror:F6.3:  NAME=elevation error SD
DEFN 13 ST=RECD,RT=;Elevdatum:A6:  NAME=elevation datum
DEFN 14 ST=RECD,RT=;Elevmethod:A3:  NAME=elevation method
DEFN 15 ST=RECD,RT=;Elevtype:A2:  NAME=elevation description
DEFN 16 ST=RECD,RT=;Stationtype:A1:  NAME=Type of station
DEFN 17 ST=RECD,RT=;Observedate:I8:  NAME=Reading date YYYYMMDD
DEFN 18 ST=RECD,RT=;Stationname:A30:  NAME=Station label
DEFN 19 ST=RECD,RT=;Countrycode:A3:  NAME=Country or State
DEFN 20 ST=RECD,RT=;Obsgrav:F12.3:  NAME=Observed gravity
DEFN 21 ST=RECD,RT=;Obsgunits:A1:  NAME=Gravity units
DEFN 22 ST=RECD,RT=;Obsgerror:F6.3:  NAME=Gravity error SD
DEFN 23 ST=RECD,RT=;Obsgdatum:A1:  NAME=Gravity datum
DEFN 24 ST=RECD,RT=;Obsgcalcdate:I8:  NAME=Calculation date
DEFN 25 ST=RECD,RT=;Obsgmethod:A3:  NAME=Gravity method
DEFN 26 ST=RECD,RT=;Obsgmeterno:A10:  NAME=Gravimeter number
DEFN 27 ST=RECD,RT=;Obsgrefstn:A12:  NAME=Gravity base stn
DEFN 28 ST=RECD,RT=;Obselevation:F10.3:  NAME=Meter elevation
DEFN 29 ST=RECD,RT=;Obseleverror:F6.3:  NAME=Meter elev. error
DEFN 30 ST=RECD,RT=;Obselevmethod:A3:  NAME=meter elev. method
DEFN 31 ST=RECD,RT=;Terraincorr:F6.2:  NAME=Terrain correction
DEFN 32 ST=RECD,RT=;TCerror:A3:  NAME=Terrain corr. error SD
DEFN 33 ST=RECD,RT=;TCmethod:A3:  NAME=Terrain corr. method
DEFN 34 ST=RECD,RT=;TCdensity:F5.2:  NAME=Density used for TC
DEFN 35 ST=RECD,RT=;Obselevmethod:A3:  NAME=meter elev. method
DEFN 36 ST=RECD,RT=;Restriction:A1:  NAME=Security code
DEFN 37 ST=RECD,RT=;Comments:A50:  NAME=Processing information
DEFN 38 ST=RECD,RT=;END DEFN
```

Alternative definitions may be used.

```
DEFN 3 ST=RECD,RT=;Northing:F11.3:UNIT=m, NAME=Northing
DEFN 4 ST=RECD,RT=;Easting:F10.3:UNIT=m, NAME=Easting
DEFN 10 ST=RECD,RT=;Elevation:F10.3:UNIT=m, NAME=elevation
```