

# The earth's gravitational field

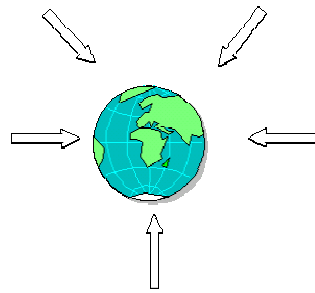
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## Gravity

Gravity is a force that for us is always directed downwards. But to say that gravity acts downwards is not correct. Gravity acts down, no matter where you stand on the Earth. **It is better to say that on Earth gravity pulls objects towards the centre of the Earth.** So no matter where you are on Earth all objects fall to the ground



## What is gravity?

Gravity is a force that attracts objects together. On earth this force attracts everything to Earth.

## The strength of gravity

The Earth is a very large object and it is also very heavy. This means that it has got a strong gravitational field.

**Earth's gravity**, denoted by ***g***, refers to the attractive force that the Earth exerts on objects on or near its surface (or, more generally, objects anywhere in the Earth's vicinity). Its strength is usually quoted as an acceleration, which in SI units is measured in  $\text{m/s}^2$  (metres per second per second, equivalently written as  $\text{m}\cdot\text{s}^{-2}$ ). It has an approximate value of  $9.8 \text{ m/s}^2$ , which means that, ignoring air resistance, the speed of an object falling freely near the Earth's surface increases by about 9.8 metres per second every second.

There is a direct relationship between gravitational acceleration and the downwards weight force experienced by objects on Earth. **Weight** is a measurement of the gravitational force acting on an object. In everyday parlance, however, "weight" is often used as a synonym for mass. **Mass** is a fundamental concept in physics, roughly corresponding to the intuitive idea of "how much matter there is in an object".

The precise strength of the Earth's gravity varies depending on location. The nominal "average" value at

the Earth's surface, known as **standard gravity** is, by definition,  $9.80665 \text{ m/s}^2$  ( $32.1740 \text{ ft/s}^2$ ). This quantity is denoted variously as ***g<sub>n</sub>***, ***g<sub>e</sub>*** (though this sometimes means the normal equatorial value on Earth,  $9.78033 \text{ m/s}^2$ ), ***g<sub>0</sub>***, gee, or simply ***g*** (which is also used for the variable local value). The symbol ***g*** should not be confused with ***G***, the gravitational constant, or ***g***, the abbreviation for gram (which is not italicized).

## Variations on Earth

The strength (or apparent strength) of Earth's gravity varies with latitude, altitude, and local topography and geology. For most purposes the gravitational force is assumed to act in a line directly towards a point at the centre of the Earth, but for very precise work the direction can also vary slightly because the Earth is not a perfectly uniform sphere.

### Latitude

Gravity is weaker at lower latitudes (nearer the equator), for two reasons. The first is that in a rotating non-inertial or accelerated reference frame, as is the case on the surface of the Earth, there appears a 'fictitious' centrifugal force acting in a direction perpendicular to the axis of rotation. The gravitational force on a body is partially offset by this centrifugal force, reducing its weight. This effect is smallest at the poles, where the gravitational force and the centrifugal force are orthogonal, and largest at the equator. This effect on its own would result in a range of values of *g* from  $9.789 \text{ m}\cdot\text{s}^{-2}$  at the equator to  $9.832 \text{ m}\cdot\text{s}^{-2}$  at the poles.

The second reason is that the Earth's equatorial bulge (itself also caused by centrifugal force), causes objects at the equator to be farther from the planet's centre than objects at the poles. Because the force due to gravitational attraction between two bodies (the Earth and the object being weighed) varies inversely with the square of the distance between them, objects at the equator experience a weaker gravitational pull than objects at the poles.

In combination, the equatorial bulge and the effects of centrifugal force mean that sea-level gravitational acceleration increases from about  $9.780 \text{ m/s}^2$  at the equator to about  $9.832 \text{ m/s}^2$  at the poles, so an object will weigh about 0.5% more at the poles than at the equator.

### Altitude

Gravity decreases with altitude, since greater altitude means greater distance from the Earth's centre. All other things being equal, an increase in altitude from sea level to the top of Mount Everest (8,850 metres) causes a weight decrease of about 0.28%. (An additional factor affecting apparent weight is the decrease in air density at altitude, which lessens an object's buoyancy.) It is a common misconception that astronauts in orbit are weightless because they have flown high enough to "escape" the Earth's gravity. In fact, at an altitude of 250 miles (roughly the height that the Space Shuttle flies) gravity is still nearly 90% as strong as at the Earth's surface, and weightlessness actually occurs because orbiting objects are in free-fall.

If the Earth was of perfectly uniform composition then, during a descent to the centre of the Earth, gravity would decrease linearly with distance, reaching zero at the centre. In reality, the gravitational field peaks within the Earth at the core-mantle boundary where it has a value of 10.7 m/s<sup>2</sup>, because of the marked increase in density at that boundary.

### Local topography and geology

Local variations in topography (such as the presence of mountains) and geology (such as the density of rocks in the vicinity) cause fluctuations in the Earth's gravitational field, known as gravitational anomalies. Some of these anomalies can be very extensive, resulting in bulges in sea level of up to 200 metres in the Pacific ocean, and throwing pendulum clocks out of synchronisation.

The study of these anomalies forms the basis of gravitational geophysics. The fluctuations are measured with highly sensitive gravimeters, the effect of topography and other known factors is subtracted, and from the resulting data conclusions are drawn. Such techniques are now used by prospectors to find oil and mineral deposits. Denser rocks (often containing mineral ores) cause higher than normal local gravitational fields on the Earth's surface. Less dense sedimentary rocks cause the opposite. Paris, France has been shown by this method to almost certainly be sitting on a huge, untouchable oilfield.

### Other factors

In air, objects experience a supporting buoyancy force which reduces the apparent strength of gravity (as measured by an object's weight). The magnitude of the effect depends on air density (and hence air pressure).

The gravitational effects of the Moon and the Sun (also the cause of the tides) have a very small effect on the apparent strength of Earth's gravity, depending on their relative positions; typical variations are 2 μm/s<sup>2</sup> (0.2 mGal) over the course of a day.

## Gravity measurements at sea

The gravity measurements at sea are seriously effected by the vertical and horizontal accelerations by the wave action of the sea water and movement of the ship / boat peculiar to the environment. The ship's vertical and horizontal accelerations are compensated by mounting the gravimeter sensors on the gimbals or the stabilized platforms. The Vening-Meinesz pendulum is the earliest instrument that has measured gravity at sea to an accuracy of 2 mGal on board submarines which could handle the small and long period accelerations. The Graf Askania gravimeters mounted on elaborate gyro-stabilized platform have been successful in measuring gravity readings on board surface-ships with an accuracy of 2 mGal. The new Lacoste Romberg gravity meters are being routinely used on board research vessels with an accuracy of 1 mGal.

## Calculation of gravity anomalies

### Gravity reduction

The reduction of the gravity data acquired at sea requires knowledge of absolute gravity reading at the location known as base station value where the ship/boat is berthed prior to the data acquisition. The ship board gravimeter reading at the berth at the start of the survey is recorded ( $gm_{start}$ ) with respect to the start time  $T_{start}$ . The gravimeter reading ( $gm_{end}$ ) and time  $T_{end}$  at the same berth is also noted at the end of the gravity survey. The measured gravimeter readings  $gm_{start}$  and  $gm_{end}$  values are tied to the berth's absolute gravity value and the absolute gravity values at the berth are determined as  $g_{start}$  and  $g_{end}$ . This information will help in determining the drift of the gravimeter, in order to incorporate drift correction, if any, for the data acquired during the survey. The drift correction is applied to each gravity reading  $gm$  and  $g$  (absolute value after tying to the base station value) observed at time  $T$  during the survey at every location in the survey area. The drift correction to the observed data is applied either to the measured gravity reading or the absolute gravity values after the reading is tied to the base station absolute gravity value.

### Drift Correction

Drift is caused by slow creep of the spring and tidal variations, which can be up to 0.3mGal in a day. Drift is measured by returning to the base station throughout the day. Assuming the drift variation of the gravimeter is linear, the drift correction at any point is given by

$$\text{Drift correction} = (gm - g_{start}) * (T_{end} - T_{start}) / (T - T_{start})$$

Although these days improved navigation data is acquired, raw crossover errors of the gravity data were still large. The apparent linear drift with time is subtracted from each observation point which caused probably by incorrect calibration. The incorrect application of drift correction result in increased initial crossover errors in

proportion to the time separation between the two tracks involved in the crossing. The crossover errors are minimized in a least-squares sense by shifting the Free-Air anomaly on each approximately straight trackline segment by a constant value (Prince and Forsyth (1984).

### International gravity formula

The formula for computation of the theoretical value of gravity at the surface of the reference ellipsoid at any given location:

$g(\theta) = 978032.7 [1.0 + 0.0053024 \sin^2(\theta) - 0.0000058 \sin^2(2\theta)]$  mGal is the International Gravity Formula 1967 based on the 1980 Geodetic Reference System. where  $\theta$  = is the geodetic latitude of the location

### Eötvös correction

Eötvös correction is typically associated with shipborne or airborne surveys, is due to the velocity of the moving platform which modifies the centrifugal acceleration of the mass of the measuring device, caused by the earth's rotation.

$$dEg = 7.503 V \cos\theta \sin\alpha + 0.004154 V^2$$

where V is the speed of the moving platform (kph),  $\theta$  is the latitude and  $\alpha$  is the course of the moving platform from true north. The Eötvös correction is minimal for the gravity data acquired along the transects running in N-S direction. Its is negative for the tracks with westward movement and positive for the eastward tracks.

### Free Air Anomaly

The first correction to this formula is the **free air correction (FAC)**, which accounts for heights above sea level. Gravity decreases with height, at a rate which near the surface of the Earth is such that linear extrapolation would give zero gravity at a height of one half the radius of the Earth, i.e. the rate is  $9.8 \text{ m}\cdot\text{s}^{-2}$  per 3200 km. The computation of the free air anomaly incorporates a correction for the difference in elevation between the observed station and the reference ellipsoid:

FA =  $g - g(\theta) + (dg/dz)h + dEg$  Thus:  
 $g(\theta) = 978032.7 [1.0 + 0.0053024 \sin^2(\theta) - 0.0000058 \sin^2(2\theta)] - 0.3086 h$   
 where h = height in meters above sea level

### Bouguer Anomaly

The Bouguer anomaly includes a further correction for the mass between the station and the reference ellipsoid :

BA =  $g - g(\theta) + (dg/dz - 2\pi G\rho)h + dEg$   
 = FA -  $2\pi G\rho h + dEg$   
 = FA -  $0.04193 h + dEg$   
 Where  $\rho$  = Density of the infinite horizontal slab

G= International Gravity Constant  $(6.67428 \pm 0.0007) \times 10^{-11} \text{m}^3\text{kg}^{-1}\text{s}^{-2}$

For flat terrain above sea level a second term is added, for the gravity due to the extra mass; for this purpose the extra mass can be approximated by an infinite horizontal slab, and we get  $2\pi G$  times the mass per unit area, i.e. (the **Bouguer correction**).

### Residual and regional anomalies

The large scale deep-seated structures often predominate the gravity anomalies to such an extent that may be difficult to recognize smaller or shallower features. Removal of the anomalies (*regional*) resulting from the deep structures from the observed gravity maps is essential to enable the anomalies (*residual*) that are caused by the shallow or small geological features of interest. There are several methods of removing the regional anomalies, one of the most common method is graphical / smoothing technique.

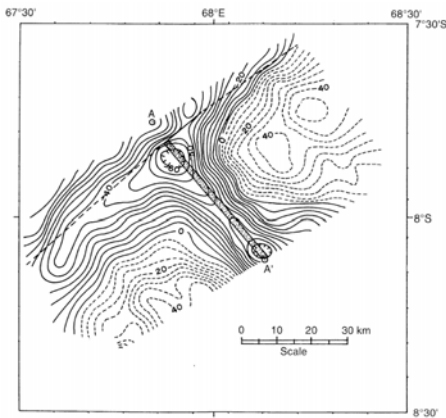
### Preparation of Free-Air and Mantle-Bouguer Anomaly maps

#### Free-air Anomaly Map:

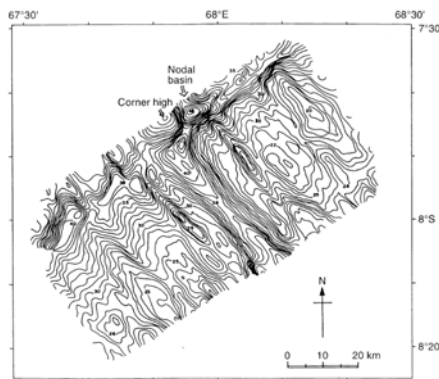
The marine gravity data with navigational position is tied to the base station and reduced for the Eötvös correction before computing the free-air anomaly. The free-air anomalies thus computed at every point with geodetic position, latitude and longitude, are used to generate contour map in the entire survey area. The survey is generally planned to include tie lines across the survey tracks in order to estimate crossover errors or misties at the line crossing of the survey tracks. In the construction of a free-air anomaly (FAA) map, it is essential to reconcile the crossover errors between ship tracks. Crossover errors are primarily due to incorrect calibration of the gravimeter at ports, navigation errors, non-linear drift of the instrument, and cross-coupling errors in the gravimeter (Talwani, 1966; Prince and Forsyth, 1984; Weissel and Watts, 1988). The misties at the crossover points of the track lines are adjusted by adding or reducing constant or gradient of gravity variation along one track with respect other. The method of adjusting the misties varies from one survey to other depending on the geology and the configuration of the regional anomaly pattern.

To interpret the gravity data of any region requires the information of bathymetry and knowledge on the geology. It is therefore requires the preparation of detailed bathymetry map of the region. Depending on the geology, variation of bathymetry and extent of the region the contour intervals are decided to depict the morphology of the study area. The marine free-air gravity anomaly map in general is dominated by the attraction from the topography reflecting major features observed on the bathymetric map. The following example is from

the Central Indian Ridge (Kamesh Raju et al., 1997) where Free-Air anomaly and exhibit a good resemblance with respect to the bathymetry. The bathymetry map is generated from the multibeam bathymetry acquired using Hydrosweep equipment.



Free-air gravity anomaly contour map, contour interval 5 mGal. Dashed contour lines are positive anomalies. Ridge axis location from the bathymetry is superimposed



Swath bathymetric map generated from the Hydrosweep data. Contour interval 50 m. Depths are labeled in hundreds of meters

This indicates that the topography, or the water/crust interface, is the most important contributor to the free-air anomaly. To gain more meaningful results, a map needs to be generated that can directly be interpreted in terms of interesting structures, a forward modelling approach of Prince and Forsyth (1988) has been used to remove the predictable components from the free-air anomaly given proper *a priori* assumptions and attribute the residuals. The predictable gravity field in the model includes (1) gravity effects from the water/crust interface; (2) gravity effects from crust/mantle interface assuming a constant crustal thickness and density; and (3) gravity effects due to 3-D mantle temperature variations. Any error in this model will contribute to the residual gravity anomaly. The error associated with the seafloor topography is small because the topography is well constrained by the hydrosweep

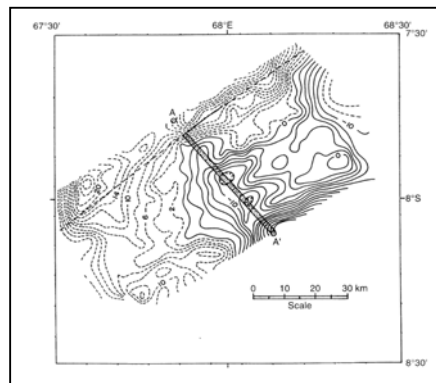
data. Errors due to neglecting sediments are small because sediments thicker than 100 m over the ridge axes. Most of the residual anomalies stem from variations in crustal thickness and density, i.e., the deviations from the assumed constant thickness and density for the crust. A care need to be exercised for variations that possibly represent an unmodelled, anomalous mantle thermal structure.

### Mantle Bouguer Anomaly Map

The free-air anomaly map depicts that the rift valley is defined by a low of about -40.0 mGal and the nodal basin is prominent with a -60.0 mGal low at the Ridge Transform intersection (RTI). In order to visualize the sub-seafloor density structure the mantle Bouguer anomaly (MBA) is computed by subtracting predictable effects of seafloor topography and the effect of the crust-mantle interface from the free-air anomaly, assuming a constant thickness of 6.0 km for the oceanic crust, following the method described by Kuo and Forsyth (1988). The method of obtaining MBA is a two step process:

1. Subtracting the effects of the water-crust interface and the sediment layers from free-air anomaly with a fully three-dimensional calculation of the attraction of the interfaces yields the conventional, Complete Bouguer Anomaly
2. Subtracting the effect of 6km crustal layer below the bathymetry gives Mantle Bouguer Anomaly (MBA)

Assumption of six km thickness of the oceanic crust is a reasonable, as global average value for the oceanic crustal thickness (Spudich and Orcutt, 1980) and any deviation of the average from the assumed value is likely to be small compared to the depth to this interface, so will have little effect on the predicted gravitational attraction. Prince and Forsyth (1988) found that as long as a constant thickness is assumed, more realistic density layering in the crust as suggested by seismic refraction data change the results by only a negligible amount.

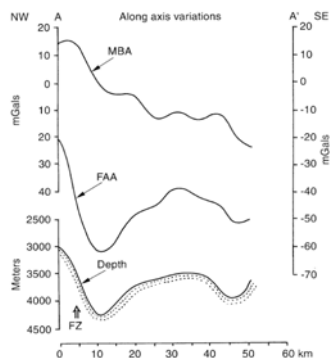


Mantle Bouguer anomaly contour map, contour interval 2 mGal (zero level is arbitrary). Dashed contour lines are positive

anomalies. Ridge axis location from the bathymetry is superimposed

Densities of 1.03, 2.73, and 3.33 g cc<sup>-1</sup> were assumed for seawater, crust and mantle. The MBA map contoured at the 2 mGal interval depicts a minimum value of -14 mGal in the middle of the segment where the median valley shallows. More pronounced typical "bull's-eye" MBA lows, ranging from about -50 to -90 mGals, observed over Mid-Atlantic Ridge segments (Lin et al. 1990; Lin and Morgan 1992; Tolstoy et al. 1993), were interpreted in terms of focused magmatic accretion resulting in significant crustal thickness variations over the ridge segments. Prominent MBA lows are observed over the segments with less prominent rift valley features. The rift valley almost disappeared at the "bull's eye" MBA low, observed at around the 33°S latitude segment of the Mid-Atlantic Ridge (Lin et al. 1990).

In the present example the along-axis variations of depth, free-air gravity, and MBA show shallowing of the spreading axis in the middle of the ridge segment with an MBA low of -14.0 mGal. The MBA low in the middle of the segment with a high toward the northern end probably indicates along-axis variations in crustal thickness. The MBA low observed here is not as prominent as in the case of typical bull's-eye MBA lows documented elsewhere. The well-developed rift valley and the feeble expression of the MBA low suggest depleted accretion probably resulting from the waning phase of magmatic activity. A gradual increase of the MBA away from the median valley occurs, which could be a manifestation of the cooling process of the lithosphere away from the spreading center. The MBA high at the transform we describe probably result from the juxtaposition of younger and older plates at the transform fault zone. The variations of depth, free-air gravity, and mantle Bouguer anomalies along the axis are presented in the following figure.



Along-axis variations of mantle Bouguer anomaly (MBA), Free-air gravity anomaly (FA), and depth along a profile A-A'

## Suggested Reading:

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