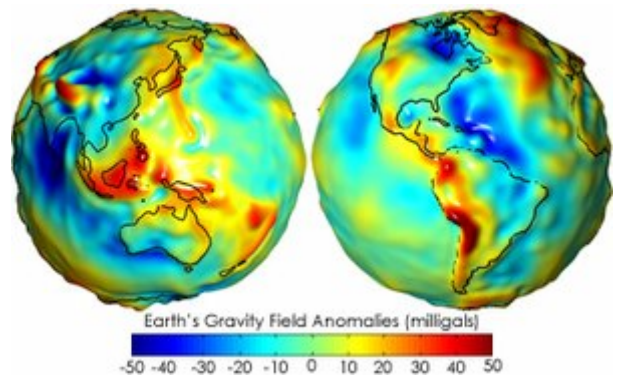


Gravity of Earth

The **gravity of Earth**, which is denoted by ***g***, refers to the acceleration that is imparted to objects due to the distribution of mass within Earth. In SI units this acceleration is measured in metres per second squared (in symbols, m/s² or m·s^{−2}) or equivalently in newtons per kilogram (N/kg or N·kg^{−1}). Near Earth's surface, gravitational acceleration is approximately 9.8 m/s², which means that, ignoring the effects of air resistance, the speed of an object falling freely will increase by about 9.8 metres per second every second. This quantity is sometimes referred to informally as *little g* (in contrast, the gravitational constant *G* is referred to as *big G*).

The precise strength of Earth's gravity varies depending on location. The nominal "average" value at Earth's surface, known as standard gravity is, by definition, 9.80665 m/s².^[2] This quantity is denoted variously as *g_n*, *g_e* (though this sometimes means the normal equatorial value on Earth, 9.78033 m/s²), *g₀*, gee, or simply *g* (which is also used for the variable local value). The weight of an object on Earth's surface is the downwards force on that object, given by Newton's second law of motion, or *F* = *ma* (*force* = *mass* × *acceleration*). Gravitational acceleration contributes to the total acceleration, but other factors, such as the rotation of Earth, also contribute, and, therefore, ~~fact~~ the weight of the object.



Earth's gravity measured by NASAGRACE mission, showing deviations from the theoretical gravity of an idealized smooth Earth, the so-called Earth ellipsoid. Red shows the areas where gravity is stronger than the smooth, standard value, and blue reveals areas where gravity is weaker (**Animated version**)^[1]

Contents

Variation in gravity and apparent gravity

- Legal definition
- Latitude
- Altitude
- Depth
- Local topography and geology
- Other factors
- Comparative gravities in various cities around the world
- Mathematical models
 - Latitude model
 - Free air correction
 - Slab correction

Estimating *g* from the law of universal gravitation

See also

References

External links

Variation in gravity and apparent gravity

A perfect sphere of uniform mass density, or whose density varies solely with distance from the centre (spherical symmetry), would produce a gravitational field of uniform magnitude at all points on its surface, always pointing directly towards the sphere's centre. The Earth is not spherically symmetric, but is slightly flatter at the poles while bulging at the Equator: an oblate spheroid. There are consequently slight deviations in both the magnitude and direction of gravity across its surface. The net force (or corresponding net acceleration) as measured by a scale and plumb bob is called "effective gravity" or "apparent gravity". Effective gravity includes other factors that affect the net force. These factors vary and include things such as centrifugal force^[3] at the surface from the Earth's rotation and the gravitational pull of the Moon and Sun.

Effective gravity on the Earth's surface varies by around 0.7%, from 9.7639 m/s^2 on the Nevado Huascarán mountain in Peru to 9.8337 m/s^2 at the surface of the Arctic Ocean.^[4] In large cities, it ranges from 9.7760 ^[5] in Kuala Lumpur, Mexico City, and Singapore to 9.825 in Oslo and Helsinki.

Legal definition

In 1901 the third General Conference on Weights and Measures defined a standard gravitational acceleration for the surface of the Earth: $g_n = 9.80665 \text{ m/s}^2$. The larger variations described below were not yet known. Therefore this definition is not a value of any particular place or carefully worked out average, but an agreement for a value to use if a better actual local value is not known or not important.^[6]

Latitude

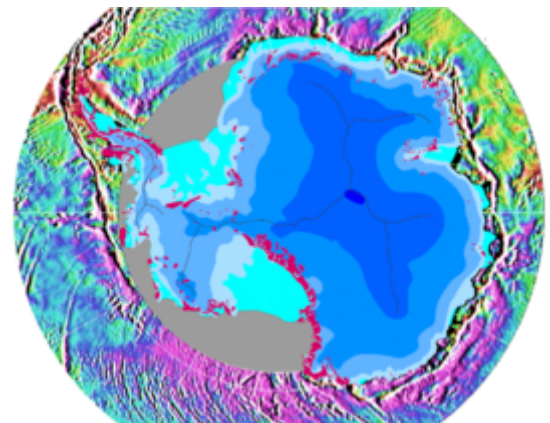
The surface of the Earth is rotating, so it is not an inertial frame of reference. At latitudes nearer the Equator, the outward centrifugal force produced by Earth's rotation is larger than at polar latitudes. This counteracts the Earth's gravity to a small degree – up to a maximum of 0.3% at the Equator – and reduces the apparent downward acceleration of falling objects.

The second major reason for the difference in gravity at different latitudes is that the Earth's equatorial bulge (itself also caused by centrifugal force from rotation) 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, an object at the Equator experiences a weaker gravitational pull than an object at the poles.

In combination, the equatorial bulge and the effects of the surface centrifugal force due to rotation mean that sea-level effective gravity increases from about 9.780 m/s^2 at the Equator to about 9.832 m/s^2 at the poles, so an object will weigh about 0.5% more at the poles than at the Equator^{[3][7]}

The same two factors influence the direction of the effective gravity (as determined by a plumb line or as the perpendicular to the surface of water in a container). Anywhere on Earth away from the Equator or poles, effective gravity points not exactly toward the centre of the Earth, but rather perpendicular to the surface of the geoid, which, due to the flattened shape of the Earth, is somewhat toward the opposite pole. About half of the deflection is due to centrifugal force, and half because the extra mass around the Equator causes a change in the direction of the true gravitational force relative to what it would be on a spherical Earth.

Altitude



The differences of Earth's gravity around the Antarctic continent.

Gravity decreases with altitude as one rises above the Earth's surface because greater altitude means greater distance from the Earth's centre. All other things being equal, an increase in altitude from sea level to 9,000 metres (30,000 ft) causes a weight decrease of about 0.29%. (An additional factor affecting apparent weight is the decrease in air density at altitude, which lessens an object's buoyancy.^[8] This would increase a person's apparent weight at an altitude of 9,000 metres by about 0.08%)

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 400 kilometres (250 mi), equivalent to a typical orbit of the Space Shuttle, gravity is still nearly 90% as strong as at the Earth's surface. Weightlessness actually occurs because orbiting objects are in free-fall.^[9]

The effect of ground elevation depends on the density of the ground (see Slab correction section). A person flying at 30 000 ft above sea level over mountains will feel more gravity than someone at the same elevation but over the sea. However, a person standing on the earth's surface feels less gravity when the elevation is higher

The following formula approximates the Earth's gravity variation with altitude:

$$g_h = g_0 \left(\frac{r_e}{r_e + h} \right)^2$$

Where

- g_h is the gravitational acceleration at height h above sea level.
- r_e is the Earth's mean radius
- g_0 is the standard gravitational acceleration

The formula treats the Earth as a perfect sphere with a radially symmetric distribution of mass; a more accurate mathematical treatment is discussed below

Depth

An approximate value for gravity at a distance r from the center of the Earth can be obtained by assuming that the Earth's density is spherically symmetric. The gravity depends only on the mass inside the sphere of radius r . All the contributions from outside cancel out as a consequence of the inverse-square law of gravitation. Another consequence is that the gravity is the same as if all the mass were concentrated at the center. Thus, the gravitational acceleration at this radius is^[10]

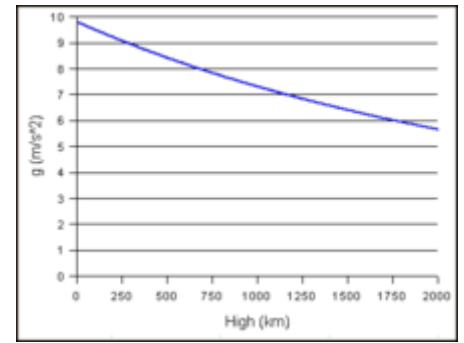
$$g(r) = -\frac{GM(r)}{r^2}.$$

where G is the gravitational constant and $M(r)$ is the total mass enclosed within radius r . If the Earth had a constant density ρ , the mass would be $M(r) = (4/3)\pi\rho r^3$ and the dependence of gravity on depth would be

$$g(r) = \frac{4\pi}{3}G\rho r.$$

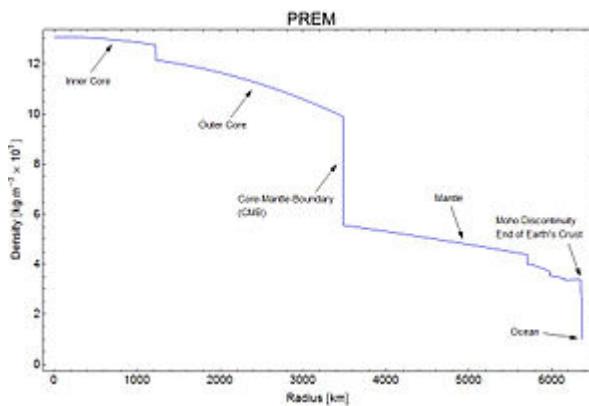
g at depth d is given by $g' = g(1 - d/R)$ where g is acceleration due to gravity on surface of the earth, d is depth and R is radius of Earth. If the density decreased linearly with increasing radius from a density ρ_0 at the center to ρ_1 at the surface, then $\rho(r) = \rho_0 - (\rho_0 - \rho_1) r / r_e$, and the dependence would be

$$g(r) = \frac{4\pi}{3}G\rho_0 r - \pi G(\rho_0 - \rho_1) \frac{r^2}{r_e}.$$

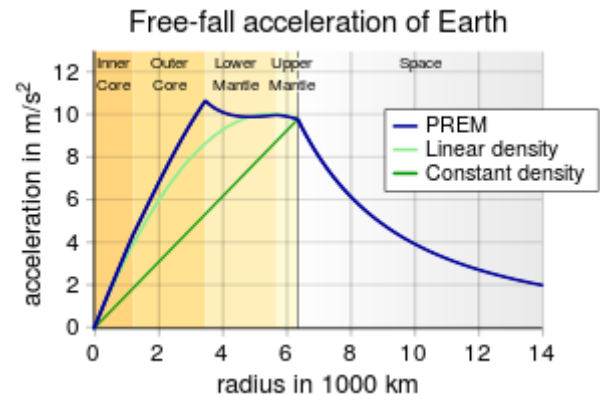


The graph shows the variation in gravity relative to the height of an object above the surface

The actual depth dependence of density and gravity, inferred from seismic travel times (see [Adams–Williamson equation](#)), is shown in the graphs below



Earth's radial density distribution according to the Preliminary Reference Earth Model (PREM).^[11]



Earth's gravity according to the Preliminary Reference Earth Model (PREM).^[11] Two models for a spherically symmetric Earth are included for comparison. The dark green straight line is for a constant density equal to the Earth's average density. The light green curved line is for a density that decreases linearly from center to surface. The density at the center is the same as in the PREM, but the surface density is chosen so that the mass of the sphere equals the mass of the real Earth.

Local topography and geology

Local differences in [topography](#) (such as the presence of mountains), [geology](#) (such as the density of rocks in the vicinity), and deeper [tectonic structure](#) cause local and regional differences in the Earth's gravitational field, known as [gravitational anomalies](#).^[12] Some of these anomalies can be very extensive, resulting in bulges in [sea level](#), 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.

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); see [Apparent weight](#) for details.

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 $2 \mu\text{m/s}^2$ (0.2 mGal) over the course of a day

Comparative gravities in various cities around the world

Tools exist for calculating the strength of gravity at various cities around the world.^[13] The effect of latitude can be clearly seen with gravity in high-latitude cities: Anchorage (9.826 m/s^2), Helsinki (9.825 m/s^2), being about 0.5% greater than that in cities near the equator: Kuala Lumpur (9.776 m/s^2), Manila (9.780 m/s^2). The effect of altitude can be seen in Mexico City (9.776 m/s^2 ; altitude

2,240 metres (7,350 ft)), and by comparing Denver (9.798 m/s²; 1,616 metres (5,302 ft)) with Washington, D.C. (9.801 m/s²; 30 metres (98 ft)), both of which are near 39° N. Measured values can be obtained from Physical and Mathematical Tables by T.M. Yarwood and F. Castle, Macmillan, revised edition 1970.^[14]

Mathematical models

Latitude model

If the terrain is at sea level, we can estimate $g\{\phi\}$, the acceleration at latitude ϕ :

$$\begin{aligned} g\{\phi\} &= 9.780327 \text{ m} \cdot \text{s}^{-2} (1 + 0.0053024 \sin^2 \phi - 0.0000058 \sin^2 2\phi), \\ &= 9.780327 \text{ m} \cdot \text{s}^{-2} (1 + 0.0052792 \sin^2 \phi + 0.0000232 \sin^4 \phi), \\ &= 9.780327 \text{ m} \cdot \text{s}^{-2} (1.0053024 - 0.0053256 \cos^2 \phi + 0.0000232 \cos^4 \phi), \\ &= 9.780327 \text{ m} \cdot \text{s}^{-2} (1.0026454 - 0.0026512 \cos 2\phi + 0.0000058 \cos^2 2\phi) \end{aligned}$$

This is the International Gravity Formula 1967, the 1967 Geodetic Reference System Formula, Helmert's equation or Clairaut's formula.^[15]

An alternative formula for g as a function of latitude is the WGS World Geodetic System 84 Ellipsoidal Gravity Formula^[16]

$$g\{\phi\} = \mathbb{G}_e \left[\frac{1 + k \sin^2 \phi}{\sqrt{1 - e^2 \sin^2 \phi}} \right],$$

where,

- a, b are the equatorial and polar semi-axes, respectively;
- $e^2 = 1 - (b/a)^2$ is the spheroid's eccentricity, squared;
- $\mathbb{G}_e, \mathbb{G}_p$ is the defined gravity at the equator and poles, respectively;
- $k = \frac{b \mathbb{G}_p - a \mathbb{G}_e}{a \mathbb{G}_e}$ (formula constant);

then, where $\mathbb{G}_p = 9.8321849378 \text{ m} \cdot \text{s}^{-2}$,^[16]

$$g\{\phi\} = 9.7803253359 \text{ m} \cdot \text{s}^{-2} \left[\frac{1 + 0.00193185265241 \sin^2 \phi}{\sqrt{1 - 0.00669437999013 \sin^2 \phi}} \right].$$

The difference between the WGS-84 formula and Helmert's equation is less than $0.68 \mu\text{m} \cdot \text{s}^{-2}$.

Free air correction

The first correction to be applied to the model is the free air correction (FAC) that accounts for heights above sea level. Near the surface of the Earth (sea level), gravity decreases with height such that linear extrapolation would give zero gravity at a height of one half of the earth's radius - (9.8 m/s² per 3,200 km).^[17]

Using the mass and radius of the Earth:

$$\begin{aligned} r_{\text{Earth}} &= 6.371 \cdot 10^6 \text{ m} \\ m_{\text{Earth}} &= 5.9722 \cdot 10^{24} \text{ kg} \end{aligned}$$

The FAC correction factor (Δg) can be derived from the definition of the acceleration due to gravity in terms of G , the Gravitational Constant (see Estimating g from the law of universal gravitation, below):

$$g_0 = G m_{\text{Earth}} / r_{\text{Earth}}^2 = 9.8196 \frac{\text{m}}{\text{s}^2}$$

where:

$$G = 6.67384 \cdot 10^{-11} \frac{\text{m}^3}{\text{kg} \cdot \text{s}^2}.$$

At a height h above the nominal surface of the earth g_h is given by:

$$g_h = G m_{\text{Earth}} / (r_{\text{Earth}} + h)^2$$

So the FAC for a height h above the nominal earth radius can be expressed:

$$\Delta g_h = \left[G m_{\text{Earth}} / (r_{\text{Earth}} + h)^2 \right] - \left[G m_{\text{Earth}} / r_{\text{Earth}}^2 \right]$$

This expression can be readily used for programming or inclusion in a spreadsheet. Collecting terms, simplifying and neglecting small terms ($h \ll r_{\text{Earth}}$), however yields the good approximation:

$$\Delta g_h \approx - \frac{G m_{\text{Earth}}}{r_{\text{Earth}}^2} \cdot \frac{2h}{r_{\text{Earth}}}$$

Using the numerical values above and for a height h in metres:

$$\Delta g_h \approx -3.086 \cdot 10^{-6} h$$

Grouping the latitude and FAC altitude factors the expression most commonly found in the literature is:

$$g\{\phi, h\} = g\{\phi\} - 3.086 \cdot 10^{-6} h$$

where $g\{\phi, h\}$ = acceleration in $\text{m} \cdot \text{s}^{-2}$ at latitude ϕ and altitude h in metres. Alternatively (with the same units for h) the expression can be grouped as follows:

$$g\{\phi, h\} = g\{\phi\} - 3.155 \cdot 10^{-7} h \frac{\text{m}}{\text{s}^2}$$

Slab correction

Note: The section uses the galileo (symbol: "Gal"), which is a cgs unit for acceleration of 1 centimetre/second².

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. $4.2 \times 10^{-10} \text{ m}^3 \cdot \text{s}^{-2} \cdot \text{kg}^{-1}$ ($0.042 \mu\text{Gal} \cdot \text{kg}^{-1} \cdot \text{m}^2$) (the Bouguer correction). For a mean rock density of $2.67 \text{ g} \cdot \text{cm}^{-3}$ this gives $1.1 \times 10^{-6} \text{ s}^{-2}$ ($0.11 \text{ mGal} \cdot \text{m}^{-1}$). Combined with the free-air correction this means a reduction of gravity at the surface of ca. $2 \mu\text{m} \cdot \text{s}^{-2}$ (0.20 mGal) for every metre of elevation of the terrain. (The two effects would cancel at a surface rock density of $4/3$ times the average density of the whole earth. The density of the whole earth is $5.515 \text{ g} \cdot \text{cm}^{-3}$, so standing on a slab of something like iron whose density is over $7.35 \text{ g} \cdot \text{cm}^{-3}$ would increase one's weight.)

For the gravity below the surface we have to apply the free-air correction as well as a double Bouguer correction. With the infinite slab model this is because moving the point of observation below the slab changes the gravity due to it to its opposite. Alternatively, we can consider a spherically symmetrical Earth and subtract from the mass of the Earth that of the shell outside the point of observation, because that does not cause gravity inside. This gives the same result.

Estimating g from the law of universal gravitation

From the law of universal gravitation the force on a body acted upon by Earth's gravity is given by

$$F = G \frac{m_1 m_2}{r^2} = \left(G \frac{m_1}{r^2} \right) m_2$$

where r is the distance between the centre of the Earth and the body (see below), and here we take m_1 to be the mass of the Earth and m_2 to be the mass of the body

Additionally, Newton's second law, $F = ma$, where m is mass and a is acceleration, here tells us that

$$F = m_2 g$$

Comparing the two formulas it is seen that:

$$g = G \frac{m_1}{r^2}$$

So, to find the acceleration due to gravity at sea level, substitute the values of the gravitational constant, G , the Earth's mass (in kilograms), m_1 , and the Earth's radius (in metres), r , to obtain the value of g :

$$g = G \frac{m_1}{r^2} = 6.67384 \cdot 10^{-11} \text{ m}^3 \cdot \text{kg}^{-1} \cdot \text{s}^{-2} \frac{5.9722 \cdot 10^{24} \text{ kg}}{(6.371 \cdot 10^6 \text{ m})^2} = 9.8196 \text{ m} \cdot \text{s}^{-2}$$

Note that this formula only works because of the mathematical fact that the gravity of a uniform spherical body, as measured on or above its surface, is the same as if all its mass were concentrated at a point at its centre. This is what allows us to use the Earth's radius for r .

The value obtained agrees approximately with the measured value of g . The difference may be attributed to several factors, mentioned above under "Variations":

- The Earth is not homogeneous
- The Earth is not a perfect sphere, and an average value must be used for its radius
- This calculated value of g only includes true gravity. It does not include the reduction of constraint force that we perceive as a reduction of gravity due to the rotation of Earth, and some of gravity being counteracted by centrifugal force.

There are significant uncertainties in the values of r and m_1 as used in this calculation, and the value of G is also rather difficult to measure precisely.

If G , g and r are known then a reverse calculation will give an estimate of the mass of the Earth. This method was used by Henry Cavendish.

See also

- Earth's magnetic field
- Gravity (Gravitation)
- Gravity anomaly, Bouguer anomaly
- Gravitation of the Moon

- Gravitational acceleration
- Gravity Field and Steady-State Ocean Circulation Explorer
- Gravity Recovery and Climate Experiment
- Newton's law of universal gravitation

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External links

- [Altitude gravity calculator](#)
 - [GRACE – Gravity Recovery and Climate Experiment](#)
 - [GGMplus high resolution data \(2013\)](#)
 - [Geoid 2011 model](#)Potsdam Gravity Potato
-

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