

Gravity Correction

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1. Introduction

A Gravity Survey is done by measuring the gravitational field at a series of different locations over an area. The objective in exploration work is to associate variations with differences in the distribution of densities and hence rock types. Occasionally the whole gravitational field is measured or derivatives of the gravitational field, but usually the difference between the gravity field at two points is measured.

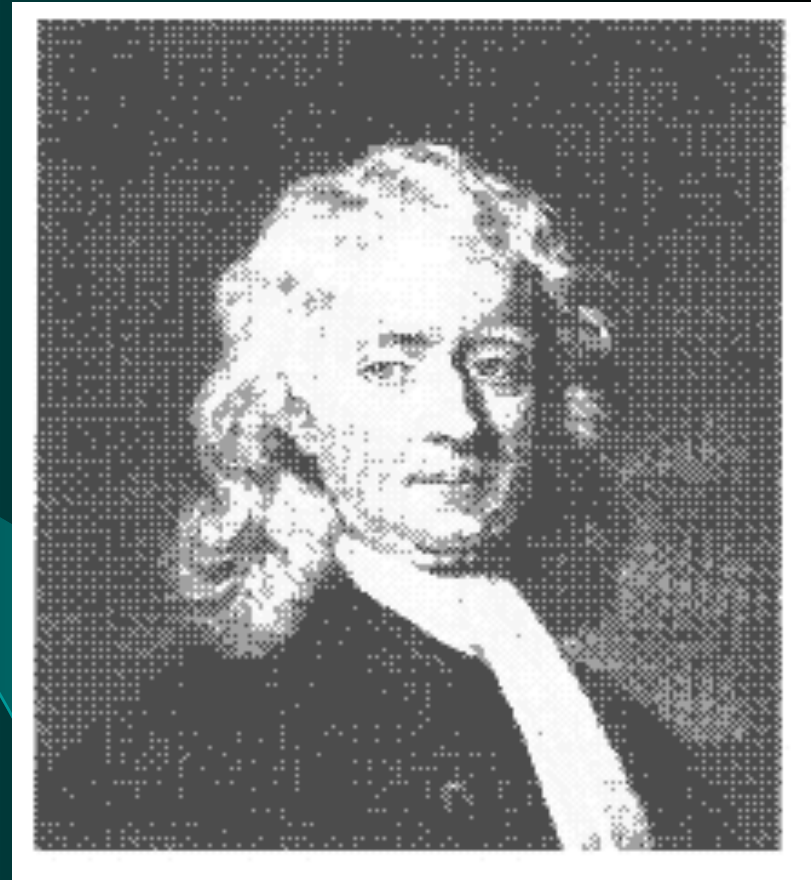


1.1. Gravitational Force



$$\mathbf{F} = \frac{G m_1 m_2}{r^2}$$

Newton's first law of gravitation states that the mutual attractive force between two point masses, m_1 and m_2 , is proportional to one over the square of the distance between them, r . The constant of proportionality is usually specified as G , the gravitational constant.



Sir Isaac Newton

1.2. Gravitational Acceleration

The gravitational acceleration (g) is the time rate of change of a body's speed under the influence of the gravitational force. In addition to defining the law of mutual attraction between masses, Newton also defined the relationship between a force and an acceleration.

$$\mathbf{F} = m_2 \mathbf{g}$$

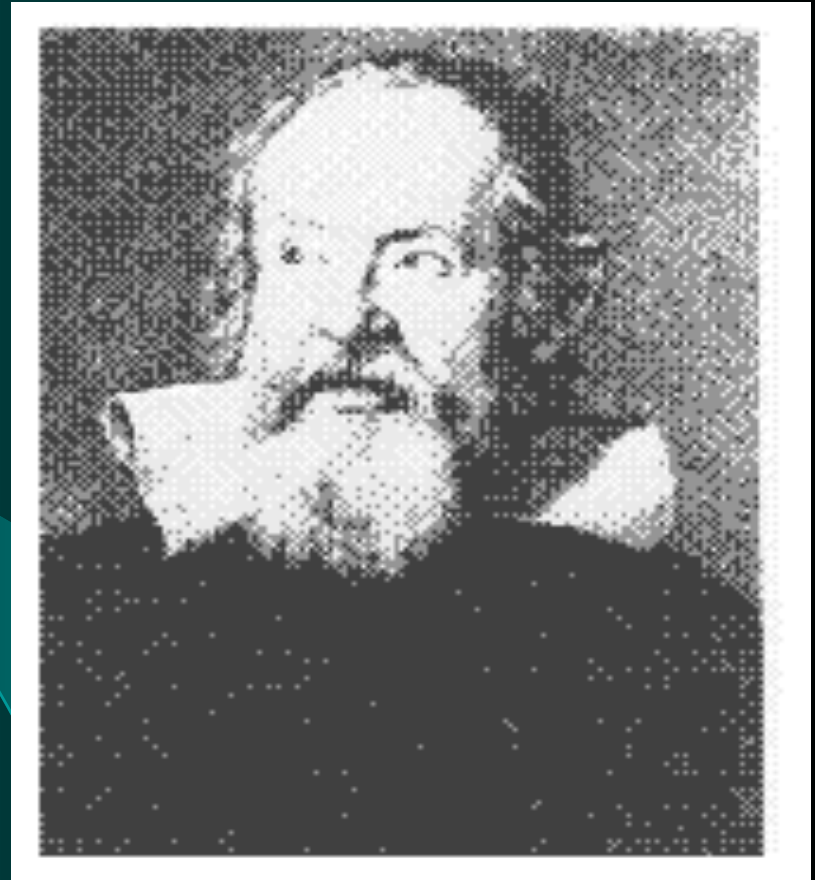
Newton's second law states that force is proportional to acceleration. The constant of proportionality is the mass of the object.

Combining Newton's first law and second law, the gravitational acceleration on the mass m_2 can be shown to be equal to the mass of attracting object, m_1 , over the squared distance between the center of the two masses, r .

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

1.3. Units cont...

The units typically used in describing the gravitational acceleration variations observed in exploration gravity surveys are specified in milliGals. A Gal is defined as a centimeter per second squared. Thus, the Earth's gravitational acceleration is approximately 980 Gals. The Gal is named after *Galileo Galilei*. The milliGal (mgal) is one thousandth of a Gal. In milliGals, the Earth's gravitational acceleration is approximately 980,000.

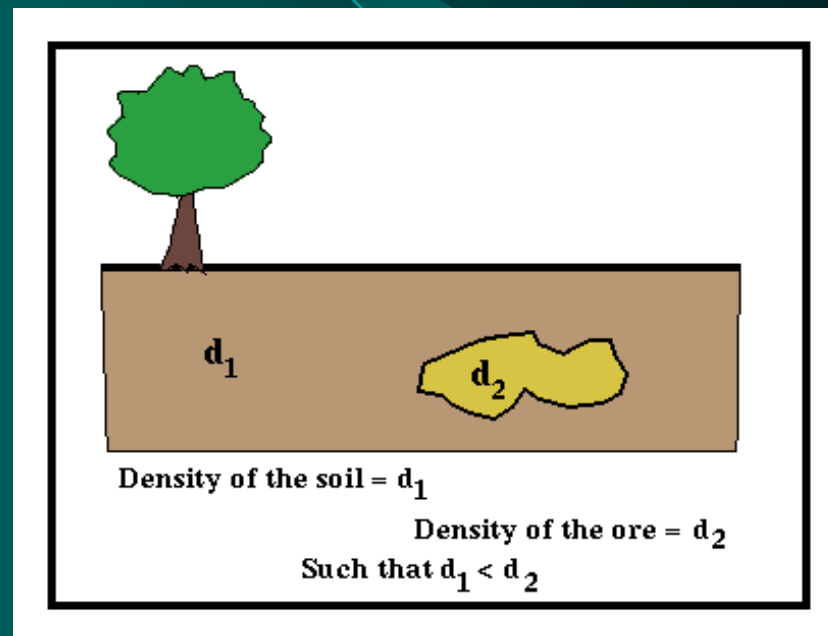


Galileo Galilei.

2. Gravity and Geology

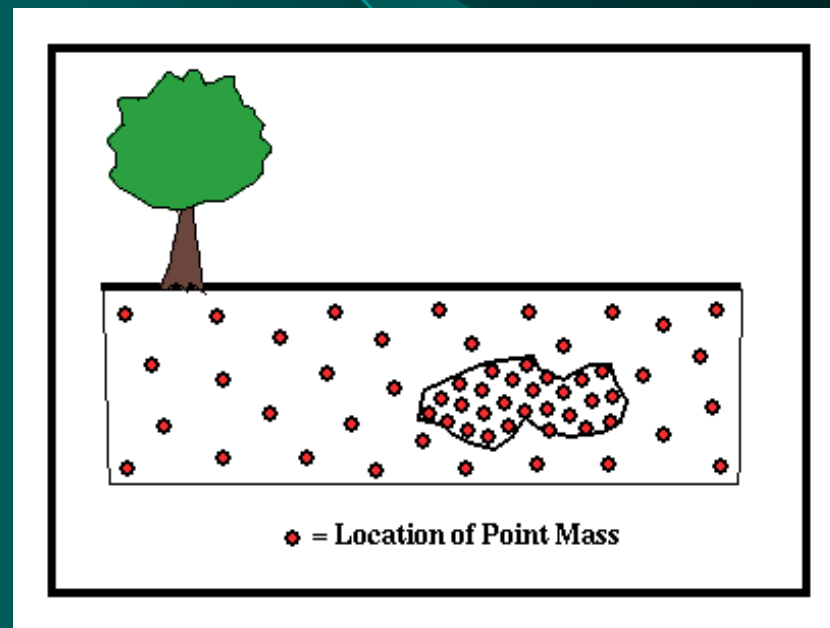
Density is defined as mass per unit volume. The units typically used to describe density of substances are grams per centimeter cubed (gm/cm^3); mass per unit volume.

Consider a simple geologic example of an ore body buried in soil. We would expect the density of the ore body, d_2 , to be greater than the density of the surrounding soil, d_1 .



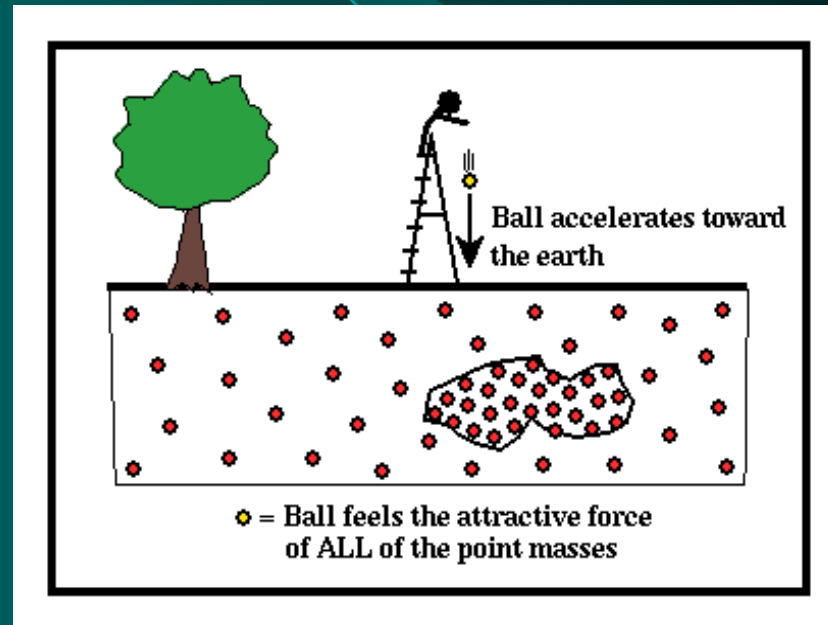
2. Gravity and Geology cont...

The density of the material can be thought of as a number that quantifies the number of point masses needed to represent the material per unit volume of the material just like the number of people per cubic foot in the example given above described how crowded a particular room was. Thus, to represent a high-density ore body, we need more point masses per unit volume than we would for the lower density soil.



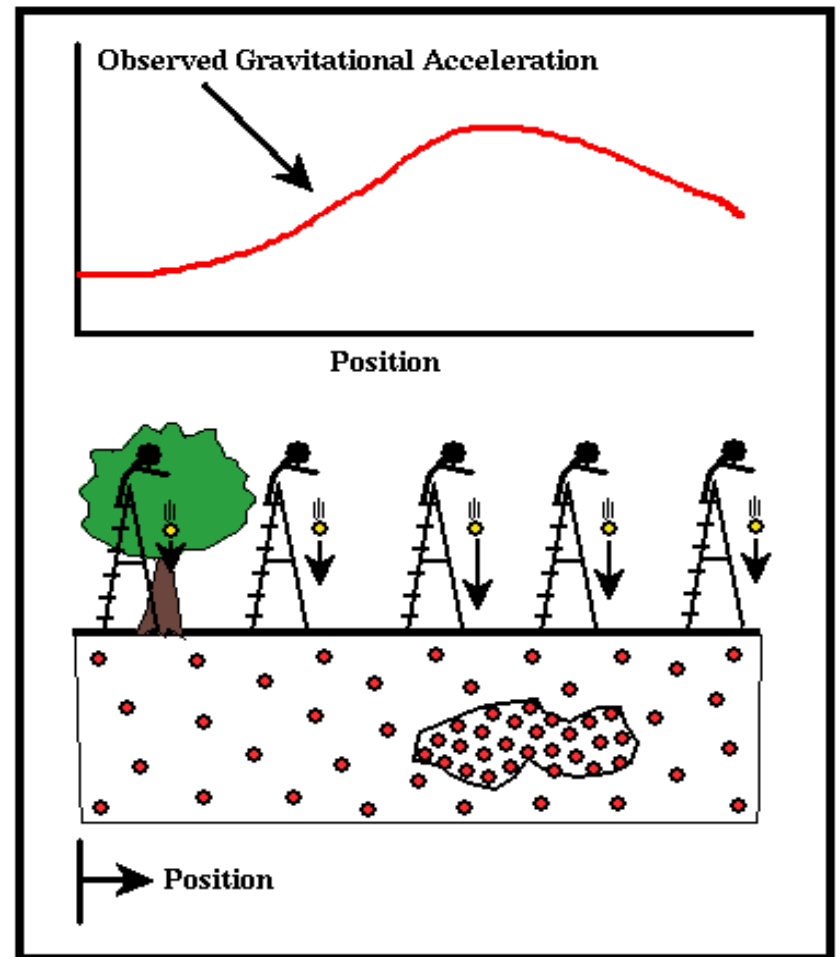
2.1. Acceleration & Geology

Now, let's qualitatively describe the gravitational acceleration experienced by a ball as it is dropped from a ladder. This acceleration can be calculated by measuring the time rate of change of the speed of the ball as it falls. The size of the acceleration the ball undergoes will be proportional to the number of close point masses that are directly below it. We're concerned with the close point masses because the magnitude of the gravitational acceleration varies as one over the distance between the ball and the point mass squared.



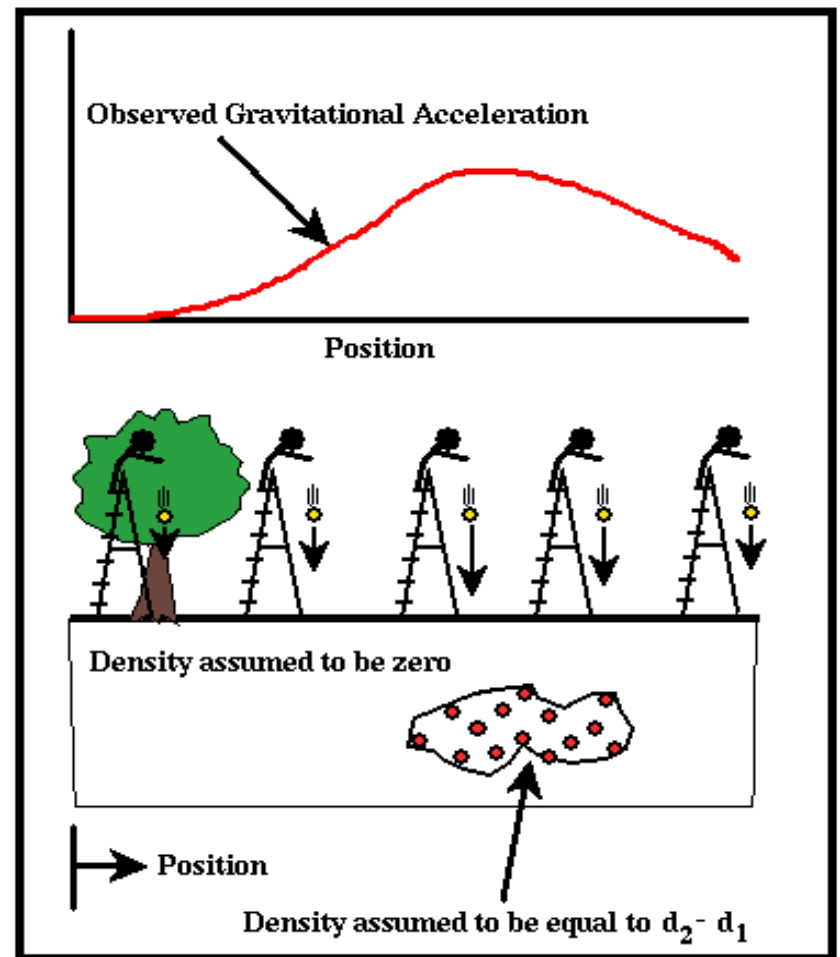
2.1. Acceleration & Geology cont...

The closer point masses there are directly below the ball, the larger its acceleration. We could, drop the ball from a number of different locations, and map out differences in the size of the gravitational acceleration experienced by the ball and is caused by variations in the underlying geology. A plot of the gravitational acceleration versus location is commonly referred to as a *gravity profile*. This simple thought experiment forms the physical basis on which gravity surveying rests.



2.2. Density Contrast

The shape of the curve describing the variation in gravitational acceleration is not dependent on the absolute densities of the rocks. It is only dependent on the density difference, or what is referred to as *density contrast*, between the ore body and the surrounding soil. That is, the spatial variation in the gravitational acceleration generated from the previous example would be exactly the same if we assume different densities for the ore body and the surrounding soil, as long as the density contrast, $d_2 - d_1$, is constant.



2.3. Rock Densities

The densities associated with various earth materials are shown below. Notice that the relative variation in rock density is quite small, $\sim 0.8 \text{ gm/cm}^3$, and there is considerable overlap in the measured densities.

Material	Density (gm/cm^3)
Air	~ 0
Water	1
Sediments	1.7-2.3
Sandstone	2.0-2.6
Shale	2.0-2.7
Limestone	2.5-2.8
Granite	2.5-2.8
Basalts	2.7-3.1
Metamorphic Rocks	2.6-3.0

2.4. A Simple Model

Spherical shape

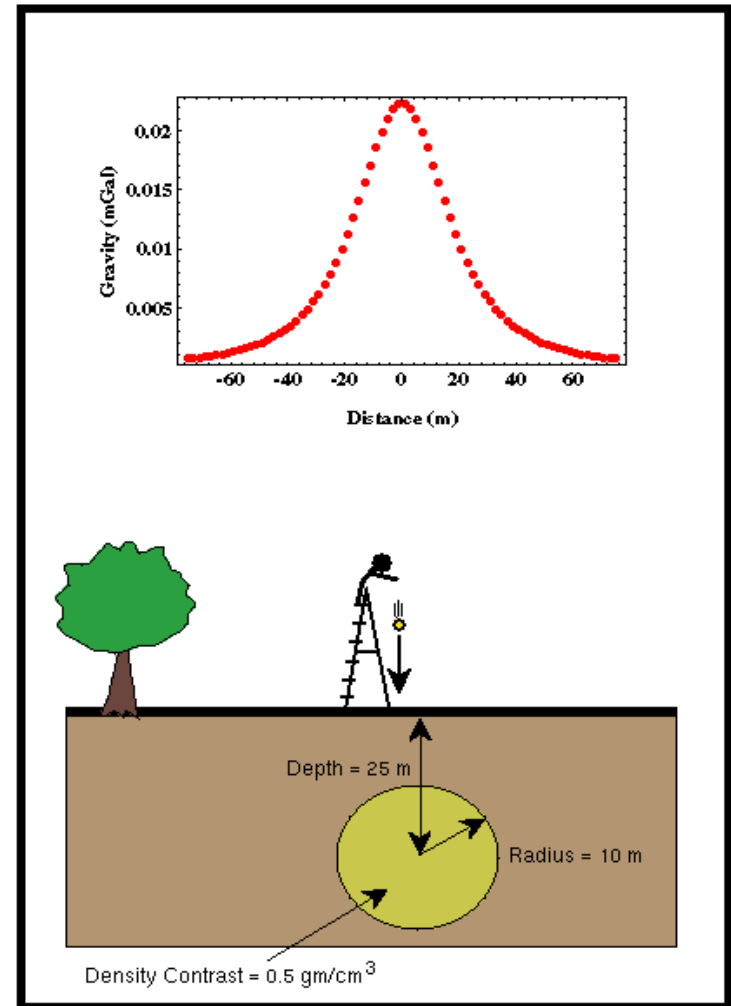
Radius = 10 m

Depth = 25 m

Density contrast = 0.5 gm/cc

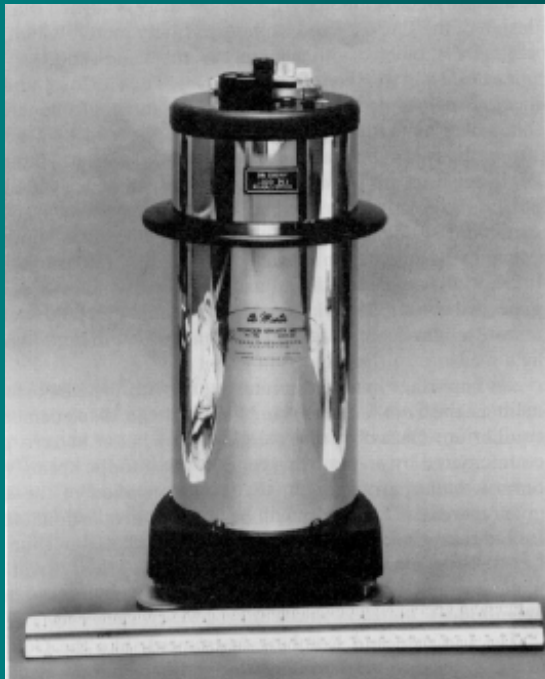
Notice the following:

- (1) The gravity anomaly is symmetric about the center of the sphere.
- (2) The maximum value of the anomaly is quite small. For this example, 0.025 mgals.
- (3) The magnitude of the gravity anomaly approaches zero at small (~ 60 meters) horizontal distances away from the center of the sphere.



3.4. Gravimeters

Scintrex Gravimeter



Worden Gravimeter



LaCoste and Romberg Gravimeter

4. Sources of Noise

Noise are other factors that can give rise to variations in gravitational acceleration that are as large, if not larger, than the expected geologic signal. These complicating factors can be subdivided into two categories:

- *Temporal based variations.* These are changes in the observed acceleration that are time dependent. These factors cause variations in acceleration that would be observed even if we didn't move our gravimeter.

* **Instrumental Drift**

* **Tidal Effect**

- *Spatial based variations.* These are changes in the observed acceleration that are space dependent. These change the gravitational acceleration from place to place, just like the geologic affects, but they are not related to geology.

* **Latitude Variations**

* **Elevation Variations**

* **Slab Effect**

* **Topographic Effect**

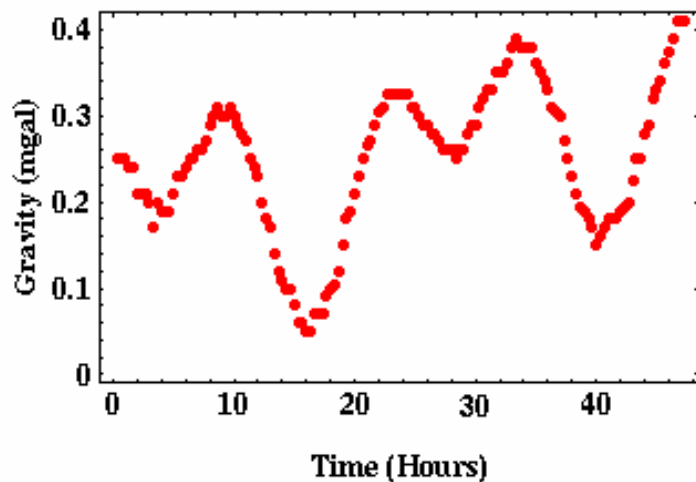
4.1. Temporal Variations

(1) Tidal Effect is the variation in gravity observations resulting from the attraction of the moon and sun and the distortion of the earth so produced. These are changes that do not relate to local geology and are hence a form of noise in our observations.

Just as the gravitational attraction of the sun and the moon distorts the shape of the ocean surface, it also distorts the shape of the earth. The size of the ocean tides is measured in terms of meters. The size of the solid earth tide is measured in centimeters.

This distortion of the solid earth produces measurable changes in the gravitational acceleration because as the shape of the earth changes, the distance of the gravimeter to the center of the earth changes. The distortion of the earth varies from location to location, but it can be large enough to produce variations in gravitational acceleration as large as 0.2 mgals.

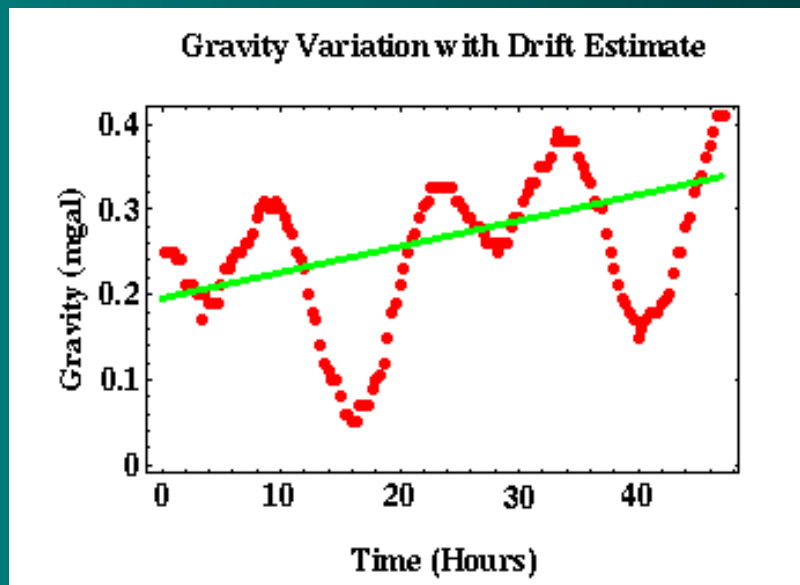
Variation in Gravity, Tulsa Oklahoma, 12/10 - 12/12 1939



4.1. Temporal Variations

(2) Instrumental Drift is a gradual and unintentional change in the reference value with respect to which measurements are made. Although constructed to high-precision standards problems do exist when trying to use a delicate instrument such as a gravimeter.

Even if the instrument is handled with great care, the properties of the materials used to construct the spring can change with time. These variations in spring properties with time can be due to stretching of the spring over time or to changes in spring properties related to temperature changes.



To help minimize the spring stretching, gravimeters are either temperature controlled or constructed out of materials that are relatively insensitive to temperature changes. Even still, gravimeters can drift as much as 0.1 mgal per day.

4.1. Temporal Corrections

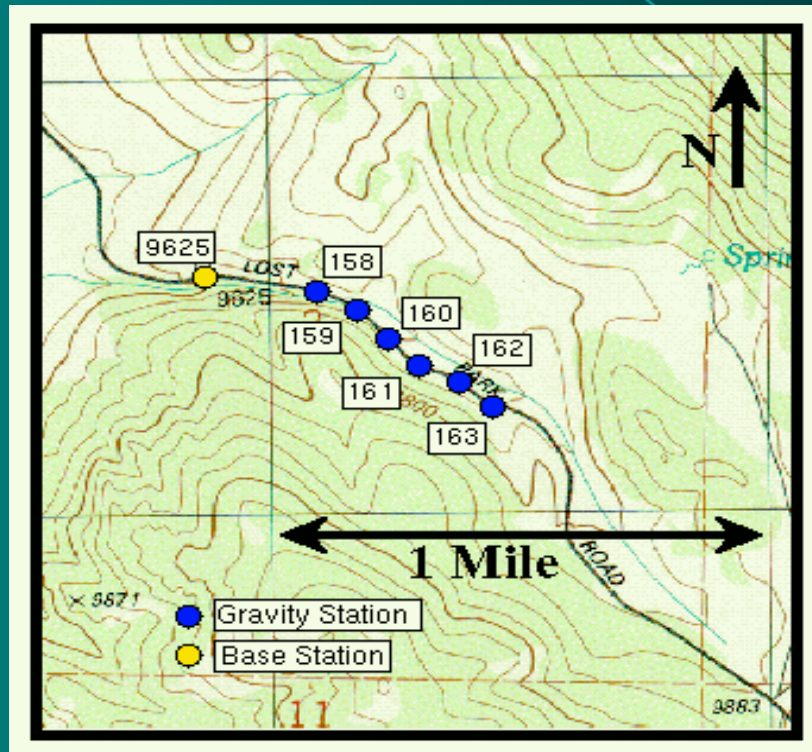
One possible way of accounting for the tidal component of the gravity field would be to establish a base station (A reference station that is used to establish additional stations in relation thereto. Quantities under investigation have values at the base station that are known accurately. Data from the base station may be used to normalize data from other stations) near the survey area and to continuously monitor the gravity field at this location while other gravity observations are being collected in the survey area. This procedure is rarely used for a number of reasons:

- It requires the use of two gravimeters.
- The use of two instruments requires the mobilization of two field crews.
- Most importantly, although this technique can be used to remove the tidal component, it will not remove instrument drift. Because two different instruments are being used, they will exhibit different drift characteristics.

4.1. Temporal Corrections

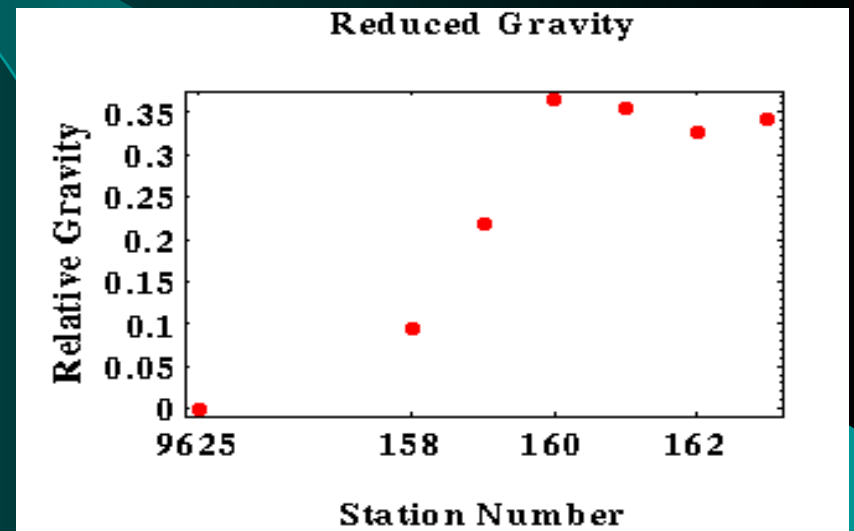
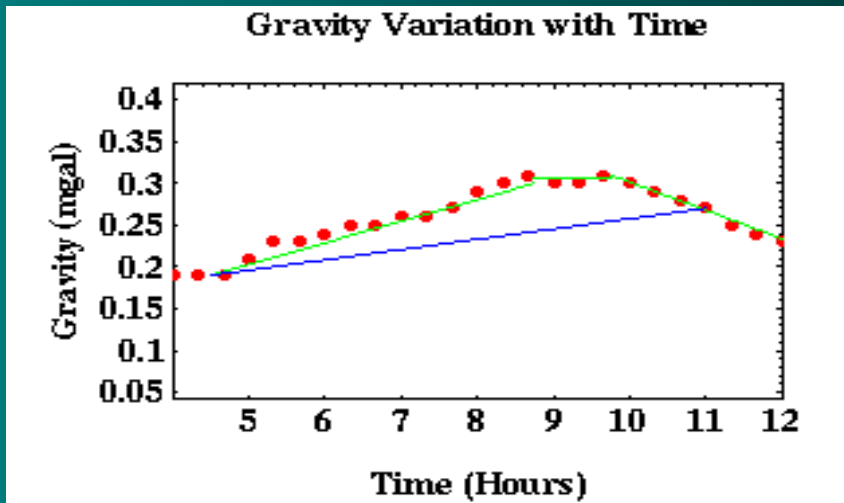
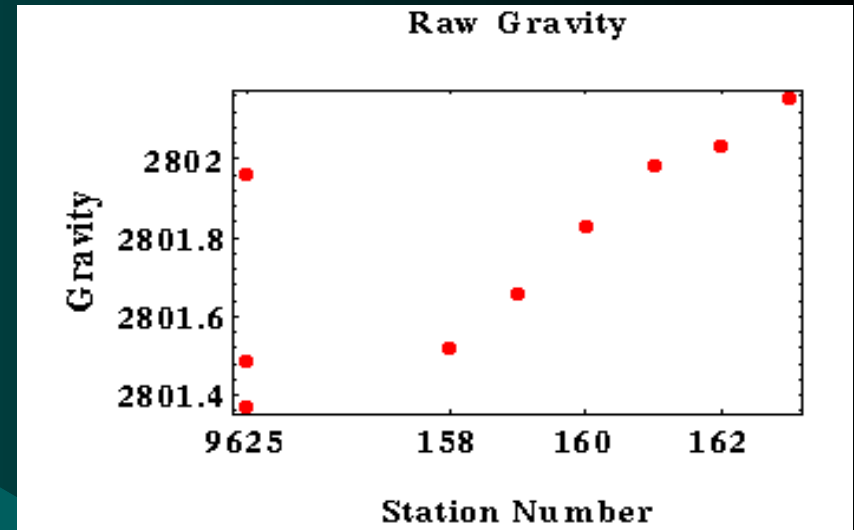
Instead of continuously monitoring the gravity field at the base station, it is more common to periodically reoccupy (return to) the base station using a single gravimeter.

- Establish the locations of the gravity stations appropriate for the particular survey.
- Before starting to make gravity observations at the gravity stations, the survey is initiated by recording the relative gravity at the base station and the time.
- We now proceed to move the gravimeter to the survey stations numbered 158 through 163 measuring gravity and the time.
- After some time period, usually on the order of an hour, we return to the base station and re-measure the relative gravity and the time.



4.1. Temporal Corrections

After recording the gravity at the last survey station, or at the end of the day, we return to the base station and make one final reading of the gravity. The procedure described above is generally referred to as a looping procedure with one loop of the survey being bounded by two occupations of the base station.

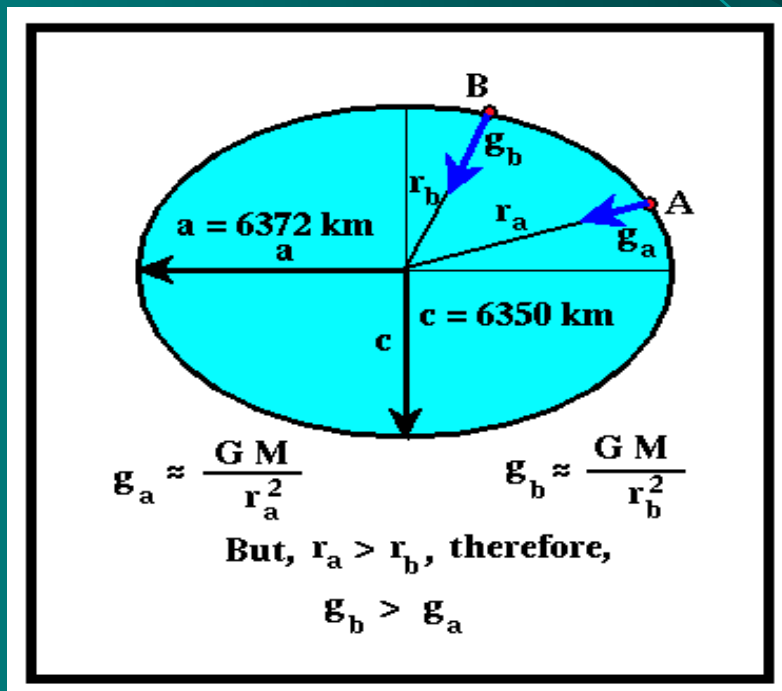


4.2. Spatial Variations

(1) **Latitude Variation** in gravity observations is caused by 2 main reasons:

(A) Shape of the earth

(B) Rotation of the earth



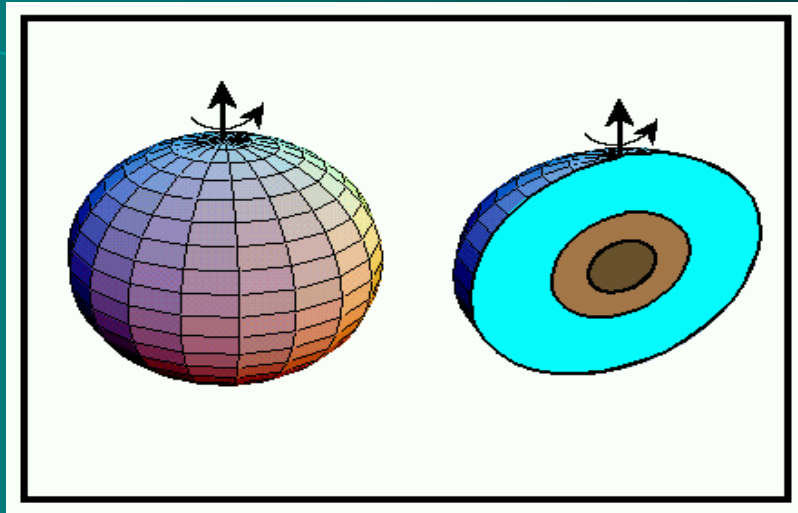
(A) Shape of the earth

The difference in earth radii measured at the poles and at the equator is only 22 km (this value represents a change in earth radius of only 0.3%).

This, in conjunction with the earth's rotation, can produce a measurable change in the gravitational acceleration with latitude.

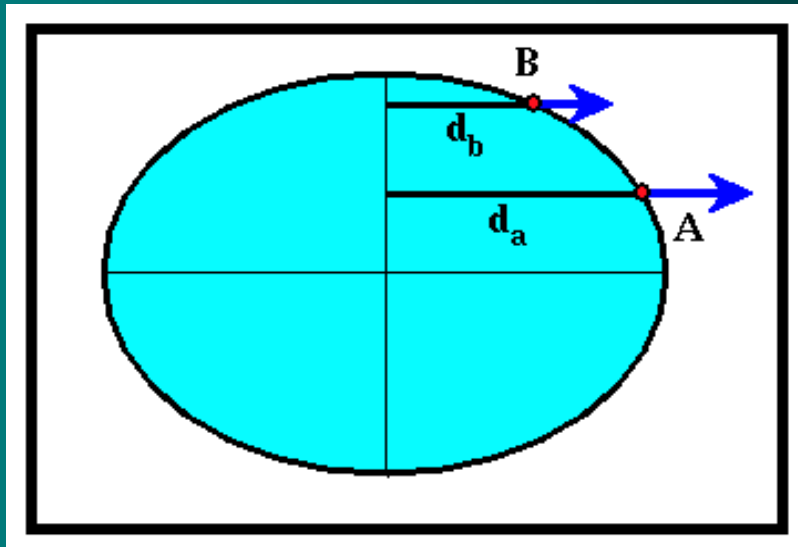
Because this produces a spatially varying change in the gravitational acceleration, it is possible to confuse this change with a change produced by local geologic structure.

4.2. Spatial Variations



(B) Rotation of the earth

If a body rotates, it experiences an outward directed force known as a centrifugal force. The size of this force is proportional to the distance from the axis of rotation and the rate at which the rotation is occurring. The size of the centrifugal force is relatively large at the equator and goes to zero at the poles. The direction this force acts is always away from the axis of rotation. Therefore, this force acts to reduce the gravitational acceleration we would observe at any point on the earth, from that which would be observed if the earth were not rotating.



4.2. Spatial Corrections

Correcting observations of the gravitational acceleration for latitude dependent variations arising from the earth's elliptical shape and rotation is relatively straight forward. By assuming the earth is elliptical with the appropriate dimensions, is rotating at the appropriate rate we can derive a mathematical formulation for the earth's gravitational acceleration that depends only on the latitude of the observation. By subtracting the gravitational acceleration predicted by this formulation from the observed gravitational acceleration, we can remove portions related to the earth's shape and rotation from the observed acceleration.

$$g_n = 978.03185 (1.0 + 0.005278895 \sin^2 \phi - 0.000023462 \sin^4 \phi) \text{ (cm/s}^2\text{)}$$

g_n = Normal Gravity: Gravitational acceleration expected for a rotating ellipsoidal earth without any geologic complications and no surface features

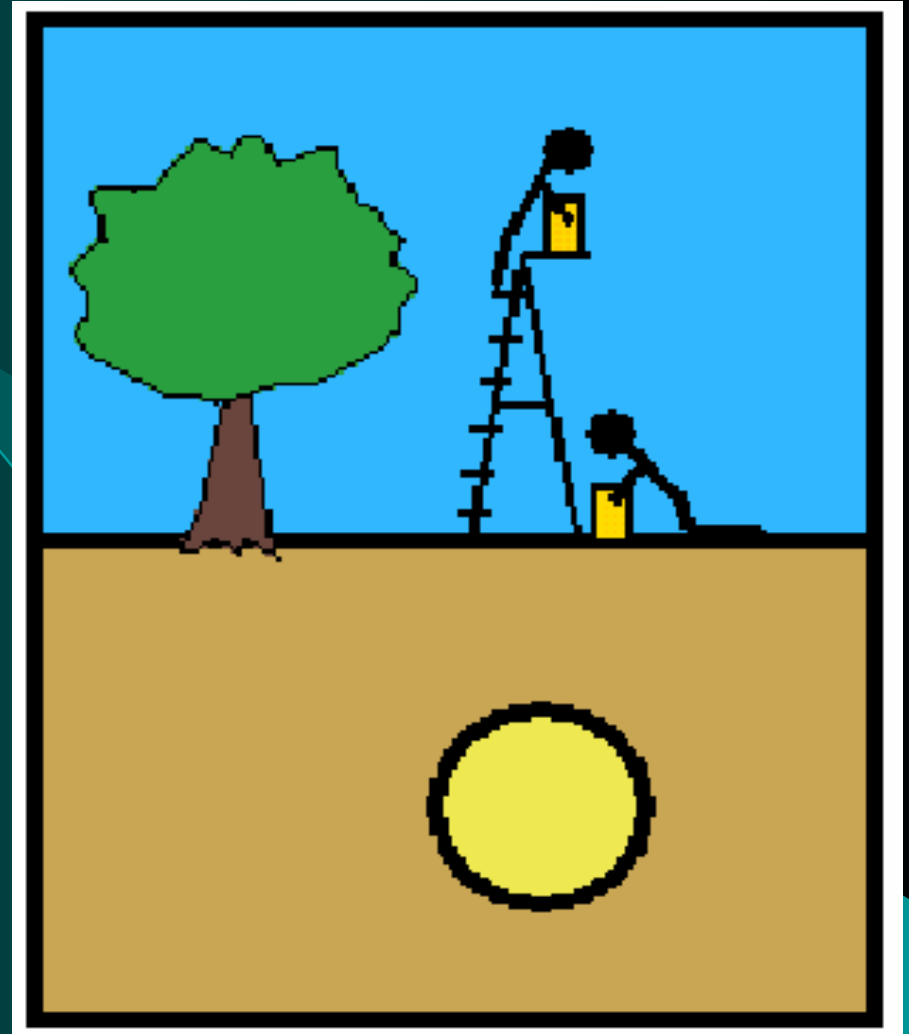
ϕ = Latitude

4.2. Spatial Variations

Elevation effect

Imagine two gravity readings taken at the same location and at the same time with two perfect (no instrument drift and the readings contain no errors) gravimeters; one placed on the ground, the other place on top of a stepladder, as shown in the figure below. Would the two instruments record the same gravitational acceleration?

No, the instrument placed on top of the stepladder would record a smaller gravitational acceleration than the one placed on the ground. Why?



4.2. Spatial Variations

Free-air correction

To account for variations in the observed gravitational acceleration that are related to elevation variations, we incorporate another correction to our data known as the Free-Air Correction. In applying this correction, we mathematically convert our observed gravity values to ones that look like they were all recorded at the same elevation, thus further isolating the geological component of the gravitational field.

The gravitational acceleration observed on the surface of the earth varies at about -0.3086 mgal per meter in elevation difference. The minus sign indicates that as the elevation increases, the observed gravitational acceleration decreases.

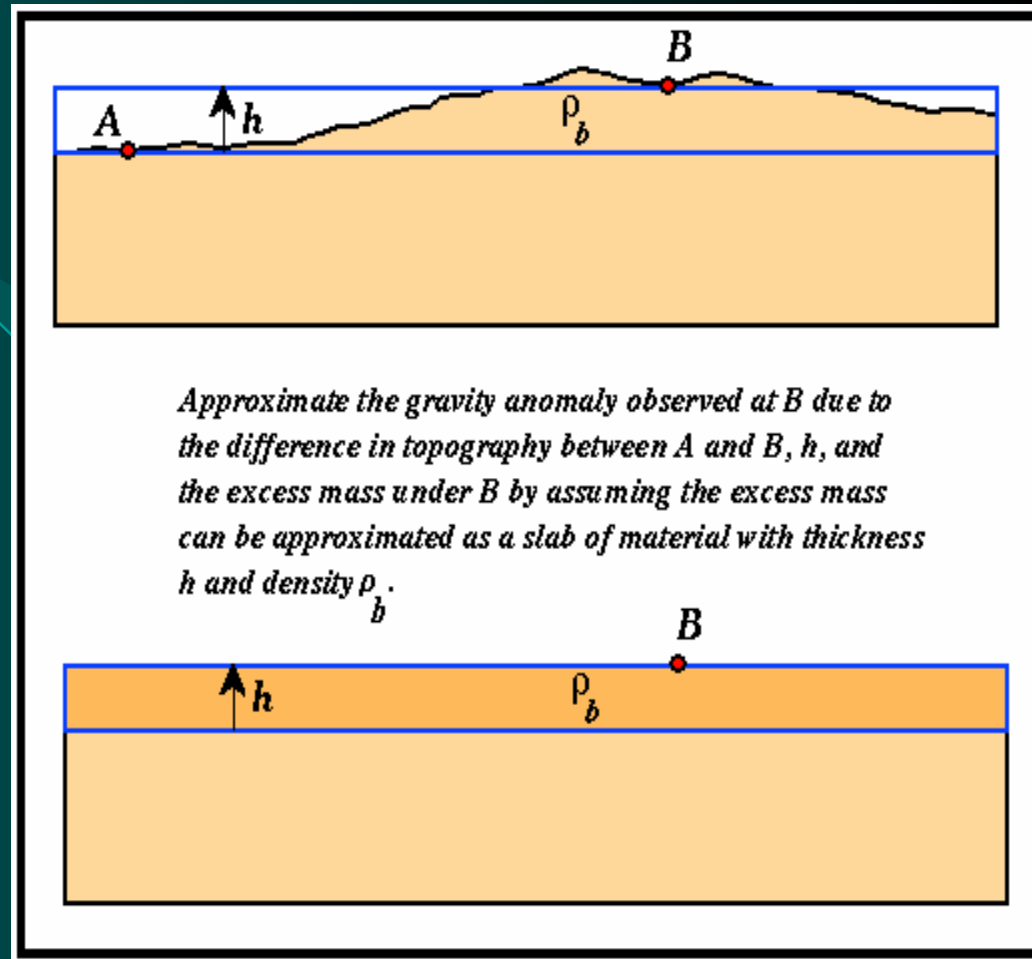
To apply an elevation correction to our observed gravity, we need to know the elevation of every gravity station. If this is known, we can correct all of the observed gravity readings to a common elevation (usually chosen to be sea level) by adding -0.3086 times the elevation of the station in meters to each reading. This common elevation to which all of the observations are corrected to is usually referred to as the datum elevation.

4.2. Spatial Variations

Slab effect

The differences between observation locations usually result from topographic changes along the earth's surface.

Therefore, in addition to the gravity readings differing at two stations because of elevation differences, the readings will also contain a difference because there is more mass below the reading taken at a higher elevation than there is of one taken at a lower



4.2. Spatial Variations

Bouguer correction

Corrections based on this simple slab approximation are referred to as the Bouguer Slab Correction. It can be shown that the vertical gravitational acceleration associated with a flat slab can be written simply as $0.04193ph$. Where the correction is given in mgals, p is the density of the slab in gm/cm³, and h is the elevation difference in meters between the observation point and elevation datum. h is positive for observation points above the datum level and negative for observation points below the datum level.

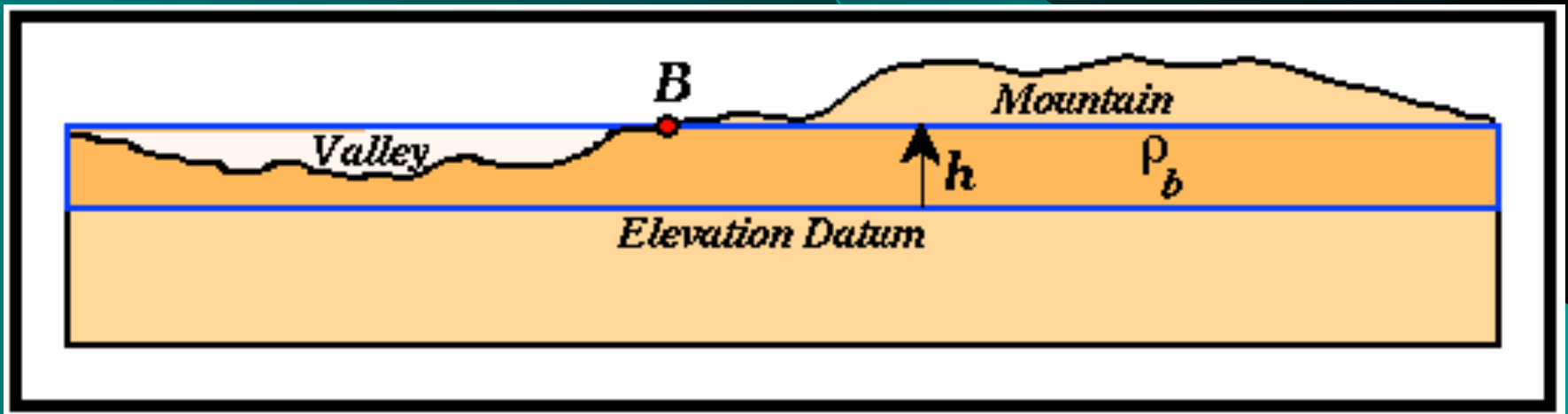
Notice that the sign of the Bouguer Slab Correction makes sense. If an observation point is at a higher elevation than the datum, there is excess mass below the observation point that wouldn't be there if we were able to make all of our observations at the datum elevation. Thus, our gravity reading is larger due to the excess mass, and we would therefore have to subtract a factor to move the observation point back down to the datum. Notice that the sign of this correction is opposite to that used for the elevation correction.

4.2. Spatial Variations

Topographic effect

In applying the slab correction in the presence of a valley to the left of point B, we have accounted for too much mass because the valley actually contains no material.

The mass associated with the nearby mountain is not included in our Bouguer correction. The presence of the mountain acts as an upward directed gravitational acceleration.



4.2. Spatial Variations

Topographic correction

To compute the gravitational attraction produced by the topography, we need to estimate the mass of the surrounding terrain and the distance of this mass from the observation point. As you are probably beginning to realize, in addition to an estimate of the average density of the rocks within the survey area, to perform this correction we will need a knowledge of the locations of the gravity stations and the shape of the topography surrounding the survey area.

Estimating the distribution of topography surrounding each gravity station is not a trivial task. One could imagine plotting the location of each gravity station on a topographic map, estimating the variation in topographic relief about the station location at various distances, computing the gravitational acceleration due to the topography at these various distances, and applying the resulting correction to the observed gravitational acceleration.

4.3. Correction Summary

- **Observed Gravity (g_{obs}):** Gravity readings observed at each gravity station after corrections have been applied for instrument drift and tides.
- **Latitude Correction (g_n):** Correction subtracted from g_{obs} that accounts for the earth's elliptical shape and rotation. The gravity value that would be observed if the earth were a perfect rotating ellipsoid is referred to as the normal gravity.
- **Free Air Corrected Gravity (g_{fa}):** The Free-Air correction accounts for gravity variations caused by elevation differences in the observation locations. The form of the Free-Air gravity anomaly, g_{fa} , is given by;

$$g_{fa} = g_{obs} - g_n + 0.3086h \text{ (mgal)}$$

where h is the elevation at which the gravity station is above the elevation datum chosen for the survey (this is usually sea level).

4.3. Correction Summary

- **Bouguer Slab Corrected Gravity (g_b):** The Bouguer correction is a correction to account for the excess mass underlying observation points located at elevations higher than the elevation datum. The form of the Bouguer gravity anomaly, g_b , is given by;

$$g_b = g_{obs} - g_n + 0.3086h - 0.04193ph \text{ (mgal)}$$

where p is the average density of the rocks underlying the survey area.

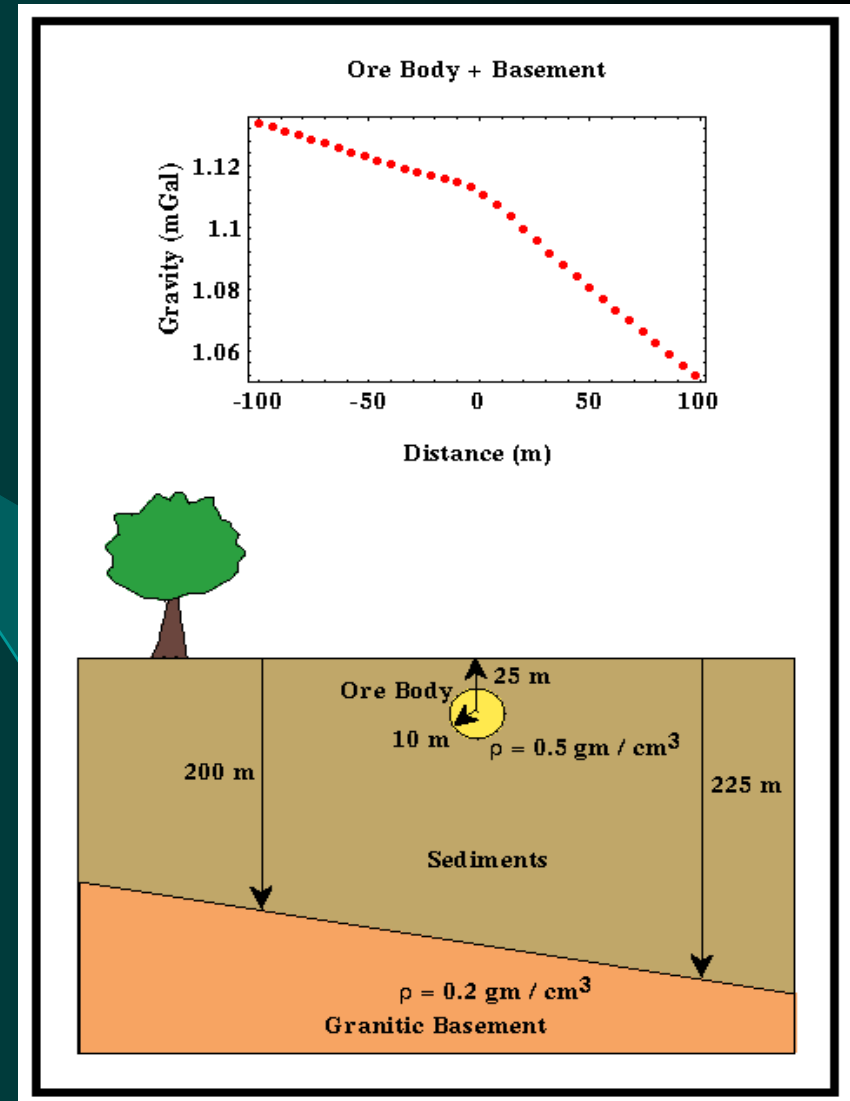
- **Terrain Corrected Bouguer Gravity (g_t):** The Terrain correction accounts for variations in the observed gravitational acceleration caused by variations in topography near each observation point. The form of the Terrain corrected, Bouguer gravity anomaly, g_t , is given by;

$$g_t = g_{obs} - g_n + 0.3086h - 0.04193ph + TC \text{ (mgal)}$$

where TC is the value of the computed Terrain correction.

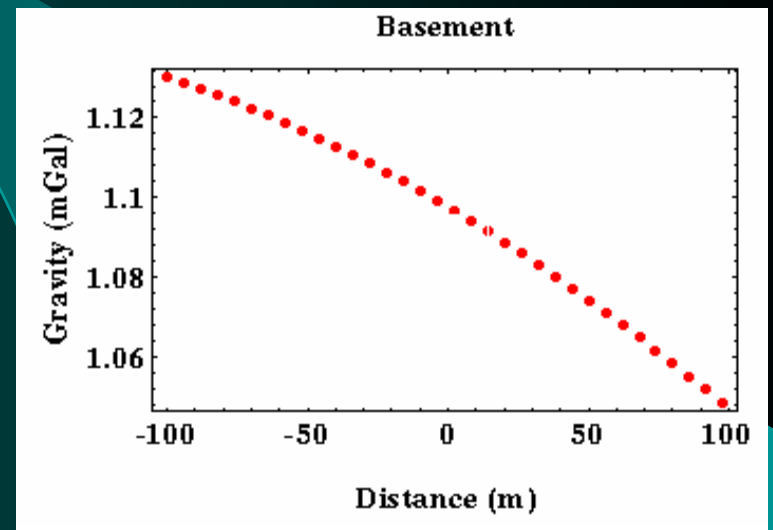
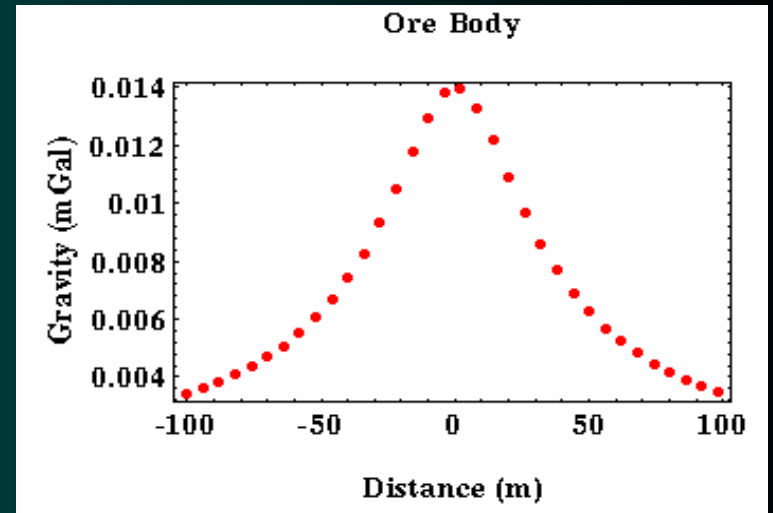
5. Isolating Gravity Anomalies

Do you remember the simple model we discussed earlier? For the time being we will still assume that the ore body is spherical in shape and is buried in sedimentary rocks having a uniform density. In addition to the ore body, let's now assume that the sedimentary rocks in which the ore body resides are underlain by a denser granitic basement that dips to the right. This geologic model and the gravity profile that would be observed over it are shown in the figure to the right. Notice that the observed gravity profile is dominated by a trend indicating decreasing gravitational acceleration from left to right. This trend is the result of the dipping basement interface.



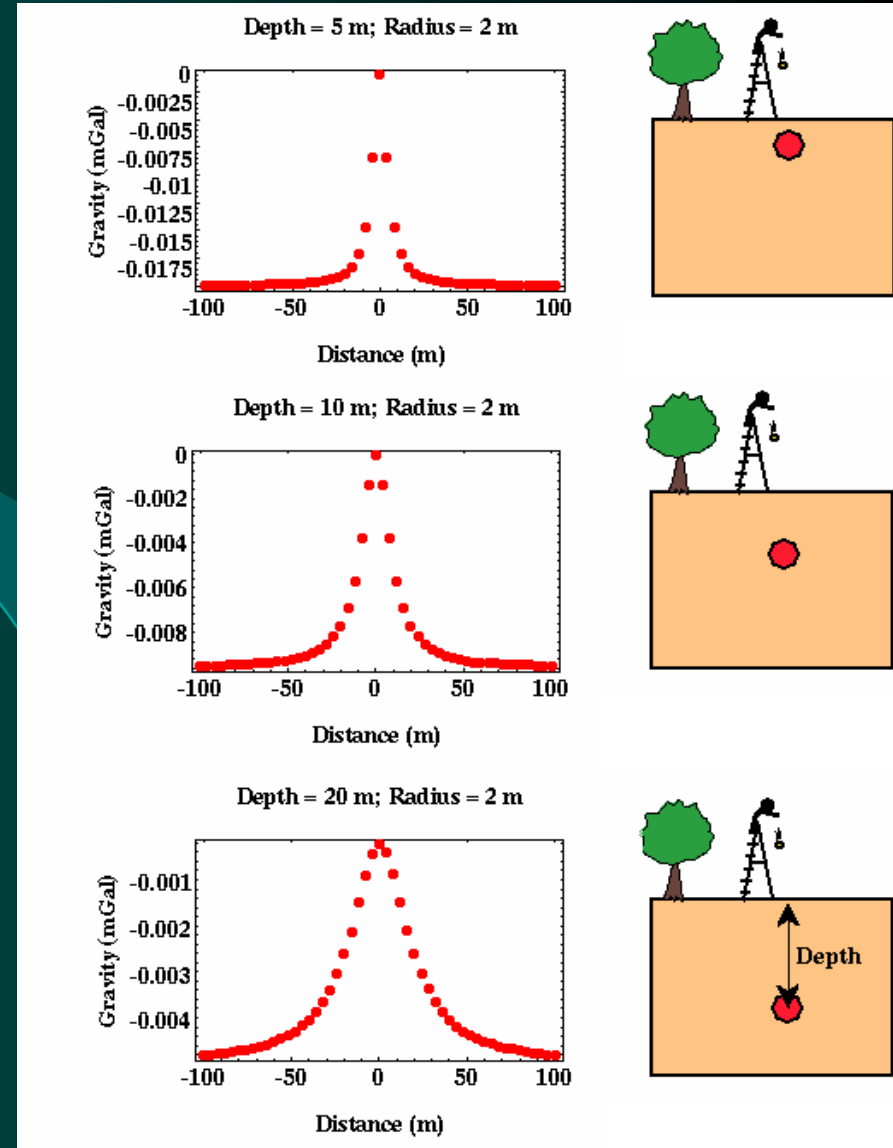
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5. Isolating Gravity Anomalies

In the example to the right, notice that as the cylinder is buried more deeply, the gravity anomaly it produces decreases in amplitude and spreads out in width. Thus, the more shallowly buried cylinder produces a large anomaly that is confined to a region of the profile directly above the cylinder. The more deeply buried cylinder produces a gravity anomaly of smaller amplitude that is spread over more of the length of the profile. The broader gravity anomaly associated with the deeper source could be considered a *Regional Gravity Anomaly*. The sharper anomaly associated with the more shallow source would contribute to the *Local Gravity Anomaly*.





Thank You