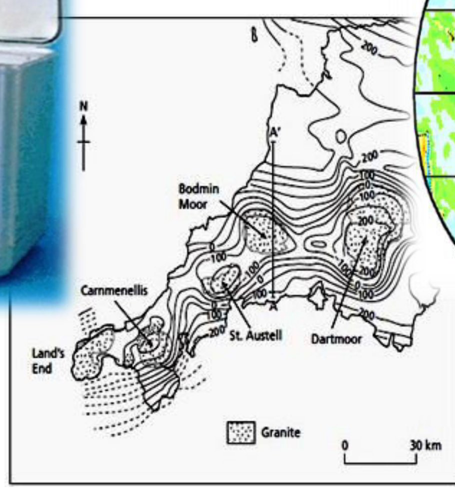
Ministry of Higher Education and Scientific Research

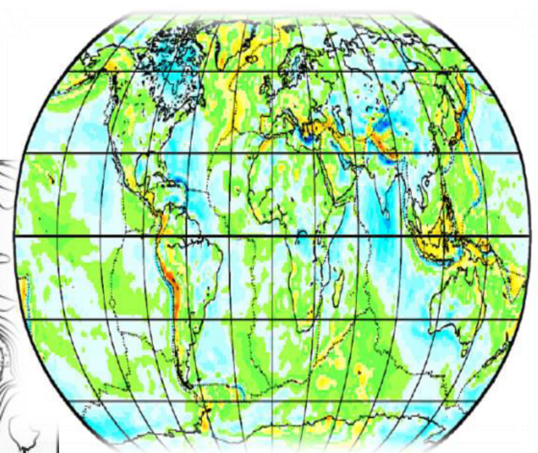
Al-Karkh University of Science

College of Geophysics and Remote Sensing

Department of Geophysics

Gravity Method





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PhD. In Geophysics

Introduction

The gravity geophysical method depends on the natural gravimetric field of the earth and Newton's law of gravity. This method may be applied for the exploration of subsurface main zones of our planet or subsurface bedrocks and the sedimentary cover for the economic detection of mineral ores accumulation or subsurface geological structures related to petrol traps, also the detection of subsurface cavities and faults which considered as weakness zones at the foundations of engineering infrastructures like dams, highways, Bridges, railways. Furthermore, gravity method could be applied to study other subsurface structures like folds , carsts, cavities , fluids migration or any other vertical and lateral subsurface variations.

Since the earth-apple relationship first discovered by Newton, the mutual attraction between all masses has been recognized as a universal phenomenon. This phenomenon accounts for the familiar fact that a body released near the earth will fall with increasing velocity. The rate of increase of velocity is called gravitational acceleration (g) , or simply , gravity , which Galileo proved to be the same for all bodies at a given location on the earth.

If the earth were a perfect sphere of uniform concentric shell structure, the force of attraction on a body lying on its surface would be the same everywhere, and the gravity would have a single constant value. But, the reality is different; our earth is non-uniform, non-spherical, and rotating, and all these facts produces variation of gravity measured over its surface. These variations are relatively small, but they are measurable accurately by using extremely sensitive instruments like (Gravimeters).

<u>Gravimetry</u>: is the measuring and analyzing of Earth's gravimetric field and its space and time variations, it's closely related to Geodesy which is concerned about measuring and analyzing the shape and dimensions of the Earth.

<u>Importance and Applications of Gravity Method</u>:

1– Studying the Internal structure of the Earth (from the surface to the core).

2– Detecting mineral ores, oil, and subsurface carsts, cavities and faults or other subsurface structures.

3– Isostasy and the mechanical properties of the lithosphere

4– Earth tides

5– Transfer of geophysical fluids between reservoirs: groundwater, magma, ice which produces temporal variations in gravity.

6– Artificial satellites orbitography and planetary gravimetry.

The measurement and analyses of gravity variation over earth's surface has become a powerful tool in the investigation of subsurface geology. The lateral variations of gravity readings on earth surface reflects the lateral contrast in the density of subsurface rocks which considered as a prime interest for the geophysicist to extract information about the subsurface geological structures at various depths. This information is always subject to a certain ambiguity in the interpretation of gravity data; therefore, this ambiguity could be reduced by assisting gravity data with other geological and geophysical data from additional studies performed previously on the gravity surveyed area.

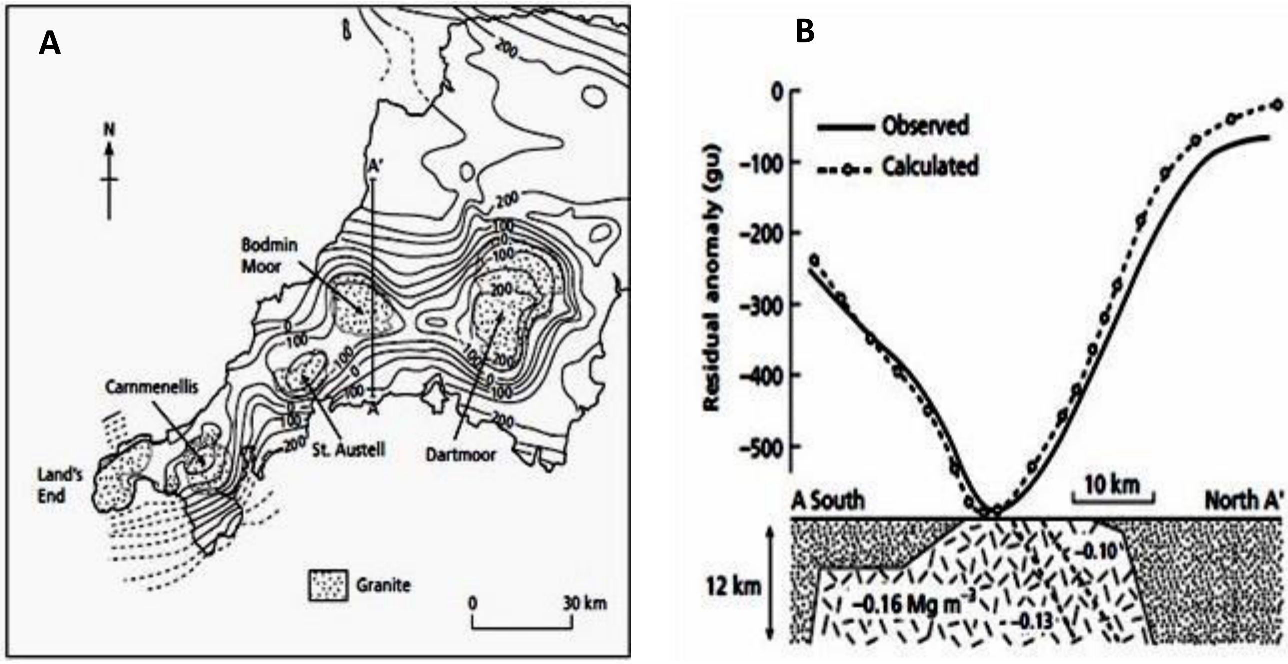


Figure (1):
A: Bouguer anomaly map of southwest England, showing a linear belt of large negative anomalies associated with the zone of granite outcrops, Contour interval 50 gu.

B: two-dimensional interpretation of the gravity anomaly of the Bodmin Moor granite, southwest England.. (After Bott & Scott 1964.)

The results of gravity interpretations may presented in the form of Bouguer anomaly contour map (figure 1-A) and two dimensional gravity profiles which shows the lateral variation in gravity values or subsurface rock densities as it shown in (figure 1 –B).

In addition to gravity surface measurements, a subsurface geological model like the one in figure 1 – B, can be conducted with the assistant of borehole lithology and depth information or other geological and geophysical information from the previous studies maintained at the concerned region.

Fundamental principles

Gravitation

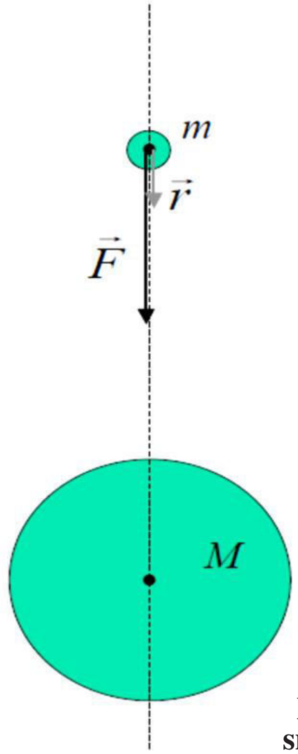


Figure (2-a): The attraction force (F) produced by the large mass (M) at the small mass (m), toward the center of the large mass (M), the distance between M and m is (r).

Newton's law of gravitation:

Two masses m and M attract each other and this attraction results in a force:

$$\vec{F} = G\frac{mM}{r^2}\vec{r}$$

Where r is the distance between the 2 masses and *G* the constant of universal gravitation, *r the* unit vector in the direction of *r*

$G = 6.67 * 10^{-8}$ $cm^3/gm.sec^2$ = $Dyne.cm^2/gm^2$ (c.g.s)

$G = 6.67 * 10^{-11}$ $m^3/km.sec^2$ = $Newton.m^2/kg^2$ (m.kg.s)

Newton's second law:

$$\vec{F} = m\vec{a}$$

Force (in Newton's) acting on mass *m* (in kg), responsible for its acceleration *a* (in $m.s^{-2}$)

- $\vec{F} = m\vec{a}$ → force(s) acting on *m*
- $\vec{F} = G\frac{mM}{r^2}\vec{r}$ → force exerted by *M* on *m*
- <u>In the absence of any other force besides the one generated by *M*</u>, one can write:

$$m\vec{a} = G\frac{mM}{r^2}\vec{r}$$

$$\Rightarrow \vec{a} = G\frac{M}{r^2}\vec{r}$$

- *a* = <u>***gravitational acceleration***</u> of mass *m* due to the <u>attraction</u> of mass *M*

a is usually called '*g*'

g should be expressed in $m.s^{-2}$, but variations on the order of 10^{-8}-10^{-3} $m.s^{-2}$

g is usually expressed in Gals:

- 1 Gal (for Galileo) = 1 $cm.s^{-2}$ = 10^{-2} $m.s^{-2}$
- 1 mGal = 10^{-5} $m.s^{-2}$
- 1 μGal = 10^{-8} $m.s^{-2}$

g on the surface of the Earth ~9.8 $m.s^{-2}$ = 982 000 mGal

1gal = 1000 or 10^3 milligal

1milligal = 0.001gal

1gu = 0.1 milligal

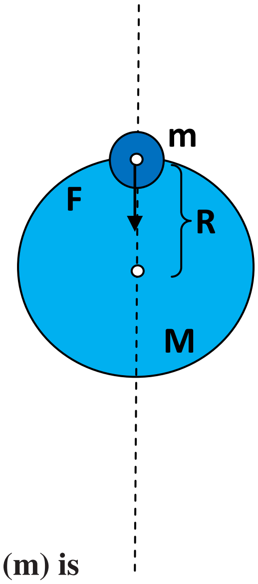


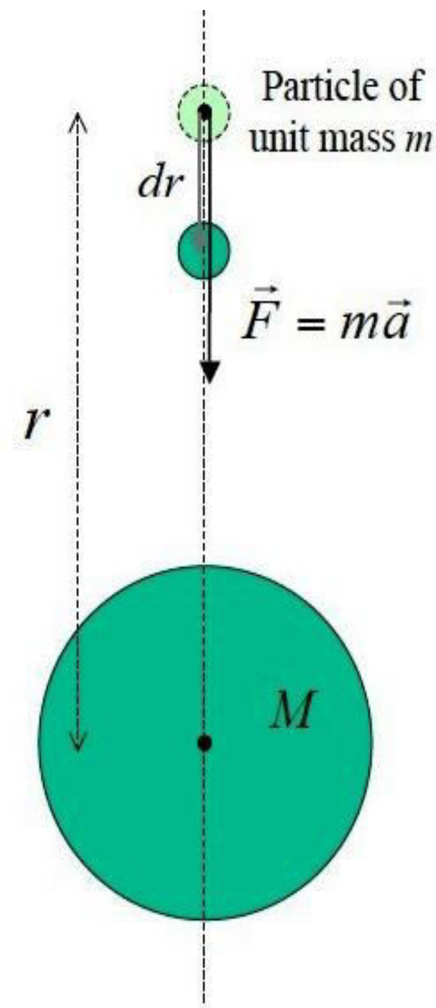
Figure (2-b): The case of the mass (m) is at the surface of the earth which has the mass (M), then the distance between the two masses (r) is substituted by (R) which is the radius of the earth.

If we considered that the small mass (m) is located at the earth surface , or represents a rock body at the earth crust, and the large mass (M) is the mass of the planet earth , then the distance (r) between the two masses represents the radius of the earth (R) , as it shown in figure (2-b). Therefore, the earth gravity acceleration (g) equation could be written as:

$$\mathbf{g} = \boldsymbol{G}\frac{\boldsymbol{M}}{\mathbf{R}^2}$$

This equation is applicable to calculate the gravity acceleration for the planets of our solar system if their masses and radius values are theoretically available.

Gravitational Potential



- Let's assume:
  - A particle of unit mass moving freely
  - A body of mass M
- The particle is attracted by M and moves toward it by a small quantity dr.
- This displacement is the result of **work** W exerted by the gravitational field generated by M:

$$W = Fdr = m \quad a \quad dr = a \quad dr$$

$$\Rightarrow W = G\frac{M}{r^2}dr$$

- The **potential** U of mass M is the amount of work necessary to bring the particle from infinity to a given distance r:

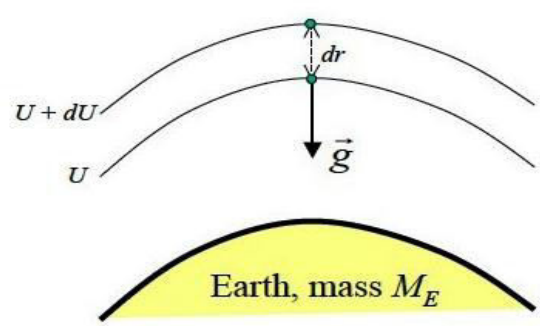
$$U = \int_{\infty}^{r} G\frac{M}{r^2}dr = GM\int_{\infty}^{r}\frac{1}{r^2}dr = GM\left[\frac{1}{\infty} - \frac{1}{r}\right]$$

$$\Rightarrow U = -\frac{GM}{r}$$

- **At distance r, the gravitational potential generated by M is U**

Gravitational Potential of the Earth

- Earth's gravitational acceleration g exerts a work to move a unit mass particle from U to $U+dU$ (spherical homogeneous non-rotating Earth):



$$U = -\frac{GM}{r} \Rightarrow \frac{dU}{dr} = \frac{GM_E}{r^2} \Rightarrow dU = -gdr$$

$$\Rightarrow g = -\frac{dU}{dr} = -grad(U)$$

(think in terms of energy)

Besides the Earth's gravitation

- Previous formulas valid if only force = attraction of the mass of the Earth
- But the Earth's rotates ⇒ 2 effects:
  - Centrifugal acceleration that opposes gravity
  - Deformation of the Earth: polar flattening
- Effects of other celestial bodies, in particular Moon and Sun:
  - Accelerations of the Earth on its orbit
  - Tides

Effect of the Earth's rotation (1/2)

- Recall that for a spherical, fixed, homogeneous Earth:

$$g = G\frac{M}{R^2}$$

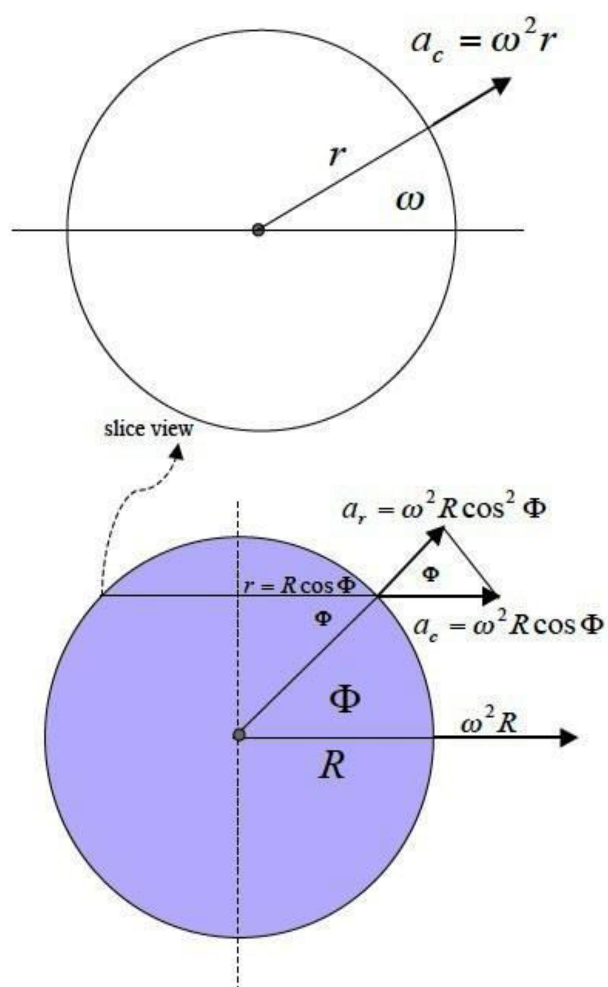
(R = mean Earth radius = 6371 km)

- Angular rotation = ω
  - Let us consider a plane parallel to the equator:
    - Centrifugal acceleration: $a_c = \omega^2 r$
    - Equator: a_c max ($r=R$)
    - Pole: $a_c=0$ ($r=0$)
  - Let us consider the spherical Earth:
    - Radial component of a_c:

$$a_r = a_c \cos\Phi = \omega^2 r \cos\Phi$$

    - Then:

$$r = R\cos\Phi \quad \Rightarrow \quad a_r = \omega^2 R\cos^2\Phi$$



Gravity Method, Dr. Wadhah M. Shakir, AL-Karkh University of Science,
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Effect of the Earth's rotation (2/2)

- Because of its rotation, the Earth is not a sphere but is flattened at the poles.
- The effect of the flattening on the gravity is:

$$\frac{3GMa^2}{2R^4}J_2\left(3\sin^2\Phi-1\right)$$

  - (see Turcotte and Schubert p. 199)
  - J_2 = dimensionless coefficient that quantifies the Earth's flattening (J_2 = 1.0827 x 10^{-3})
  - a = equatorial radius = 6,378 km (polar radius = 6,357 km)

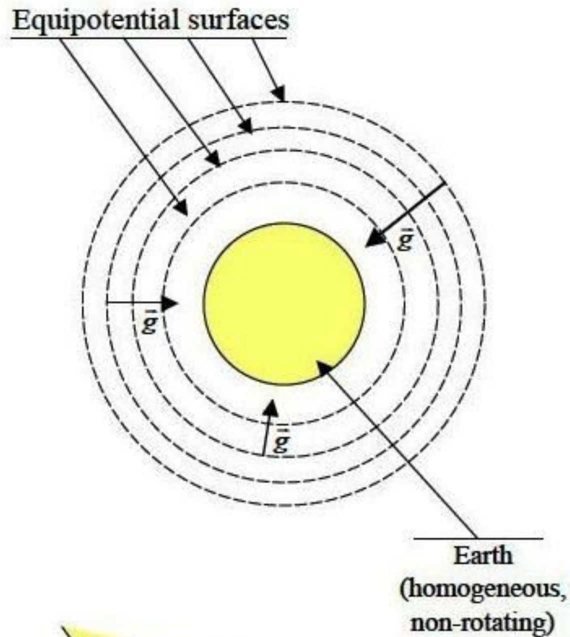
- Gravity potential of the Earth = - gradient of gravity
- Since gravity = gravitational attraction + centrifugal acceleration + flattening, therefore:

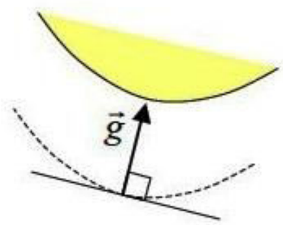
$$g=-grad(U)$$

$$\Rightarrow U=-\frac{GM}{R}+\frac{GMa^2}{2R^3}J_2\left(3\sin^2\Phi-1\right)-\frac{1}{2}\omega^2R^2\cos^2\Phi$$

Equipotential surfaces

- = surfaces on which the potential is constant
- U = constant, recall that: $dU = -g\,dr$
  - $\Rightarrow$ dU = zero on equipotential surfaces
  - $\Rightarrow$ g not necessarily constant on equipotential surfaces
- Non-rotating homogeneous Earth:
  - Recall that: $U = GM_E/r$
  - Therefore, $U = constant \Rightarrow r = constant \Rightarrow$ equipotential surfaces = spheres centered on M_E
- Practical use of equipotential surfaces:
  - Definition of the vertical = direction of the gravity field = perpendicular to equipotential surfaces
  - Equipotential surfaces = define the horizontal





The geoid

- There is an infinity of equipotential surfaces
- There is a particular surface on the Earth that is "easy" to locate: the mean sea level
- **The Geoid = the particular equipotential surface that coincides with the mean sea level**
- This is totally arbitrary.
- But is makes sense because the oceans are made of water (!): the surface of a fluid in equilibrium must follow an equipotential.

Over the oceans, the geoid represents the ocean surface (assuming no currents, waves, etc) , while over the continents its called the reference level. The geoid is not the topographic surface (its location can be calculated from gravity measurements).

Geoid “undulations” are caused by the distribution of mass and rocks density of the Earth.

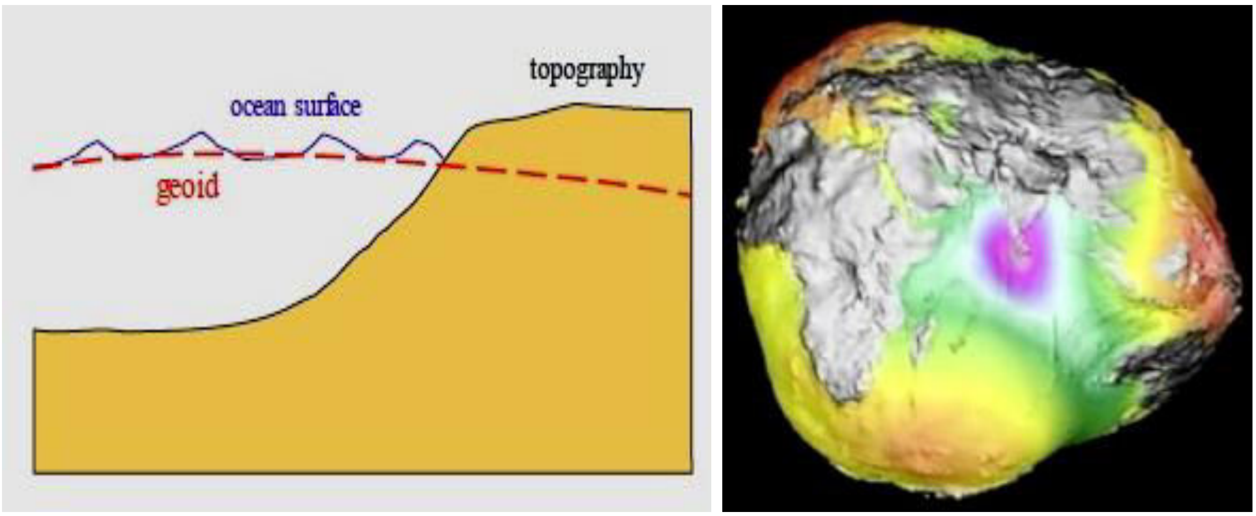
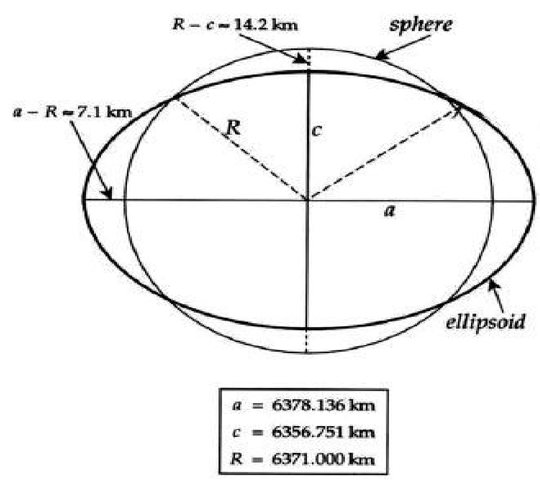


Figure (3): The gravitational equipotential surface of the earth (Geoid).

The Ellipsoid

- First evidence that the Earth is round: Erathostene (275-195 B.C.)
- First hypothesis that the Earth’s is flattened at the poles: Newton
- First measurement of the Earth’s flattening at the poles: Clairaut (1736) and Bouguer (1743)
- **<u>The shape of the Earth can be mathematically represented as an ellipsoid</u>** defined by:
  - Semi-major axis = equatorial radius = a
  - Semi-minor axis = polar radius = c
  - Flattening (the relationship between equatorial and polar radius): $f = (a-c)/a$
  - Eccentricity: $e^2 = 2f - f^2$



Comparison between the WGS-84 ellipsoid and a sphere of identical volume

The Reference Ellipsoid

Reference ellipsoid could be defined as the ellipsoid that best fits the geoid. It is totally arbitrary, but practical. The best calculated reference ellipsoid is (WGS-84). The geoid undulations represent the differences, in meters, between the geoid and reference ellipsoid or geoid "height", figure (4).

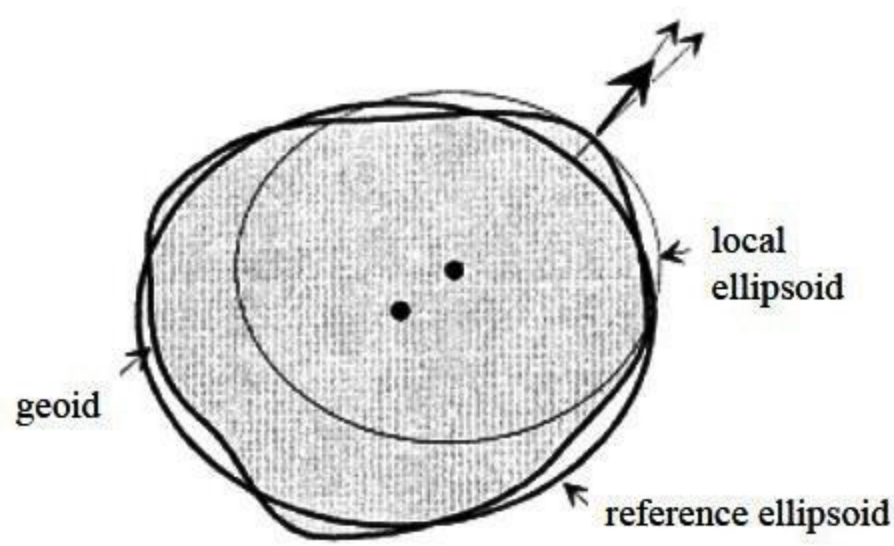


Figure (4): The geoid, reference ellipsoid and local ellipsoid of earth.

Gravity on the reference ellipsoid

- It can be shown (Clairaut, ~1740) that the (theoretical) value of gravity on the rotating reference ellipsoid is:

$$g = g_o(1 + k_1 \sin^2 \Phi - k_2 \sin^2 2\Phi)$$

  - g_o = gravity at the equator
  - k_1 and k_2 = constant that depend on the shape and rotation of the Earth
  - g_o, k_1, and k_2 are estimated from actual measurements. For GRS-1967:
    - g_o = 978 031.846 mGals
    - k_1 = 0.005 302 4
    - k_2 = 0.000 005 8

The value (g) from the previous equation is also called the theoretical gravity value and might be written as (g_ϕ).

According to this Equation:

– *g* depends only on latitude value (ϕ) in degrees, no longitude dependence.

– *g* does not vary linearly with latitude.

– g increases/decreases when latitude increases

This equation based on considering a homogeneous Earth, while heterogeneities represent the deviations from this equation, these deviations are called **gravity anomalies.**

The geoid represents the equipotential surface of the Earth's gravity field that best fits (in a least squares sense) the mean sea level.

The gravimetric potential is constant on the ellipsoid, while, Gravity is not constant on the geoid.

The reference Ellipsoid represents the theoretical ellipsoid that best fits the geoid, figure (5).

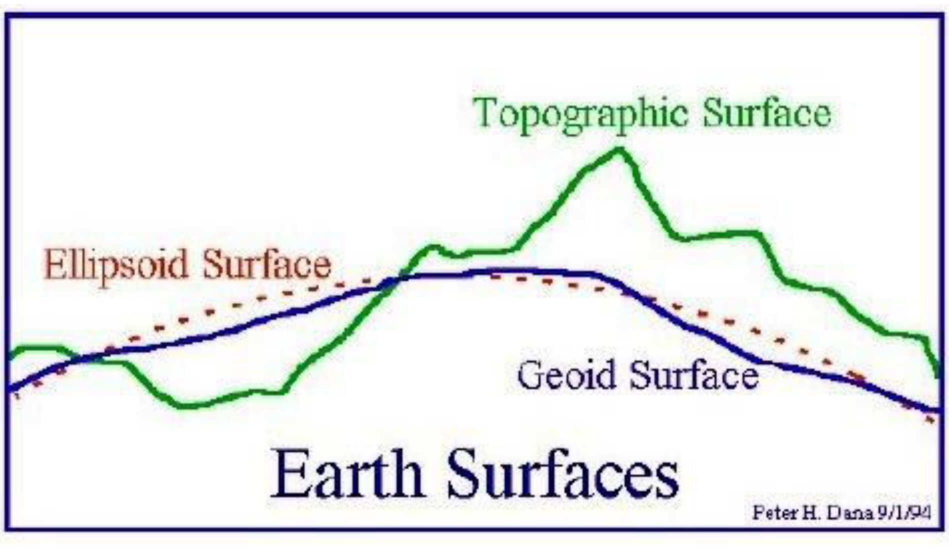
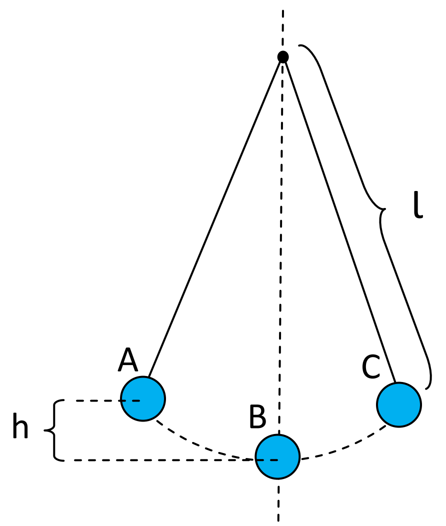


Figure (5): The geoid, ellipsoid and topographic surfaces of earth.

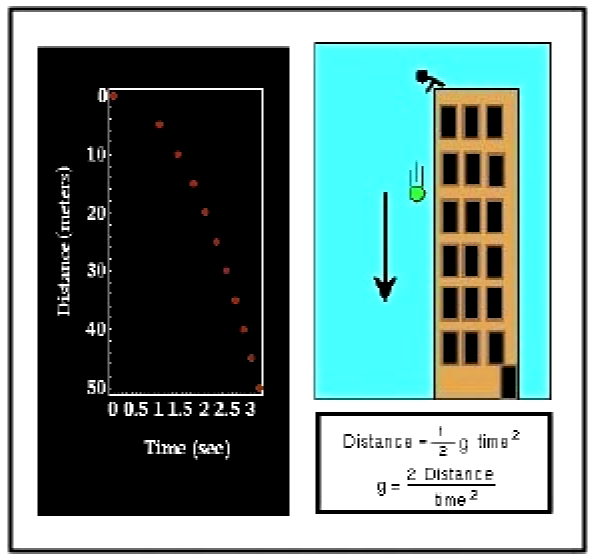
Gravity Measurement and Instrumentation

Absolute gravity measurment

At the 17th century pendulum clocks had to be tuned when moved from Paris (49N) to Cayenne (5N). The first gravity measurements made with a pendulum by using absolute measurements (Acceleration of a mass in free fall).



The simple pendulum



absolute measurement

Figure (6): The simple pendulum and the free falling body in absolute gravity measurement.

The simple pendulum considered as a free falling body with a simple harmonic motion which is simply a mass hanged by a wire its length is (l) , (figure 6).from the figure (h) represents the free falling distance for the pendulum mass from point A to point B. The period (T) represents the time of one cycle where the pendulum start moving from the point (A) passing through (B), then reaching to point (C) and move back to the point (A) to finish one oscillation cycle. (T) can be calculated according to the following equation:

$$T = 2\pi\sqrt{\frac{l}{g}}$$

T = period
l = wire length

Then:

$$\boldsymbol{T^2 = 4\pi^2\ \frac{l}{g}}$$

Or:

$$\boldsymbol{g = 4\pi^2\ \frac{l}{T^2}}$$

Were (g) is the absolute earth gravity acceleration.

The pendulum frequency (F) represents the number of its cycles devided by 60 , where:

F= No. of Cycles per minute / 60

And the period (T) in seconds represent the reciprocal of frequency where:

T=1/F

The simple experiment of pendulum could be achieved in the laboratory by counting the number of cycles per minute for each time with increasing the length (l) of pendulum arm , then drawing a simple plot to calculate the ratio ($\frac{l}{T^2}$) , (figure 7).

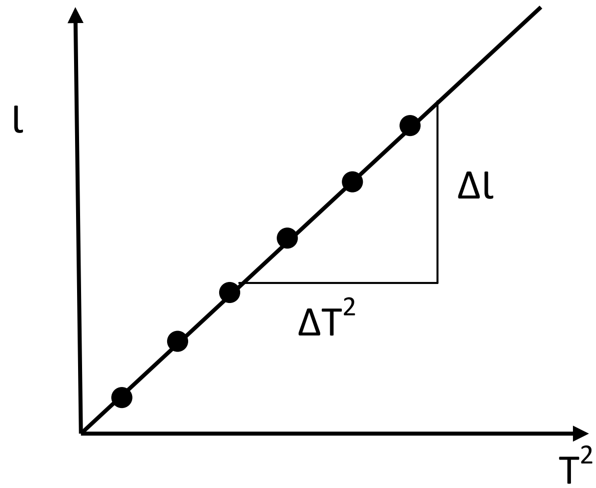
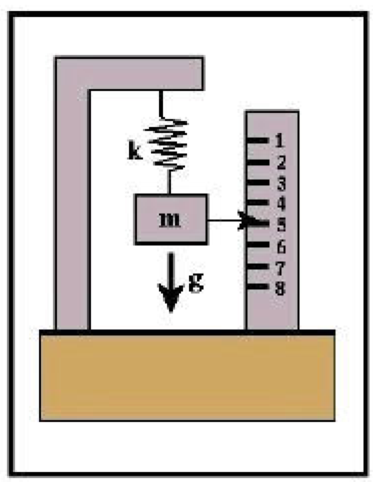


Figure (7): The experimental relation between the pendulum length and the square value of period, which used to find (g).

<u>Relative Gravity measurements</u>:

– Extension of a sensitive spring with a reference position.



relative measurement

– Levitation of a metal mass in an electromagnetic field by using supraconducting gravimeters, this method require reference sites where absolute gravity is known. The principle of relative gravity measurement instruments is simply a mobile mass attached to a sensitive spring and they are mainly in two types:

– **Stable gravimeters**: these devices measure the extension of the sensitive spring and called (Scintrex).

– **Unstable gravimeters**: it depends on measuring the displacement which happens to the spring then bringing it back to its equilibrium position like (LaCoste & Romberg gravimeter), figure 8.

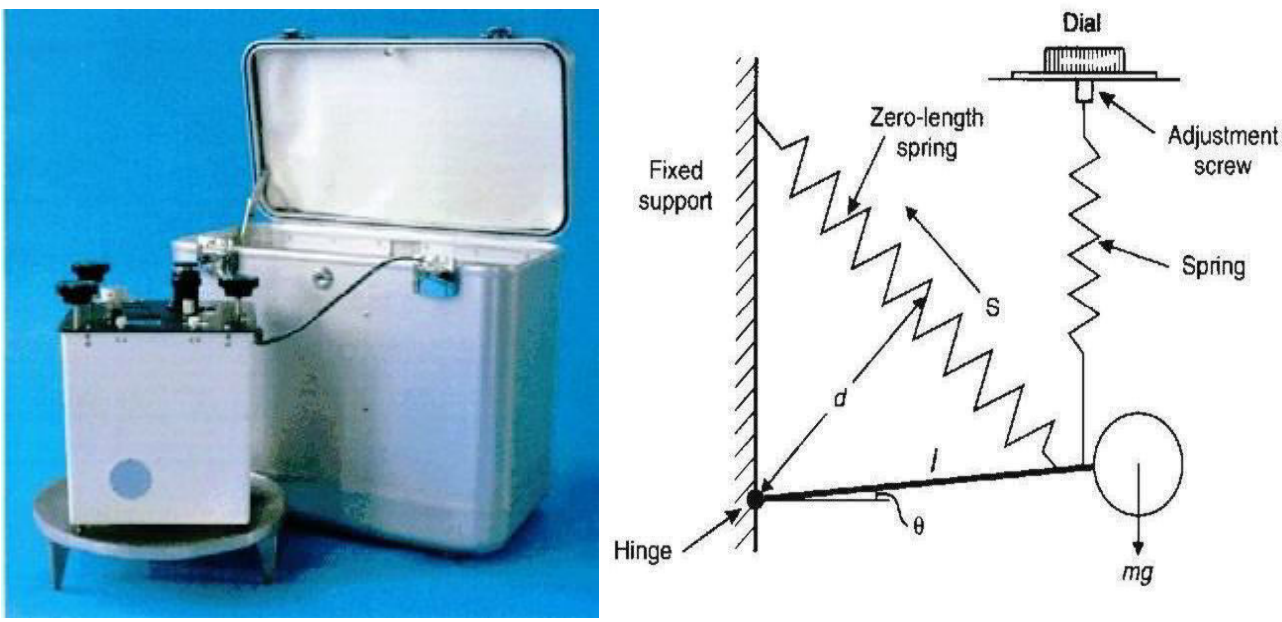


Figure (8): The LaCoste and Romberg gravimeter external shape and cross section showing its components.

The mechanical properties of sensitive springs depend on the temperature during measurement, therefore, a thermostat included within the device. Perfect leveling is also necessary and could be achieved with the assistant of leveling plate, screws and balances. The elasticity of springs varies according to the age and transportation of the device which produces what called the (instrumental drift).

The instrumental drift is a complex, function of age, transportation, and other related to the device factors which affects the precision of gravity reading and calculated and provided by the gravimeter manufacturing company as a number called (the gravimeter device constant), this constant used to be multiplied by the direct gravimeter measurement value which is in the unit of (scale division) to obtain readings in mGal. The acceptable precision of unstable gravimeters is ~ 0.01 mGal.

Another type of unstable gravimeters is the (Worden Gravimeter), figure 9, it is smaller in size and easier to carry in the field but with less precision than the LaCoste and Romberg one.

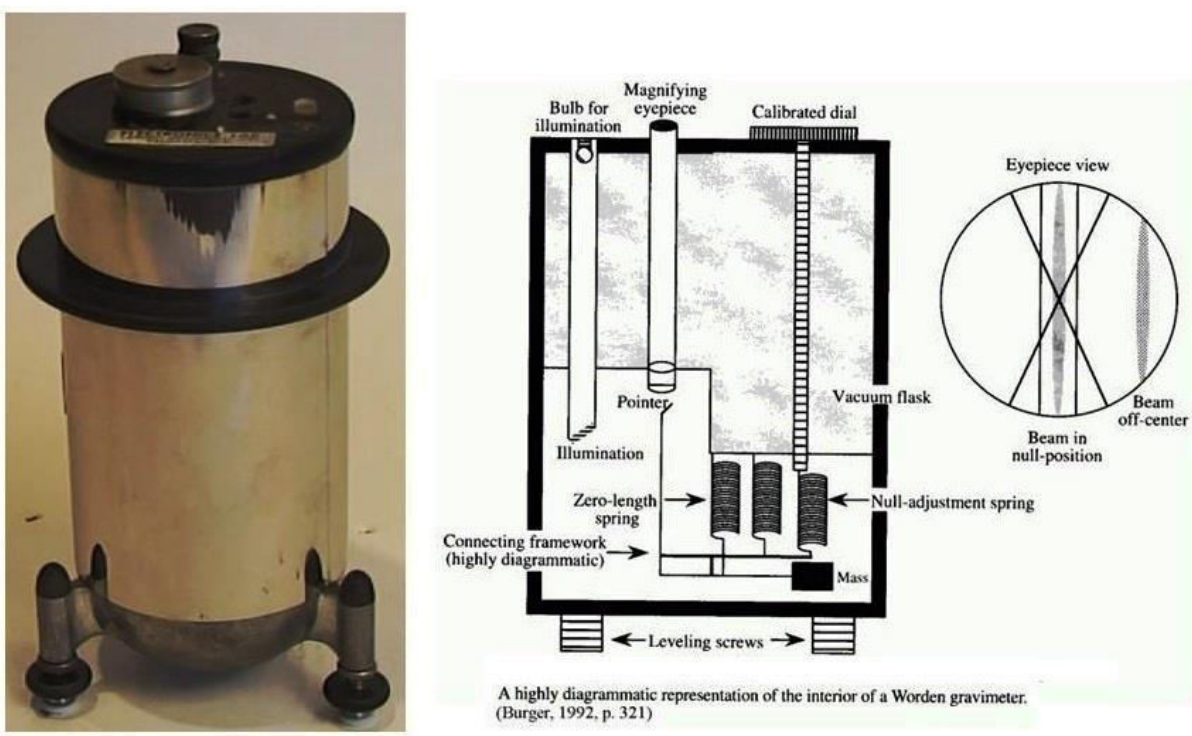


Figure (9): The Worden gravimeter external shape and cross section showing its components.

The LaCoste and Romberg gravimeter device, model G-198 of Geophysical Engineering of Montana Tech. external appearance and switches are shown in the figure 10.

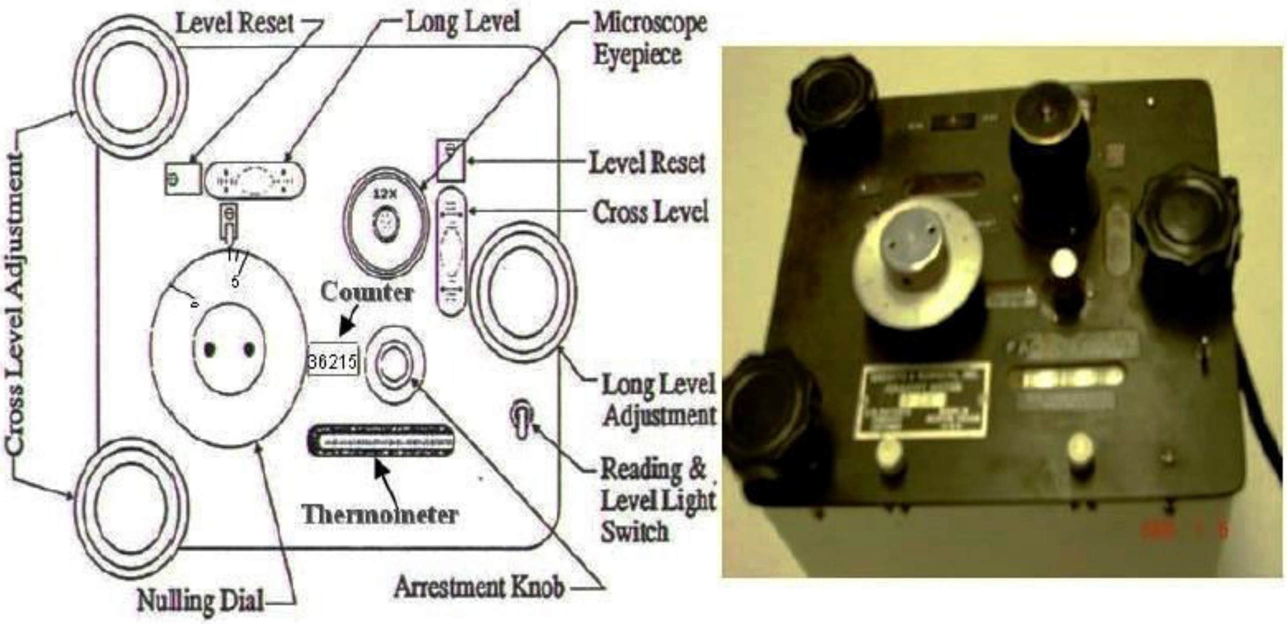


Figure (10): The LaCoste and Romberg gravimeter external appearance and cover switches.

<u>Basic Steps of Gravity measurement by using LaCoste and Romberg Device</u>:

1. Place a circular aluminum base plate on a flat area.
2. Remove the gravimeter from carrying case and place it on the base plate. Gently slide the meter in the concave base plate until the meter levels indicate the gravimeter is approximately level.
3. Connect power source. Wait for 2 to 5 hours because a gravimeter requires so long to reach an equilibrium operating temperature. (This should be done indoor well before field trip to save time.)

4. Level the gravimeter using the three black leveling knobs. For efficiency, you may wish to level the Cross Level (also called traverse level that is at 90° with the direction of the meter's beam) first using the two Cross Level Adjustment leveling knobs on the left side atop the gravimeter (see Figure 10) Then, level the Long Level with the Long Level Adjustment knob on the right side. The accuracy of the gravity readings will depend on the accuracy of the meter leveling. **Check Levels Frequently! (**Note: for the gravimeter of Model G-198, the leveling screws and their knurled turning flanges are under the meter.)

5. Turn on the reading light and the spirit level lights. The switch is located on the near right side of the black lid. Do not leave the light turned on for a prolonged time, especially in hot weather. Observe the position of the beam. It will be close to the bottom stop (clamped position) Turn the Arrestment knob **counterclockwise** to its furthest extent **TO RELEASE THE INTERNAL BEAM FROM CLAPING**. The knurled arrestment knob is located on the near side of the microscope eyepiece. **DO NOT MOVE GRAVIMETER and KEEP THE GRAVOMETER LEVELED!**

6. Turn the nulling dial to locate the lower and upper stops (the interval between lower stop and upper stop is about 14 small optical divisions). Position the crosshair about one small optical division above the bottom stop. Be sure to approach the **reading line** (see Figure 11) from the left (clockwise turn of the nulling dial). **The reading line for D-66 is 2.60. The reading line for G-198 is 3.20.**

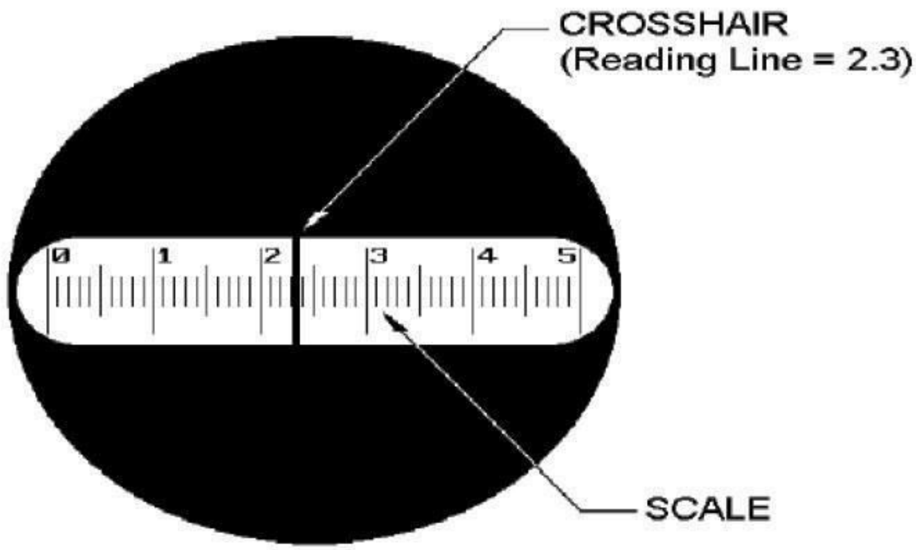


Figure (10): Meter reading from the crosshair in the eyepiece. (from L&R manual, 2004).

7. To take a reading, Peer through the eyepiece and locate the crosshair. Adjust the nulling dial (Nulling Dial) to bring the left side of the crosshair to match the left side of the reading line (2.60 for D-66, 3.20 for G-198). **If the crosshair need to move to the left of the reading line, turn the dial counterclockwise, otherwise, turn clockwise.**

8. Record the number in the counter, the station number (position and elevation of the station), and the time when the gravimeter reading is taken. There is a decimal place to the right of the last digit. For model **G-198**, the last digit on the counter should match the last digit on the dial. This number is tenths of unit. Estimate one more digit from the dial (hundreds of unit). **Example: The counter number is 36215 and the dial number is 52. The meter reading is then 3621.52.** Here 5 in 36215 is estimated, but after match the reading from the dial, it is an accurate number. 2 in 52 is a real estimate from the dial (see Fig. 10). After reading is

finished at one station, **clam the meter by turning the Arrestment Knob clockwise to the end of travel to clamp the beam to protect it**.

9. Converting the counter reading to mGals: To convert the meter readings G-gravimeter to gravity in mGals, the calibration table for the specific G gravimeter is needed. Suppose the **meter reading** is 3621.52 using Montana Tech's G-198 meter. The meter reading in milligals is obtained by finding the highest **tabled value** lower than the new reading (thus we got 3600, see the following calibration table).

Milligal Values for LaCoste & Romberg, Inc. Model G Gravity Meter # 198

Counter Reading*	Value in Milligals	Factor for Interval	Counter Reading*	Value in Milligals	Factor for Interval
000	000	1.05673			
100	105.67	1.05686	3600	3807.31	1.05874
200	211.36	1.05706	3700	3913.19	1.05870
300	317.07	1.05701	3800	4019.06	1.05868
400	422.77	1.05675	3900	4124.92	1.05870
500	528.44	1.05675	4000	4230.79	1.05870
600	634.12	1.05687	4100	4336.66	1.05869
700	739.80	1.05700	4200	4442.53	1.05866
800	845.50	1.05705	4300	4548.40	1.05864
900	951.21	1.05705	4400	4654.26	1.05860
1000	1056.91	1.05705	4500	4760.12	1.05855
1100	1162.62	1.05705	4600	4865.98	1.05850
1200	1268.32	1.05708	4700	4971.83	1.05843
1300	1374.03	1.05712	4800	5077.67	1.05840
1400	1479.74	1.05719	4900	5183.51	1.05831
1500	1585.46	1.05726	5000	5289.34	1.05822
1600	1691.19	1.05735	5100	5395.16	1.05813
1700	1796.92	1.05745	5200	5500.98	1.05800
1800	1902.67	1.05749	5300	5606.78	1.05788
1900	2008.42	1.05755	5400	5712.56	1.05774
2000	2114.17	1.05760	5500	5818.34	1.05760
2100	2219.93	1.05768	5600	5924.10	1.05745
2200	2325.70	1.05777	5700	6029.84	1.05726
2300	2431.48	1.05787	5800	6135.57	1.05707
2400	2537.26	1.05800	5900	6241.28	1.05685
2500	2643.06	1.05812	6000	6346.96	1.05662
2600	2748.88	1.05819	6100	6452.62	1.05638
2700	2854.70	1.05823	6200	6558.26	1.05611
2800	2960.52	1.05827	6300	6663.87	1.05583
2900	3066.35	1.05832	6400	6769.46	1.05553
3000	3172.18	1.05838	6500	6875.01	1.05524
3100	3278.02	1.05845	6600	6980.53	1.05489
3200	3383.86	1.05851	6700	7086.02	1.05450
3300	3489.71	1.05861	6800	7191.47	1.05408
3400	3595.57	1.05868	6900	7296.88	1.05362
3500	3701.44	1.05871	7000	7402.24	1.05315

Note: Right hand wheel on counter indicates approximately 0.1 milligal.

10. Record the value of the table value in milligals (thus we got 3807.31). Subtract the **table value** (3600) from the **meter reading** (3621. 52) and multiply this difference (3621.52 - 3600 = 21.52) by the tabled **interval factor** (**1.05874**, see the calibration table) to convert this difference to milligals (21.52 x 1.05874 = 22.7840848 mGals). Add the tabled milligal value (3807.31 mGals) to the calculated value (22.7840848 mGals), we got the converted gravity value (22.7840848 + 3807.31 = 3830.094085 mGals).

Another Example (using model G-198):

Meter reading: 3721.21, Highest tabled value: 3700, Difference: 21.21, Interval factor: **1.05870** (from caliboration Table)

Difference x Interval Factor=21.21x1.05870 = 22.455027 mGal

Highest tabled value in milligals: 3913.19 mGal (from the calibration Table)

Sum: 3913.19 mGal + 22.455027 mGal = 3935.645027 mGal.

It is also possible to obtain the approximate grvity value in Gal from another table according to the previously mentioned counter or corresponding reading and the latitude as shown in the following table.

Latitude	Approximate Gravity	Corresponding reading
0	978.046	1430
10	978.203	1600
20	978.652	2050
30	979.337	2750
40	980.178	3600
50	981.078	4530
60	981.93	5400
70	982.623	6100
80	983.073	6560
90	983.223	6700

Types of Gravity Surveys:

As we learned previously the unstable gravimeters are the most reliable portable devices which used to achieve the gravity surveying. Gravimeters could be designed to achieve two main types of geophysical surveys which are:

1- Gravity ground survey: is the most common type of geophysical surveying methods, where the concerned region or area is gridded into stations, and gravity measurement and other related readings are recorded for each station of this grid. Constant spacing between a station location and other must be taken in consideration; also, inter-station spacing value must be fixed as much as possible. This will also depends on the depth of the detected subsurface target.

2- Marine Gravity survey: a boat or vessel carries the gravimeter to take gravity measurements across seas and oceans; this type of surveying has less application in Iraq. Internationally, LaCoste & Romberg produced the world's first marine gravimeter in 1955, and gravity measurements were made on submarines. In 1965, the Stabilized Platform marine gravimeter, which is the base of the current model, was developed, and it was possible to measure gravity at a reproducibility of 1 mGal at sea. Since then, more than 120 systems have been delivered. The current LaCoste & Romberg marine and aircraft gravimeters consist of a zero length spring gravity sensor with damping on the Stabilized Platform, a digital controller that controls them, and a data acquisition device that records data. The Optical fiber gyros are used for 2-axisand3-axisplatforms. Since it has a measuring range of 12000mGal, it can measure the gravity of the whole world. Figure 11 shows the LaCoste and Romberg marine gravimeter.

Figure (11): The LaCoste and Romberg Marine gravimeter.

3-Satellite orbitography: Orbits of artificial satellites are controlled by the variations of earth gravity field. Therefore, the precise measurements of their trajectory represent the gravity field effect. "Geodetic" satellites and ground tracking stations network are used in the estimation of precise orbit which represent the restitution of gravity field. Satellite trajectory is derived from Satellite Laser Ranging (SLR), figure 12 showing the (Starlette geodetic satellite) which launched in 1975, 48 cm diameter and 47 kg mass.

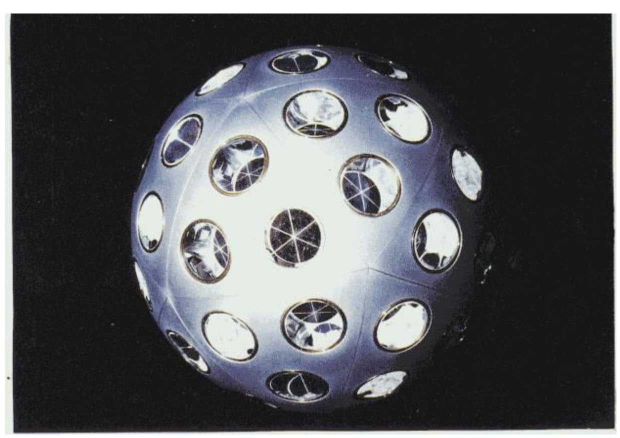


Figure (12): The Starlette geodetic satellite.

The figure 13, showing the process of tracking satellite with a network of SLR stations. Figure 14, showing the SLR at Goddard Geophysical and Astronomical Observatory. The two laser beams are coming from the network standard SLR station, MOBLAS-7(MOBile LASer) and the smaller TLRS-3 (Transportable Laser Ranging System) during a collocation tracking a satellite with a network of SLR stations. Current version of global gravity field = GRIM5 [21 satellites, data since 1971, precision =3 mGals]. Method advantage guarantees gravity field recording with a global coverage.

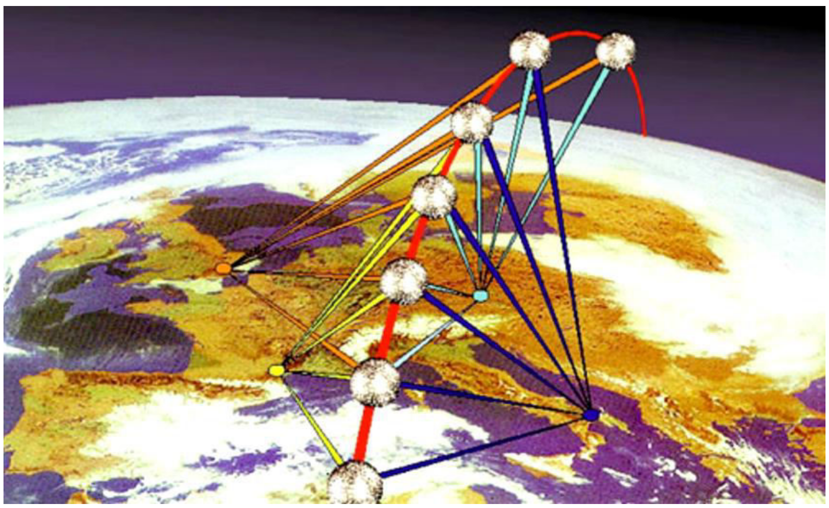


Figure (13): The process of tracking satellite by using the Satellite Laser Ranging (SLR) technique with a network of ground stations.

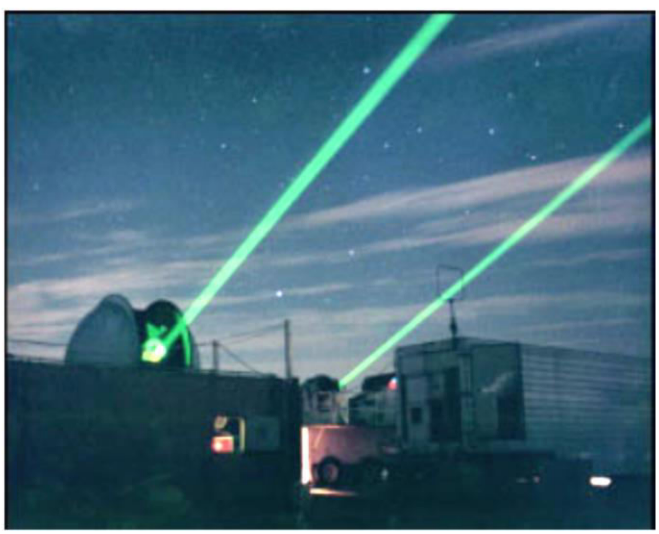


Figure (14): The process of tracking satellite by using the Transportable Laser Ranging System (TSLR) ground stations.

The Required Steps to Achieve a Gravity Survey:

The achievement of gravity geophysical survey could be done by following the basic required steps or procedures:

1- Determining the objective of gravity surveying, and this might be applied to investigate the subsurface structural traps of petroleum, detecting mineral ore bodies, cavities and faults and weakness zones within infrastructures foundations and its depth and extension below ground surface. Determining the depth of the target will control the distance between a gravity measurement station and another at Earth's surface, also, it decides the area which required to be covered by the gravitational grid network.

2- A detailed surface geological map must be available in the office before achieving the survey. This map includes topography or the elevation above sea level information, the outcrop of at surface or near surface geological formations, the geomorphologic features like the locations of rivers , lakes , mountains…..etc.. In addition this map must include a precise drawing scale, coordinates, the north direction and suitable legend. This geological map used to derive the base map of the gravity survey and the locations of measurement stations could be located on it before attending the field survey.

3- Gathering surface and subsurface geological information about the study area. And this could be done by providing data of previous geophysical or geological studies which achieved in the past at the concerned area. Geological data related to boreholes , seismic sections or well logging could be very helpful in reducing the ambiguity which related to the interpretation of gravity survey results which are mostly the Bouguer anomaly gravity maps and profiles.

Ambiguity in gravity method could be defined as the uncertainty in interpreting the anomalies which related to subsurface variations in density or depth due to the lack of subsurface geological information like rocks density variation due to tectonic, structural or sedimentological reasons. The ambiguity can be reduced by assisting gravity method results with borehole information or by the results of additional geophysical methods like magnetic, seismic, electrical and well logging methods.

The deep boreholes can provide valuable information about the depth and density of subsurface rocks. Core samples obtained from boreholes could be tested in the laboratory to study rocks density, porosity, permeability and other petro physical properties.

4- The provision of the proper geophysical instruments to achieve the gravity survey. This is mainly the sensitive gravimeter, Global Positioning System (GPS) device, manual or digital compass, base map and field tools that guarantee taking a proper and precise measurements at field. Furthermore, field team must be trained and include geophysicists, survey engineers , trained and non-trained workers , drivers in addition to the provision of camping requirements if required.
5- In order to ensure that gravity readings covering the whole concerned region, an ideal grid pattern may be adopted and fixed on the base map, figure 15-a. And if it is not possible to achieve an ideal grid actually, due to some field obstacles, a random pattern could be achieved, but trying to keep constant distances between one station and the other as much as possible, figure15-b. The stations and base stations are numbered and fixed on the base map.

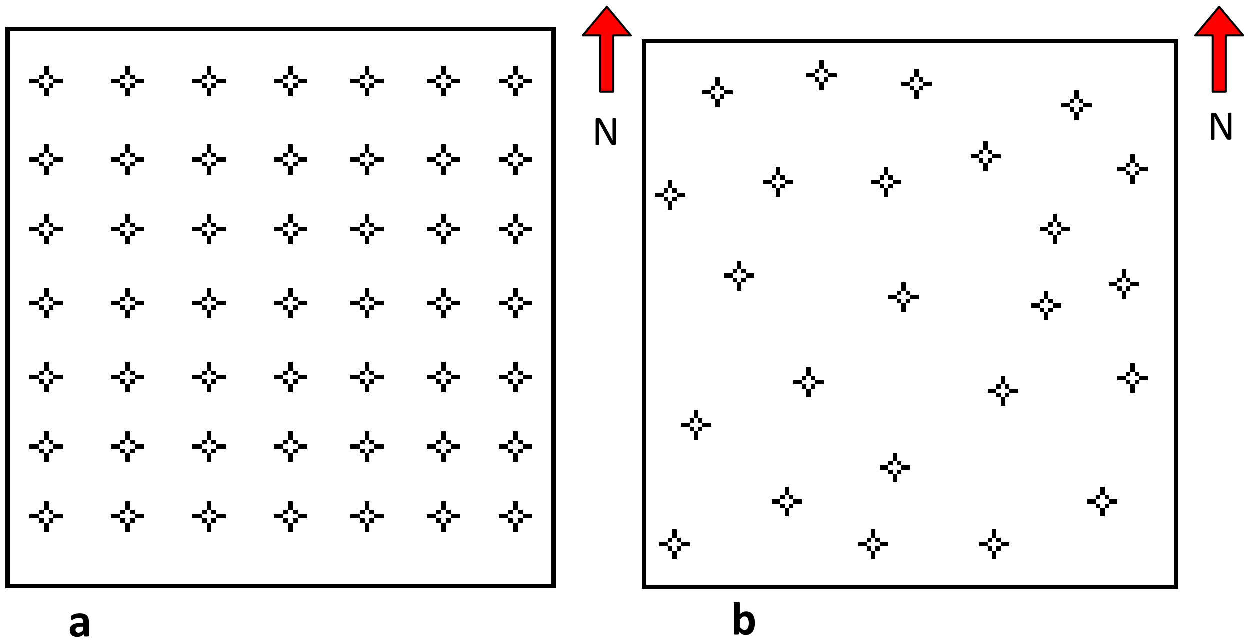


Figure (15): Grid pattern of gravity stations , a: Ideal grid pattern , b: random pattern .

The gridding spacing or interstitial spacing could be decided before achieving the survey; also, station locations and numbers are fixed on the base map. This will follow the goal or the target of the subsurface investigation.

6- The preparation of a field table which include the following information: station number, elevation above sea level in meters, latitude and longitude vales of the station location, density of the rocks at the station location in g|cm^3, gravimeter counter reading, date and time of measurement in hours and minuets, gravity observed gravity reading in mGal, reading correction values and the final gravity corrected reading in mGal, theoretical gravity value ($g\phi$), and the Bouguer anomaly gravity value.

7- After calculating the Bouguer anomaly values for every station in the area they superimposed on the base map and a contour map of gravity Bouguer anomaly is drawn, figure 16. The Bouguer anomaly contour map considered as the raw material for both descriptive and qualitative interpretation , figure 17, this contour map usually constructed by using a contouring software like (Surfer) and by using kriging interpolation method .

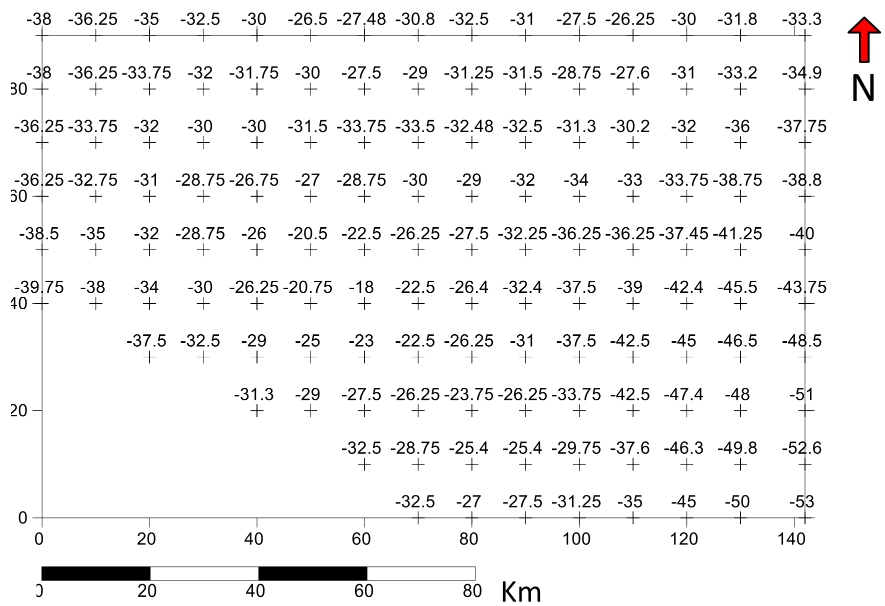


Figure (16): Grid pattern of gravity stations on base map, where Bouguer anomaly values are superimposed near every station.

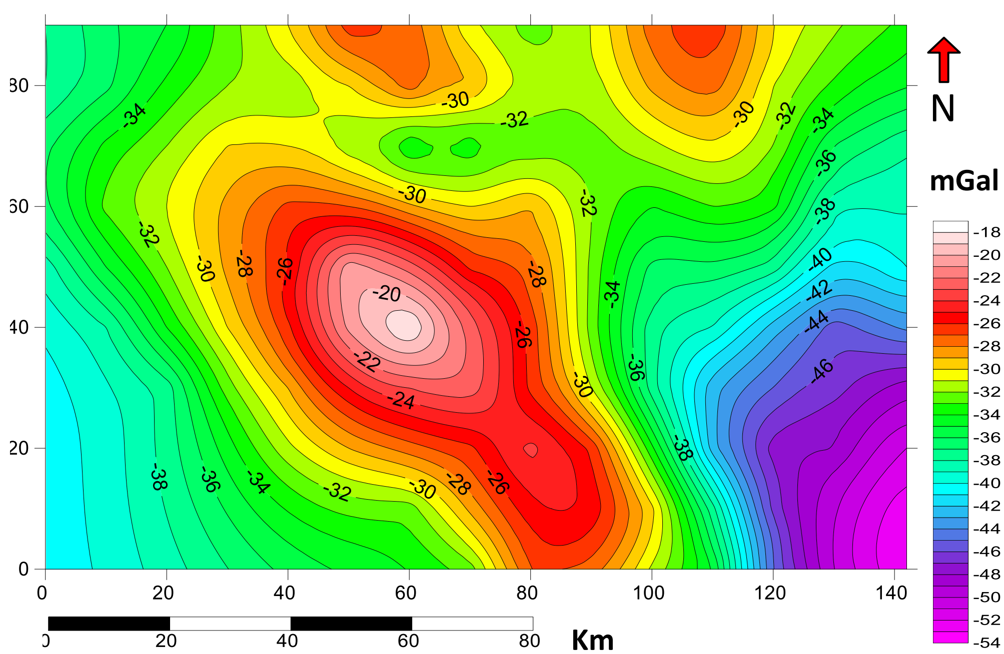


Figure (17): The Bouguer anomaly map, drawn by using Surfer software.

Correction of Gravity Readings

Before going into how these corrections are made, the effects of the gravity deviation related to the gravimeter which used to measure gravity arises as a result of elongation of the sensitive spring inside the device. This elongation is produced by transportation while continuous readings taken at field in addition to the effect of the rising temperature and the age of the device.

After taking gravity measurement by using gravimeter for every station in the surveyed area, these reading measurements should pass through a series of corrections. The reason behind applying these corrections is to eliminate the effect of some factors that affects the gravity reading on a certain station at ground surface like: the elevation above sea level, time of measurement, subsurface rocks density effect, station location according to latitude and the terrain or topography of the region. These corrections represent the following:

1- Drift and Tidal correction
2- Free air correction } Total Elevation Correction
3- Bouguer correction }
4- Latitude correction and the theoretical gravity value (g_ϕ)
5- Terrain correction
6- Isostatic correction

1- Drift and Tidal Correction

The gravity measurement value which taken for a certain station at ground surface differs with time during the same day after some hours, this effect is called the **drift effect**. Gravitational readings are also influenced by the tides which produced by the gravitational attraction force of the sun and moon's to the mass of the Earth during the hours of a day. It is possible to eliminate this effect by correcting our readings according to what called **base stations**. The base station is a gravity station in which gravity measurement value is known on the bases of day and hours. The correction could be done by plotting a drift curve and by using data of the nearby base stations which considered as a reference to correct this drift, figure 18. It is intended to refer to the nearby base station every hour, two or three hours according to the distance of the reference station from the point of measurement.

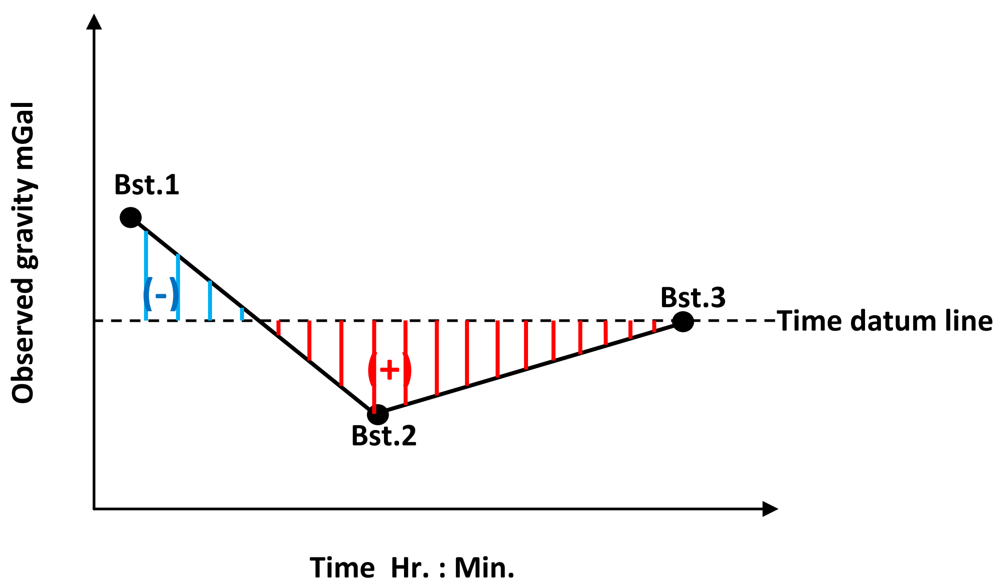


Figure (18): Gravity readings Drift graph , the black points represent the base stations, the disconnected line represents the time datum line taken from the Bst.3 and used as an index line to correct the normal stations measurements, short vertical lines over the datum line represent the increasing drift values at normal stations, while the below datum line represent the decreasing drift values at normal stations.

Figure 18, showing the drift correction graph. It represents an experimental relation between the observed gravity values which measured at normal and base stations. One of the base stations (Bst.3) considered drawing the time datum line which represents the reference line in correcting the other stations drift. The drift that happened in gravity readings for the normal stations represents the vertical short lines. Short lines over the datum line represent the unwanted positive drift which must be subtracted from the station observed reading, while the short lines below the datum line represents the unwanted negative drift which should be added to the station observed reading.

2-Free Air Correction

This correction takes into account the decrease of gravity vertically by increasing the elevation of the measurement station above sea level. This will cause the increase of distance from the center of the earth and the measurement station. The amount of decrease is about (-0.3086 mGal) for every one elevated meter above the sea level. The correction is done by returning readings to a reference level (Datum plane or the reference ellipsoid), which is often the sea level, figure 19.

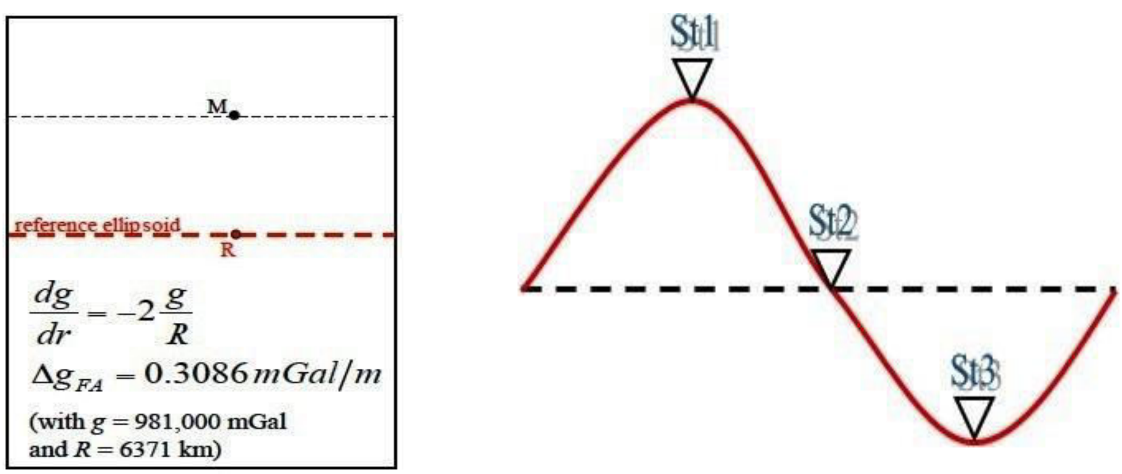


Figure (19): The free Air effect on gravity measurement at three stations, St.1 is located over the sea level datum which (decrease in gravity), St.3 is located below sea level (increase in gravity), and St.2 is located within the sea level (no effect in gravity).

The free Air effect on gravity measurement on earth surface could be expressed by the equation:

$$\textbf{Free Air effect (mGal)} = \pm 0.3086 \times h$$

Were (h): is the measurement station elevation above sea level.

3-Bouguer Correction

This type of correction is concerned with the attraction of rock materials which located between the reference level (reference ellipsoid), and the measurement station at the earth surface, figure 20. It is proposed that these rock materials represent a horizontal plate (Horizontal slab) which extends to infinity and its thickness is equivalent to the height difference between the measurement station and the reference level. The Bouguer effect is based on the assumption that the station is subjected to a downward gravimetric attraction due to the rocks mass and density in addition to the opposite force upward which caused by the Free Air effect.

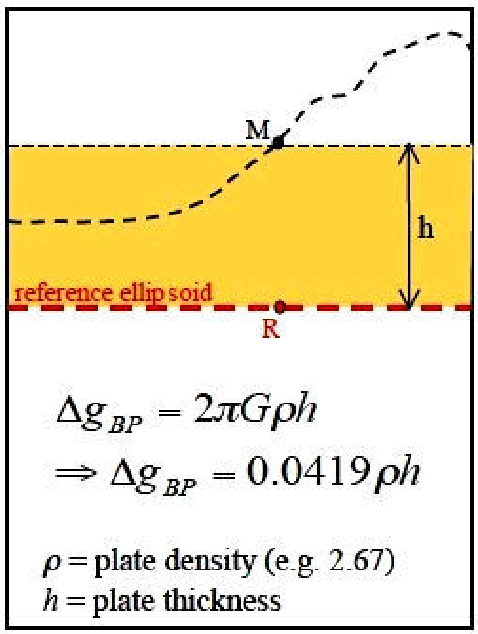


Figure (20): The Bouguer effect or correction at the surface gravity measurement station (M).

The Bouguer effect is expressed by the following equation:

$$\textbf{Bouguer effect (mGal)} = \pm 0.0419 \times \rho \times h$$

Where : (ρ) is the rocks density of the horizontal slab extending to infinity with a thickness equivalent to the difference between the reference level and the measurement station location, its unit is ($g \backslash Cm^3$) or ($Kg \backslash m^3$).

(h): is the elevation above sea level.

The Bouguer correction takes both (h) and (ρ) into account. This correction effect value is negative for the stations which are located above the reference level and usually get subtracted from the station observed reading. Vice versa happens for the stations located below the reference level where Bouguer effect value is positive and usually get added to the station observed reading.

Since (Free Air and Bouguer) effects or corrections are both dependant on the elevation above sea level (h), then the both effects are able to be calculated in one equation and this is what called (Total Elevation Correction), In other words the equations of total Elevation effect could be written as:

For the stations located above the reference level:

Total Elevation Effect (mGal) = (Free-air effect) - (Bouguer effect)

For the stations located below the reference level:

Total Elevation Effect (mGal) = - (Free-air effect) + (Bouguer effect)

Or

$$\textbf{Total Elevation Effect (mGal)} = (0.3086 \pm 0.0419\,\rho)\,h$$

4-Latitude Correction and the Theoretical Gavity Value (g_ϕ)

The value of gravity increases as we move from the equator toward the poles because of earth low rotation velocity and the decrease of centrifugal force at the poles. Furthermore, Earths radius at the northern and southern poles is less than that at the equator with the amount of about 21 Km, this produces a gravity value difference between Earth poles and equator of about (5172) mGal or (5.1) Gal. Gravity increases gradually when we move from the equatorial regions toward polar regions with latitude at average increase rate of (w), where:

$$W = 0.8122 \sin 2\Theta \quad \text{mGal / km} \quad , \quad W = 1.307 \sin 2\Theta \quad \text{mGal / mile}$$

W: The average increase or decrease rate of gravity with latitude.

Θ: is the latitude angle in degrees.

If the vertical distance away from the equator toward north or south is known then, the latitude effect of gravity could be expressed by the following equation:

$$\textbf{Latitude Effect mGal} = w \times \text{distance}$$

The theoretical gravity value (g_ϕ) is the gravity value of the reference ellipsoid which mentioned previously. The **International Gravity Formula** is used to find the (g_ϕ) in the unit of (Gal) for any station located at earth surface, this formula is:

$$g_\phi = g_0 (1 + a \sin^2\Theta - b \sin^2 2\Theta)$$

Where: g_0 is the gravity at the equator

a and b : constants which depend on the tilting of earth rotation axis, the angular velocity of Earth rotation and earth flattening as shown in figure 21.

Θ: is the latitude angle value in degrees.

Therefore, the final shape of the international gravity formula is:

$$\mathbf{g_{\phi} = 978.049\ (1+0.0052884\ \sin^2\Theta - 0.0000059\ \sin^2 2\Theta)} \qquad \mathbf{Gal}$$

The theoretical gravity value (g_ϕ) which calculated by the above equation is in the unit of (Gal) , so it must be multiplied by 1000 to convert it to the unit of (mGal). It is worth to mention that:

g_ϕ when $\Theta = 0°$ is 978.049Gal at the Equator

g_ϕ when $\Theta = 90°$ is 983.221Gal at the Pole

g_ϕ when $\Theta = 45°$ is 980.629Gal at the middle distance between equator and pole.

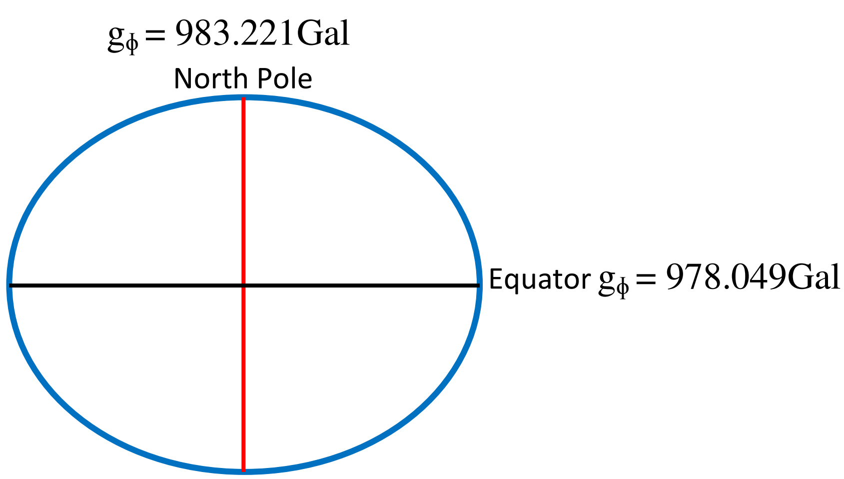


Figure (21): The difference in the theoretical gravity value (g_ϕ) between the earth's equator and pole.

5-Terrain Correction

This type of correction is concerned with the tangential pulling attraction force which produced by different terrains such as valleys and hills in the areas surrounding the measurement station. This attraction force affects the measured gravity value which supposed to be vertical and toward the center of the earth. This effect is related to the topography rocks mass which adds unwanted effect to the gravity measurement value, figure 22.

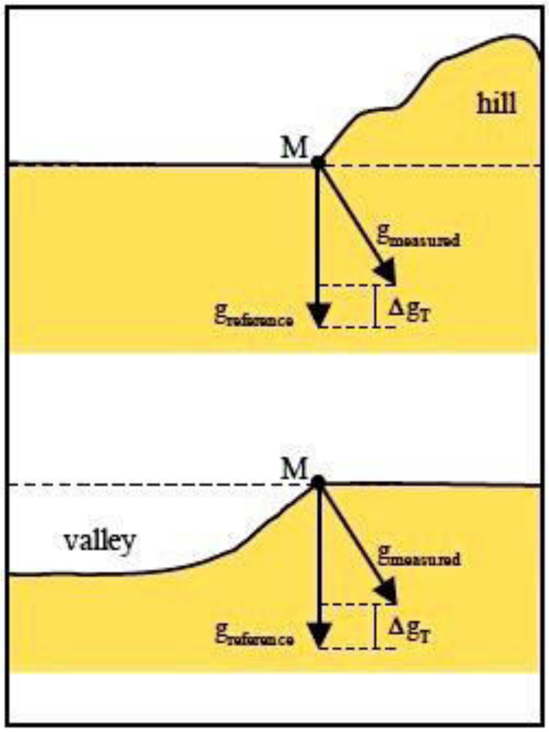


Figure (22): The effect of terrain or topography on the measured gravity at station (M) in the case of surrounding by a hill or valley.

The terrain or topographic effects should be taken in consideration by calculating the gravity of rock blocks which will be added to the valleys below the measurement level or that will be subtracted from the hills above the measurement level.

Terrain corrections is achieved by using a special calibration models and tables designed for this purpose and called (**Hammer`s circles**),figure 23, which is a group of concentric circles with lines or rays emanating from the center point and divided these circles into a group Zones, and be either A circle or half circle drawn in two dimensions (x, y), see figure 23.

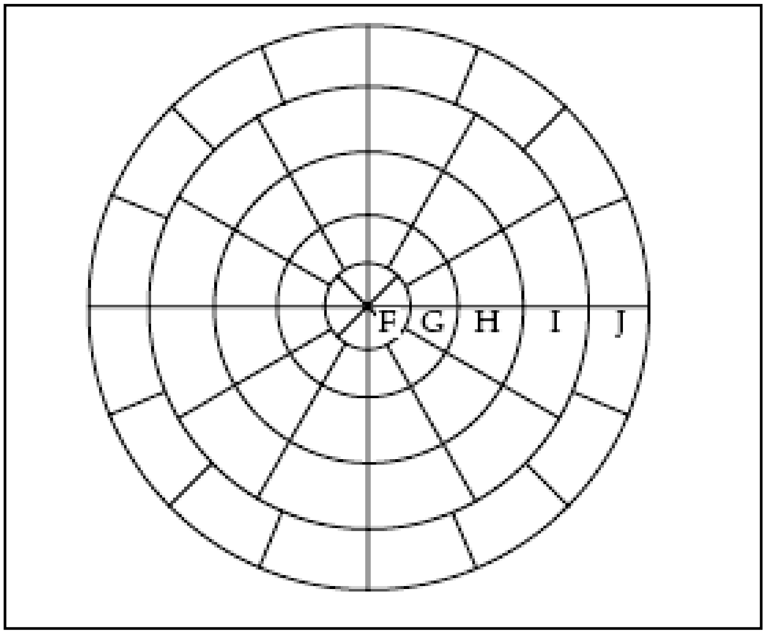


Figure (23): The standard Hammer`s circles which used in gravity terrain correction.

The center of these circles is superimposed at the measurement point of the topographic map for the surveyed area, which must has the same drawing scale for these circles (drawn on a transparent sheet), then we calculate the average elevation for each band. The correction value for each range is obtained from the standard tables (Hammer`s Table), after that these correction values are collected to obtain the total correction value which is added to the gravity reading of the measurement station.

6-Isostatic Correction

It is carried out in large areas of regional gravity studies and cannot be carried out in local gravity explorations. This correction reduces the effect of unbalanced rock blocks of earth crust which related to the theory of Isostasy and the mechanical properties of the lithosphere.

The calculation of Bouguer Anomaly value

In all gravity and geodetic studies, Bouguer gravity anomaly value represent the difference between the observed gravity value which measured in the field (after making all the necessary corrections) and the theoretical gravity value (g_ϕ) which obtained by applying the international gravity equation (International Gravity Formula) for the same measurement station. The Bouguer anomaly value could be obtained from the following formula:

Boug.Anom.Value mGal = (observed gravity station reading± all corrections) - g_ϕ

After calculating the Bouguer anomaly values for every station in the area they superimposed on the base map and a contour map of Bouguer anomaly is drawn, figure 16. The Bouguer anomaly contour map considered as the raw material for both descriptive and qualitative interpretation, figure 17.

Gravity Data Interpretation

The final outcome of the gravitational field survey after applying all the necessary corrections is a contour map of Bouguer anomalies which representing the anomalies that produced by all subsurface objects. The depth, location and shape of subsurface structures could be estimated by identifying the characteristics of the anomalies (such as amplitude, shape, sharpness), after making a cross sections or profile across the Bouguer map pass through the anomalies. The main thing reflected in this map is the heterogeneity of the densities in both the horizontal and vertical directions.

The interpretation process is more complex than some thought and is called ambiguity in the interpretation of **gravity ambiguity**.

The reasons behind gravity ambiguity are:

1- The gravitational field measured at any point on the Earth's surface represents the sum of the gravitational pull of all sources from the Earth's surface downward rather than to the single structure or object to be determined. Sometimes the process of separating this body from the rest of the objects and varying its gravitational effect alone is very difficult or impossible.
2- Infinite numbers of subsurface structures can produce similar gravitational data on the surface. For example, embedded river channel and igneous objects that penetrate layers horizontally can be rounded to a simple geometric shape representing a horizontal cylinder, so it is sometimes difficult to determine which model is most acceptable. This requires the application of more than one model to get the most acceptable one.
3- Gravitational explanations are not conclusive or definitive, but require a great deal of speculation and assumptions, but it can be said in general if the anomalies drawn on the map sharp (Sharp) It indicates that the sources of these anomalies located at shallow depths (Shallow), and medium-sharp anomalies indicate Their sources which are geologically significant, while very broad anomalies point to deep regional sources such as the presence of basement rocks.

Assisting gravity interpretations with additional geological information like borehole information or by the results of additional geophysical methods like magnetic, seismic, electrical and well logging methods may eliminate the ambiguity.

The deep boreholes can provide valuable information about the depth and density of subsurface rocks. Core samples obtained from boreholes could be tested in the laboratory to study rocks density, porosity, permeability and other petro physical properties such information may help in reducing ambiguity to an acceptable rate.

Qualitative Interpretation

The Bouguer anomaly contour map considered as the tool for the qualitative interpretation of gravity field for a certain area. It represents a visualizing tool that shows the locations of positive anomalies (the high gravity values) as crests, also, it shows the negative anomalies (the low gravity values) as troughs. Positive gravity anomaly is usually produced by subsurface high density body if compared to the hosting rocks, or it may be related to the close to surface basement rocks (dense rocks). A negative anomaly refers to subsurface low density body or cavity surrounded by the hosting rocks, and it may refer to the high depth of the basement rocks. The figure 24, shows the Bouguer anomaly contour map and the location of the profile A-A$^{\backslash}$. The gravity profile for the total Bouguer anomaly represents a descriptive method to describe the lateral variation of subsurface densities along the profile line, like the profile A-A$^{\backslash}$ in figure 24.

Separating the residual gravity field from the residual Field

The Total Bouguer anomaly map represents the total effect of deep and shallow subsurface rocks. It represents the summation of both the very deep dense basement rocks gravity and the near surface or shallow gravity field which related to the sedimentary cover. Therefore, it is required to separate the both effects, especially when we are looking for the specifications of a burred structure located within the residual anomaly which related to the sedimentary cover. Generally, a graphical method with the assistance of computer software is applied to the total

Bouguer anomaly by taking the 2^{nd} order polynomial regression to obtain the regional field.

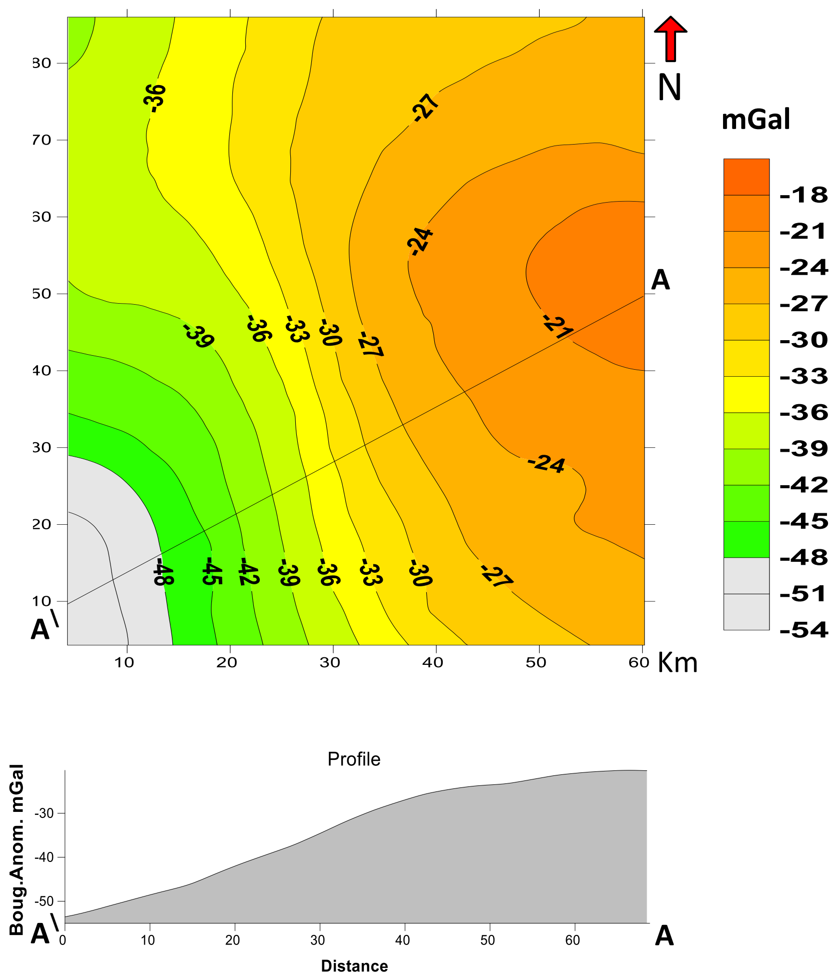
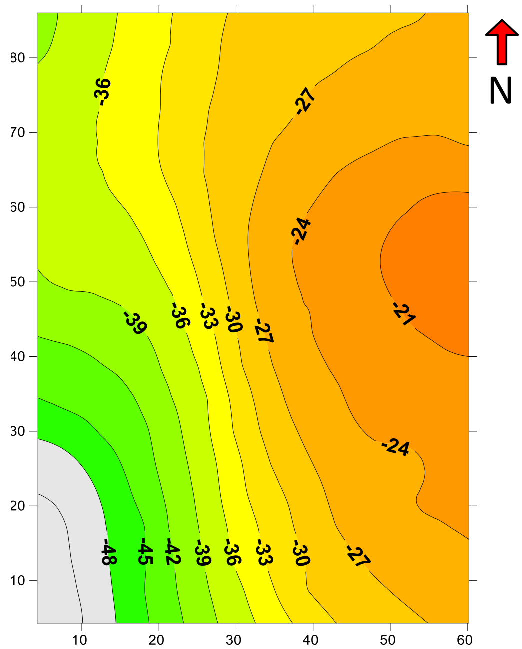
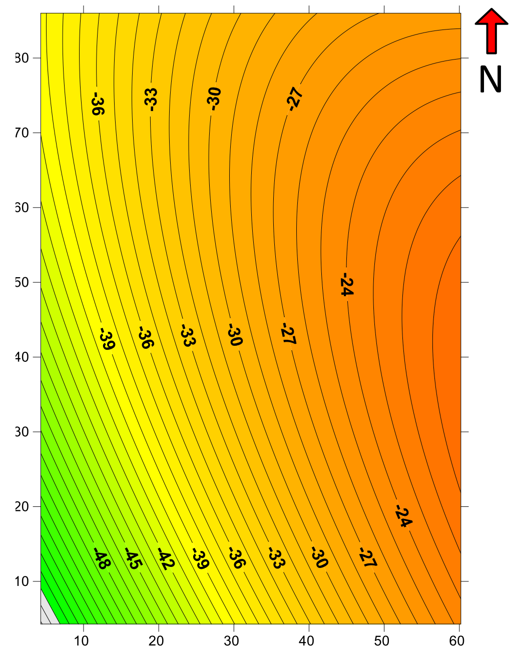


Figure (24): The total Bouguer anomaly contour map showing the locations of positive and negative anomalies , and the profile A-A\ is passing through both of them.

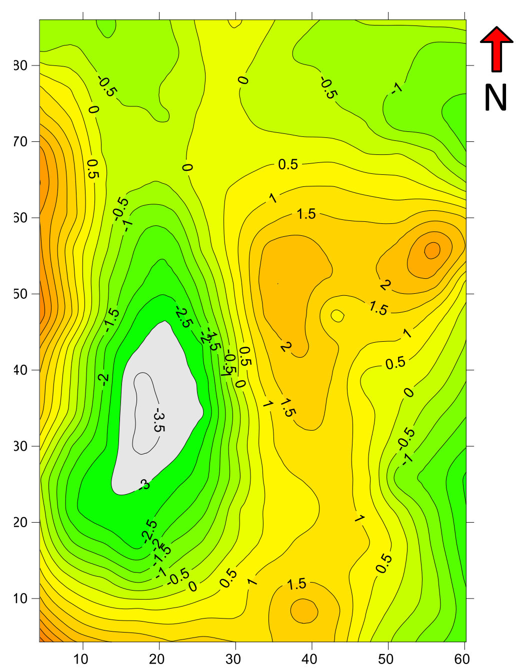
Figure 25-A, shows the regional field of the total Bouguer anomaly which is going to be used in obtaining the residual gravity field, figure 25-C. The residual gravity field is obtained by subtracting the regional field, figure 25-B, from the total field, figure 25-A.



A



B



C

Figure (25): The Residual Bouguer Anomaly map (C), is obtained by subtracting the regional Bouguer field (B) from the total Bouguer field (A).

The residual Bouguer anomaly map, figure 25-C, considered as the raw material for the quantitative interpretation of the gravity data.

Quantitative Interpretation

Gravity profile could be drawn across the map of the residual gravity anomaly by making it passing through the concerned anomalies which required to be interpreted quantitatively like the profile A-A\ in figure 26.

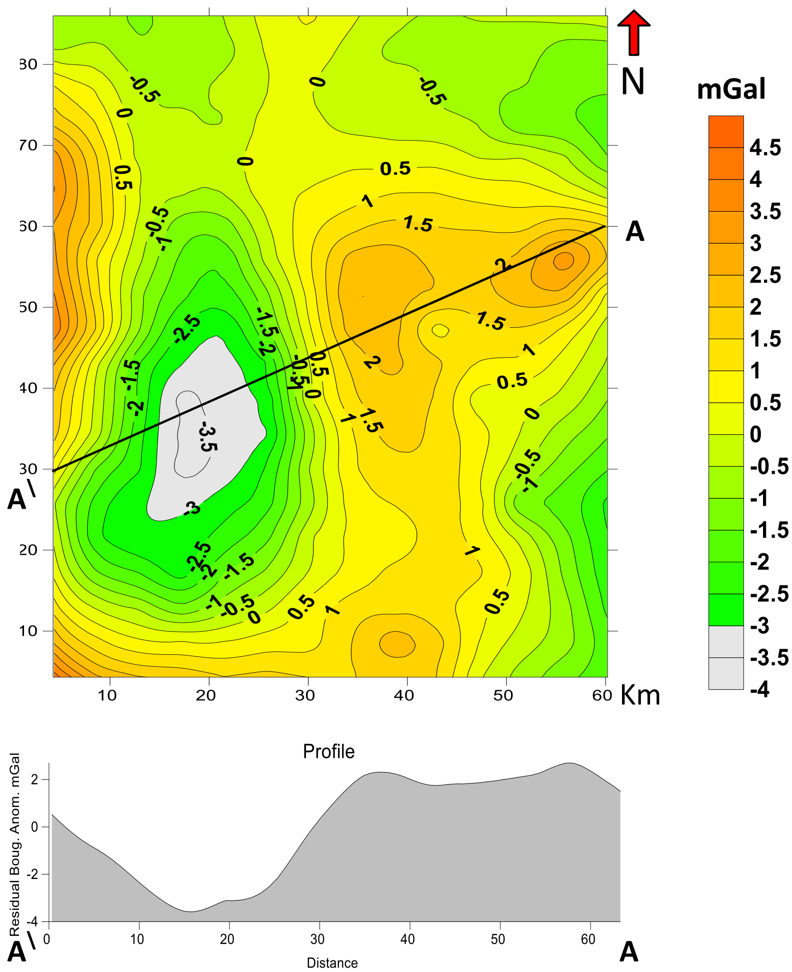


Figure (26): The Residual Bouguer Anomaly map and the profile line A-A\ which is ready to be interpreted quantitatively.

The quantitative interpretation is achieved by adopting a suitable geometrical modeling for the subsurface body which produced the anomaly. Therefore, the subsurface bodies shape is approximated to a geometrical body like: sphere, vertical or horizontal cylinder, sheet or slab and faulting case.

1- <u>Sphere</u>

Assume a ball with a mass (M) and a radius (R), its density (ρ), figure 27, then its mass = volume × density, if the center of the ball is at the depth (Z) below the earth surface, the force of gravity to the center of the ball to the mass unit at the surface at a horizontal distance (X) from the center will be:

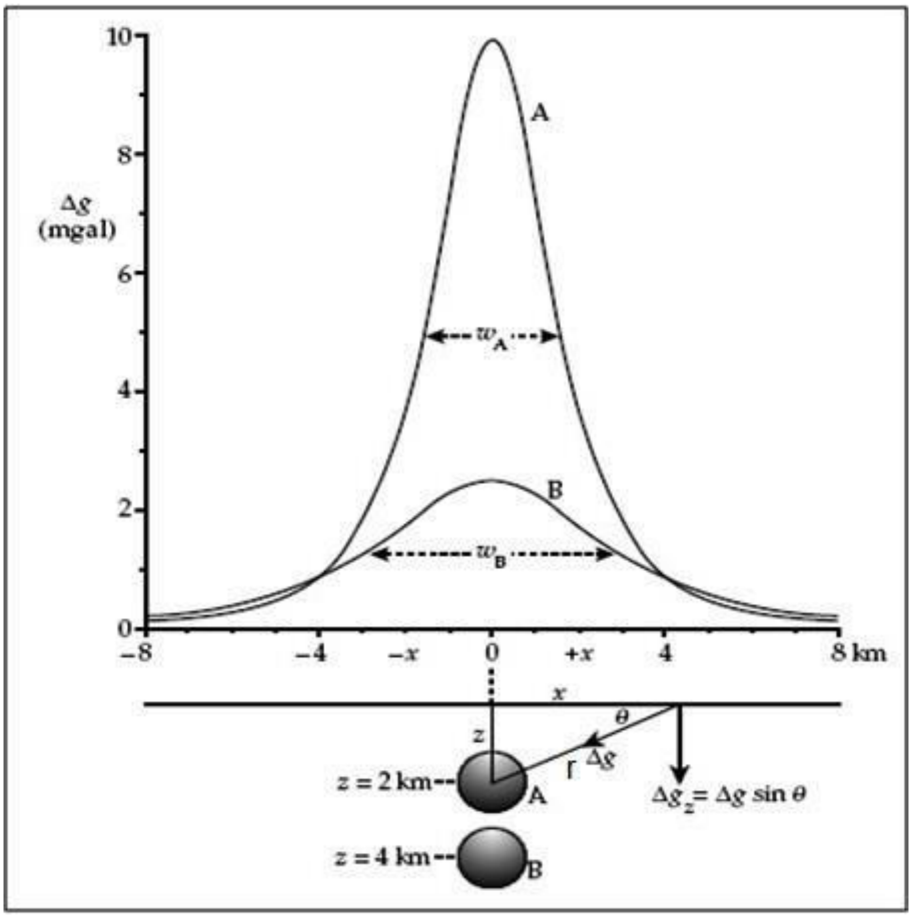


Figure (27): The gravity anomaly of a geometrical sphere.

The mass for the sphere: $$M = \frac{4}{3} \pi R^3 \rho$$

The gravimetric field produced by the sphere is:

$$g = G \frac{M}{r^2} = \frac{4 \pi R^3 \Delta\rho G}{3 (Z^2 + X^2)}$$

Δρ : is the density contrast value between the sphere and the surrounding hosting rocks , G: the gravity constant.

$$r = \sqrt{Z^2 + X^2} \qquad r = (Z^2 + X^2)^{1/2}$$

$$\cos\theta = \frac{Z}{r} = \frac{Z}{(Z^2 + X^2)^{1/2}}$$

$$g_z = G \frac{M}{r^2} \cdot \frac{Z}{r} = \frac{4}{3} \pi R^3 \Delta\rho \frac{Z}{(Z^2 + X^2)^{3/2}} \ldots\ldots (1)$$

Nettleton noted that the relationship (1) should be rearranged as follows:

$$g_x(\text{in mgals}) = \frac{8.53 \Delta\rho R^3}{Z^2 \left(1 + \frac{X^2}{Z^2}\right)^{3/2}} \ldots\ldots\ldots\ldots (2)$$

The values (X, R and Z) are measured in kilo feet = 1000 feet, and the density (ρ) is measured in units (g / Cm^3). 1Kilofeet = 3×10^4 Cm.

Equation (2) is better and more practical because it is possible to find the value of (g_z) at any distance (X) easily by multiplying the value of the maximum anomaly peak by a factor based on the ratio (X / Z) only, that is, when the value of X = zero, then:

$$g_x \text{(in mgals)} = \frac{8.53\,\Delta\rho\, R^3}{Z^2}$$

Density Contrast represents the difference between the density of a buried mass underground and the density of surrounding materials. For example, salt domes always give negative anomalies because the density of salt rocks is less than the density of the hosting surrounding sedimentary formations. The magnitude of the expected gravity anomaly of a spherical salt dome can be estimated from the above equation.

2- Buried Horizontal Cylinder

Assume an infinite buried horizontal cylinder in length that has a radius of (R) embedded at a distance (Z) below the surface of the earth, figure 28, the vertical component (g_z) will be measured in mGal as follows:

$$g_z = \frac{2\,\pi\, R^2\, G\, \Delta\rho\, Z}{r^2} = \frac{2\,\pi\, R^2\, G\, \Delta\rho\, Z}{(X^2 + Z^2)}$$

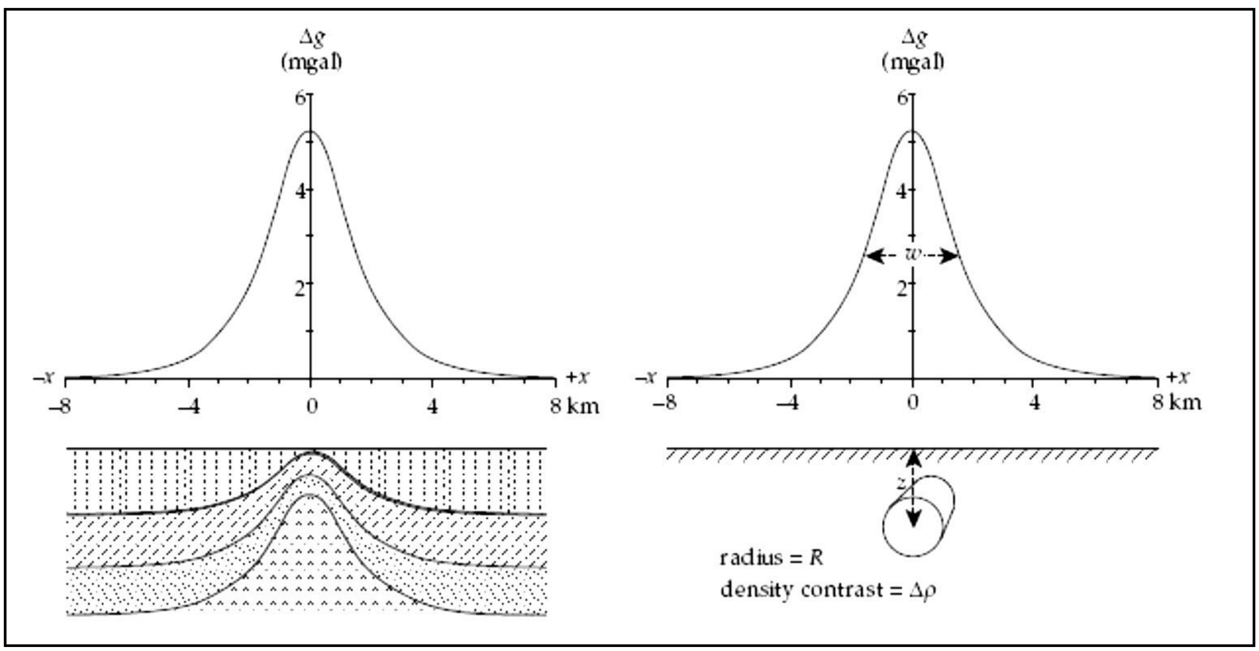


Figure (28): The gravity anomaly of a horizontal cylinder.

The gravity model of an endless horizontal cylinder represents the calculation of gravity anomaly which produced by anticline fold, figure 28.

3-Buried Vertical Cylinder

Suppose that there is a infinite embedded cylinder of length (L) and radius (r), whose upper base is embedded at a depth (d) from the Earth's surface (the depth of the cylinder), figure 29.

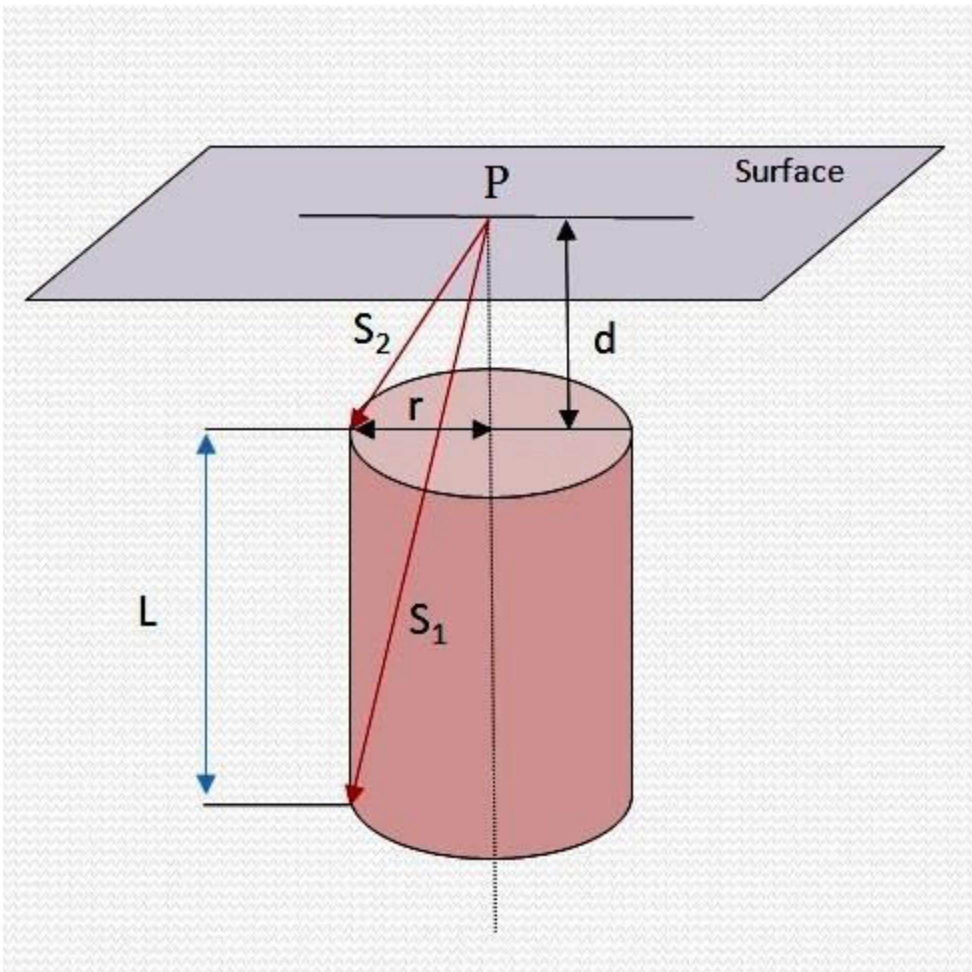


Figure (29): The vertical gravity component g_z of a vertical cylinder.

The vertical component of gravity (g_z) at the point (P) at earth's surface which passing through the cylinder axis is given by:

$$g_z = 2\pi G \Delta\rho (L - S_1 + S_2)$$

$$g_z \text{ (in mgals)} = 12.77\ \Delta\rho\,(L-S_1+S_2)$$

Where: Δρ is the density contrast value in g\Cm^3, between the cylinder and the hosting surrounding rocks density.

The **(L, S_1, S_2, d)** distances are measured in kilo feet.

If the cylinder has an infinite length then: $S_1 = L + d$

And the gravity equation will be written as:

$$g_z = 12.77\ \Delta\rho\ \ (L - (L - d) + S2)$$

$$g_z \text{ (in mgals)} = 12.77\ \Delta\rho\ (S_2 - d)$$

According to the geological point of view, the buried vertical cylinder represents approximately the shape of buried salt domes and dike.

4-Buried Slab

Assume a buried plate or slab of dense rocks which has an infinite length and thickness (L), with a depth below ground surface (d), figure 30.

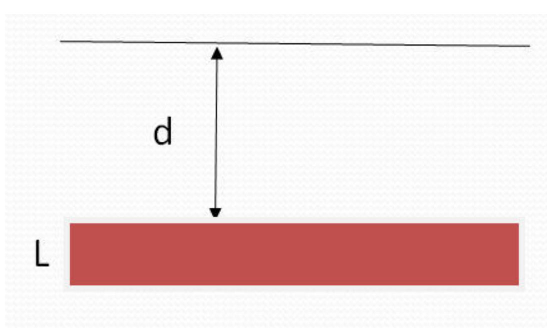


Figure (30): The vertical gravity component g_z of a buried slab.

Then the vertical component of gravity g_z which produced by this dense slab at a measurement point on earth surface is given by:

$$\mathbf{g_z = 12.77\ \Delta\rho\ L}$$

g_z in this case depends on the thickness of the slab and not its length.

5-Faulted Horizontal Slab

Assume a buried infinite slab in length, its thickness is (t) and stroked by a fault (normal direction to the paper plane) figure 31, then the vertical component of gravity g_z which produced by this fault at the location of the fault plane is given by:

$$g_z\ (in\ mgals) = 4.05\ \Delta\rho\ t\left(\frac{\pi}{2} - \tan^{-1}\frac{X}{Z}\right)$$

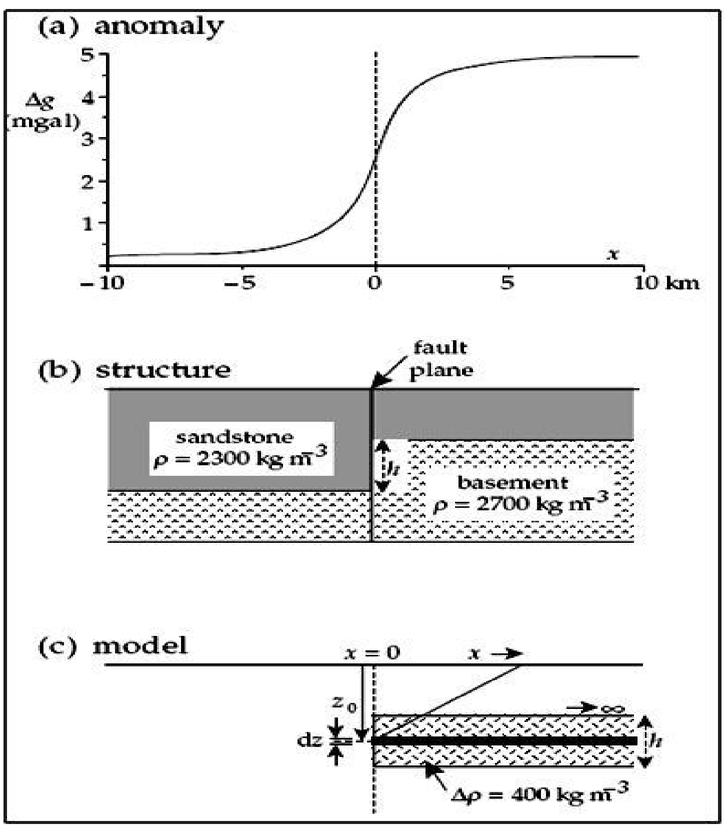


Figure (30): The vertical gravity component g_z over a faulted slab.

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