Earth Science 1023a/2123a

Lab 5

Gravity

1. Purpose

This lab will demonstrate the use of a gravimeter, a device used to measure minute variations in the magnitude of the Earth's gravitational field. These variations can be used to locate a body buried within the Earth if that body exhibits a sufficient density contrast from the surrounding material. In this lab, we will try to experimentally derive the free-air correction, a correction that is usually applied to data collected in a gravity survey.

2. Applications

Gravity has applications anywhere where a physical density contrast exists. It can be used for subsurface detection of dense mineral deposits (iron, nickel, lead, uranium, etc.) or for finding large subsurface cavities (air or water are significantly less dense than rock). In archeology, gravity has been used to locate underground tunnels used by ancient civilizations. In other applications, gravity is used to monitor water levels in aquifers or even used to predict volcanic eruptions.

3. Gravitational Field

Gravity is an attractive force produced by the presence of mass. For an object spherical object, such as the Earth, the effect of the combined mass of the Earth is to produce a very large gravitational force directed approximately towards the centre of the Earth. One of the first things you learn in physics is that the force of gravitational acceleration on Earth is approximately 9.8 m/s. However, this number is not exact, and may vary over the surface of the Earth depending on a number of factors.

Gravity is measured in terms of acceleration, typically in metres per squared second (m/s^2), however the small variations that we are interested in measuring lend themselves to a smaller unit. Traditionally, and with older equipment, we use a unit called the gal, named for Galileo Galilei, who made the first scientific measurements of gravity. In these units, the gravitational acceleration of the Earth is roughly 980 gals. This is still too large for exploration purposes, so we introduce the milligal, or mgal. Here the Earth's acceleration is measured at 980,000 mgal. This means that 100,000 mgal = 1 m/s^2. In modern geophysical applications, the Gravity Unit G.U. is used. 1,000,000 G.U. = 1 m/s^2. For the purposes of this demonstration, we will use *mgals* when recording gravity variations.

4. Gravity and Acceleration

Properly conducting a gravity survey is not an easy task. Since the instrument used in the survey is recording acceleration, it will record any acceleration it experiences, regardless of whether that force is due to gravity, or otherwise. For example, if you took a gravity reading in an elevator as it was beginning to accelerate upwards, the instrument would record a value much higher than expected. So what can cause unwanted acceleration to occur, and how do we design a survey to account for these things?

A full demonstration of gravity processing would require more data and time than is available in this lab, however if you are to perform a gravity survey, it would be important to learn the following corrections in much greater detail.

1. **Tides:** the gravitational force of the Moon or the Sun will exert a force on the Earth. These changes happen slowly over the course of a day, just like tides. In order to correct for this, we must do base-station readings and *drift corrections*, much like in a Magnetics survey.
2. **Rotation of the Earth:** since the Earth is spinning, someone on the equator is experiencing a small force that is trying to make them 'fly off the Earth'. Fortunately this force is quite small when compared to gravity, so things stay put, however it is large enough to affect our experiments: a gravimeter at the poles would not experience this effect. The magnitude of this effect depends on the latitude of the recordings, so if we are only interested in density contrasts, we must perform a *latitude correction*.
3. **Coriolis Effect:** the shape of the Earth complicates making measurements of acceleration from a moving vehicle travelling around the curvature of the Earth. This provides an acceleration which tends to curve the direction of travel. This effect explains why strong tropical winds will tend to wrap around into hurricanes. If a gravity survey is being done from a moving vehicle, such as an airplane, the *Ëotvos correction* must be applied to account for this acceleration.
4. **Elevation:** if the gravity reading is being taken at two different elevations over the same location on the Earth, you will get two different results. This is due to the R^2 in the denominator of the gravity equation which makes gravity readings obey the inverse-square law. If you take a reading at the top of a tower, you are farther from the centre of the Earth, so gravity will be less than a reading at the bottom of the tower. Typically, all gravity surveys are adjusted so that they will be taken from some reference elevation. This is called the *free-air correction*.
5. **Landscapes:** if you are only interested in a density contrast, your gravity survey can be ruined simply because of a few hills. If you take a reading at the peak of a mountain, and then another reading at the same elevation as the peak, but from an airplane, you would expect different results. This is because there is more mass beneath you when at the mountain peak than when in the airplane. In order to correct for the effect that variations in landscape elevation has on the survey, a *Bouguer correction* is applied. This tries to remove the effect of the excess mass caused by the mountain peak to leave only density contrasts.

In this lab, we will be concentrating on the effect of ***elevation*** on gravity.

5. Density and Gravity

The most important use for the gravity method is in the measurement in density variations. One litre of granite is obviously much heavier than one litre of water, and therefore denser than water (Granite is approximately 2.65 kg/L and water is approximately 1.00 kg/L). The same thing is true for air, which has a density approaching zero. These variations in density correspond to a variation in the amount of mass that is contained within an area.

Since gravity is the force of attraction to mass, it would follow that objects with higher density, and therefore higher mass, have higher gravitational attraction. This is defined by the Universal Law of Gravitation, first formulated by Sir Isaac Newton. The force of attraction F between two bodies M and m separated by a distance R is given by the following:

$$F = G\frac{Mm}{R^2} \quad \textbf{(Equation 1)}$$

Where G is the gravitational constant of the Universe.

If we use Newton's second law, $F = ma$, and combine with the above equation, we get:

$$a = G\frac{M}{R^2} \text{ (\textbf{Equation 2})}$$

Where a is the magnitude of acceleration. With the G, M and R all being known for the Earth, this equation yields roughly 9.8 m/s2.

This equation can be rewritten in terms of relative differences, as follows:

$$\Delta a = G\frac{\Delta M}{R^2} \text{ (\textbf{Equation 3})}$$

For an object of total volume V and density contrast Δρ, this object will have an excess mass (or shortage in mass) defined by ΔM = VΔρ. Plugging ΔM into the above equation, as well as the measured acceleration, will yield the following:

$$\Delta a = G\frac{V\Delta\rho}{R^2} \text{ (\textbf{Equation 4})}$$

This is the most commonly used form of the gravity equations, as geologists are most interested in variations due to density. However, in this lab, we are interested in variations due to changing elevation over some point with a fixed density. The theoretical relationship is 0.3086 mgal/m. This produces the straight line below:

$$\Delta a_{FA} = -0.3086z \text{ (\textbf{Equation 5})}$$

Where Δa_{FA} is the relative gravity reading, and z is height above reference elevation.

6. Exercise

6.1 Data Collection

In this experiment a Worden Gravimeter will be used to measure the total acceleration at a several points corresponding to one location on the Earth. This survey will be conducted as a vertical profile in the south stairwell of Middlesex College, with several readings conducted on each floor. This will then be used to derive the free-air correction formula, which will then be compared to the accepted value.

1. Using a tape measure, measure the elevation of the surface of each floor relative to the surface of the basement floor. Record an estimate of measurement error.
2. In groups of 5, take measurements (one per person) on each floor of Middlesex College, trying to ensure that the measurements are taken as close to on-top-of one another as possible. Record an estimate of measurement error. Record the elevation of the instrument from the floor at each station.
3. (Time permitting) Repeat the first measurements taken in order to get an estimate on instrument drift.

6.2 Treatment of Data

1. Average multiple readings on each floor to produce a single value for the floor. Multiply this by the dial constant found on the side of the gravimeter.
2. Plot the readings against the relative elevation of the instrument (with error bars), using the ground floor as a base elevation.

3. Using a line of best-fit, draw a dashed line through the data points. Determine the slope of the line passing through the data points (rise over run).
4. Plot the line corresponding to the free-air correction formula. You can do this by plugging some values into the formula, plotting them on your graph, and then drawing a straight, solid line through the points.
5. Qualitatively explain whether the experimental results confirm the equation. What sources of error may have contributed to your results?
6. Look up values for the gravitational constant of the Universe, the mass of the Earth, and the distance to the Moon. Find the acceleration that a gravimeter on the Moon would feel due to the presence of the Earth. Based on your earlier estimate for measurement error for the Worden Gravimeter, would the Earth's gravity be detectable from the Moon with a similar instrument?
7. (Bonus) Calculate the standard deviation for each station and redraw the graph with a line of best-fit and a line of worst-fit. Show at least one example calculation. How well do these slopes compare to the predicted slope?

7. What to hand in

A laboratory report covering the following points should be handed in:

a) Title Page: The first page of each lab report submitted must be a title page, and must contain the following information in order for you to receive credit for the lab:

Name:

ID. Number:

Lab Group:

Lab. No. & title:

Date performed:

Head teaching Assistant:

b) Give a brief introduction as to the purpose of this lab (do not copy the lab manual). What is to be achieved by this experiment or exercise? What principles or methods does it illustrate?

c) Procedure: The general procedure is given above. Do not copy this into your report but instead describe the procedure used in doing the work in your own words; if things went right, or wrong, report this. Provide a brief description of the equipment used.

d) Observations and Results: Provide tables of the raw data; complete the tasks and calculations as outlined in section 6.2. above (number the sections 1–7 as above). Provide final results as tables, graphs, profiles, maps etc.