GRAVIMETRIC MEASUREMENT TECHNIQUES

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Contents

Summary

Methods for measuring the gravitational acceleration of the Earth can be classified into two broad categories: measurements made at or near the Earth’s surface versus those made from space. Gravity field determinations near or at the Earth’s surface rely upon gravimeters that directly measure the field (actually the force required to oppose gravity). Gravimeters are either “absolute” meters that measure the entire magnitude of the gravity field, or “relative” meters that measure the difference in gravity between two locations. Absolute meters tend to yield very accurate but time-consuming measurements. Relative gravimeters are the most common, and are designed for a variety of both static (motionless) and dynamic applications. Static applications include land, underwater, and borehole measurements. Dynamic measurements are made from moving platforms and are primarily relative sensors mounted in gyro-stabilized

platforms. These platforms align the sensitive axis of the sensor with the gravity field. Absolute gravimeters and superconducting relative gravimeters make highly accurate static measurements that are opening vast new opportunities for gravity applications in time-varying aspects of the gravity field, including tides, ground water motion, and magma motion.

Gravity gradiometry is an exciting development in both static and dynamic gravity measurements. Measuring the gradient of gravity directly has significant advantages in noise suppression, data interpolation, and data interpretation. Only a few meters are operational at this time, although several have been successfully tested in a laboratory.

Measurement of the global gravity field is being advanced through satellite measurement. Initially, the long wavelength components of the gravity field were measured by tracking the perturbations of satellite orbits. Accurate determinations of the gravity field over the world's oceans to wavelengths as short as 19 km have been achieved through satellite radar altimetry. New global gravity models incorporate both the long wavelength and the satellite altimetry data plus surface gravity data to solve for global gravity models of higher resolution.

Future improvement in gravity measurement lies in further development of instrumentation, especially the gravity gradiometers, and in the continued deployment of dedicated geopotential satellite missions.

1. Introduction: Gravity Basics

As humans, one of the first lessons we learn is how to move under the force of gravity. The gravity field that we experience daily is the direct result of the enormous mass of the Earth. Isaac Newton captured the essence of gravity as the force of attraction that exists between any two bodies. This force is proportional to the mass of the two bodies, and inversely proportional to the square of the distance between the bodies (see chapter *Gravity Field of the Earth*). Thus, the force decreases quickly as the distance between the bodies increases.

Although the gravity field results from a force, we instead focus on the acceleration that results from the force of gravity. The force of gravity upon an object is proportional to its mass, and thus the force varies with the mass considered. However, the acceleration of any mass caused by the gravity field is the same regardless of the object's mass. How that acceleration is measured is the topic of this article.

The gravitational acceleration of the Earth at its surface is approximately equal to 9.8 m s^{-2}, or about 980 000 mGal. The Earth's field varies with latitude and ranges from a minimum of ~978 000 mGal at the equator to ~983 000 mGal at the poles. These two values differ because the Earth is flattened at the poles (the polar radius is ~21 km shorter than the equatorial radius) and because the spinning Earth has an outwardly directed (from the rotation axis) centrifugal force that reduces the total gravity field. This centrifugal force is greatest at the equator and diminishes to zero at the poles.

The magnitude of the gravitational acceleration (or gravity, for simplicity) at any place on Earth is determined by the amount of mass between the observation point and the center of the earth. Large scale geologic features, such as mountain ranges, canyons, ocean trenches, and some mid-ocean ridges, result in large lateral mass and/or density changes and have associated gravity changes (or anomalies) ranging from a few to a few hundred mGal. Small to medium features, such as hills, valleys, and smaller scale ocean floor features, have gravity anomalies ranging from a mGal to a few tens of mGal. Mineral deposits and ore bodies may range from a few tenths of a mGal to a few mGal. A whole host of subsurface phenomena have gravity expressions in the tenths to thousandths of a mGal (or one part per billion of the Earth's field), such as ground water motion, elevation changes associated with seismic activity or with strain accumulation before earthquakes, or magma movement in volcanic regions.

2. Types of Gravity Meters

Gravity meters fall into two basic categories. The first type, the absolute gravity meter, measures the magnitude of the entire gravity field. The second type, the relative gravity meter, measures the difference in gravity between two locations. Although the acceleration of gravity is a vector quantity (that is, it has a magnitude and a direction), the vast majority of gravity meters measure the scalar magnitude of the acceleration. This simply means that we align the gravity meter with the direction of maximum acceleration and measure its size.

2.1 Absolute Gravity Meters

Absolute gravity meters measure the size of the entire field. Although these were the first kind of gravity measurements ever made, they are also very difficult to do precisely. There are two primary types of absolute meters: pendulums and falling body instruments.

2.1.1 Pendulum Measurements

The first gravity measurement was made using a pendulum in a clock. In 1672, Richer, a French astronomer, noted that a clock that kept perfect time in Paris lost 2.5 minutes a day at the equator. In fact, a shorter pendulum was required at the equator to keep the correct time. In 1673, Huygens developed the theory of pendulum behavior. The period, *T*, of the oscillation of the pendulum is directly related to the gravitational acceleration, *g*, by the following formula:

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

where *k* is a proportionality constant that depends upon the pendulum's length and mass distribution. A pendulum, once displaced from its vertical rest position, is acted upon by gravity to return it to its original position. However, once it reaches its original position the momentum of the pendulum motion causes its swing to continue upward the other way until gravity slows it again and pulls it downward. If there were no friction or wind resistance to slow the pendulum, it would continue this oscillation indefinitely.

A pendulum was the instrument used by Galileo to make his first gravity measurement. The pendulum was the first instrument that was sufficiently accurate and rugged to be a viable field instrument. It was also the first instrument to measure gravity from a moving platform, used by Vening Meinesz aboard a submarine in 1923.

To measure gravity to great accuracy, the pendulum must oscillate over a long period of time. One must count the number of oscillations, and then divide the total time of observation by the number of oscillations to obtain the period *T*. The limitations on the quality of pendulum measurements include the nonlinear properties of a pendulum's swing and the difficulty in maintaining a constant pendulum length over a long period of observation. Temperature control and the timing mechanism are of critical importance. The pendulum was the standard instrument for absolute gravity measurement until the 1960s when falling body devices were developed which could eclipse the pendulum in accuracy of measurement.

2.1.2 Falling Body Instruments

The absolute value of gravity can be measured directly by noting the time it takes for an object to fall a given distance. The distance of the fall of any object is proportional to the time required for its fall, and the acceleration of gravity is that proportionality constant. While conceptually easy, this method is quite difficult in practice because it demands very precise measurement of both time and distance. Galileo, although he tried this technique, ultimately made his famous gravity measurements using a pendulum.

Figure 1. The FG5 absolute gravimeter manufactured by Micro-g Solutions, Inc. (photo courtesy of Micro-g Solutions, Inc.).

New developments with lasers and atomic clocks in the second half of the twentieth century now allow very precise measurement of time and distance. A variety of absolute instruments employ falling bodies in their measurement. All these sensors use a calibrated laser standard coupled with an atomic clock to measure free-fall of a reflecting body in a vacuum. These measurements are directly referenced to atomic standards of length and time. We describe the operation of the most commonly used instrument, the FG5 absolute gravimeter manufactured by Micro-g Solutions, Inc. (Figure 1).

The meter consists of a cylindrical free-fall chamber that is operated in a hard vacuum (at one billionth of an atmosphere). A special mass with a reflector on one side (called a corner cube reflector) drops in free-fall for a distance of 20 cm. Ahead of the mass a small elevator accelerates downward, removing stray remaining molecules from its path. At the end of its journey, the elevator catches the reflecting mass and gently returns it to its starting position. While the mass is dropping, a iodine-stabilized laser passes through a beam splitter, sending a reference beam directly to a photodetector, while a test beam goes up the dropping chamber and reflects off of the free-falling reflector. The reflected beam travels downward to another reflector at the base of the instrument that is mounted upon a "superspring" (a sensitive spring suspension system that shields the measurement from vibrational and seismic noise), which reflects it back to merge with the reference beam. As the mass drops, interference fringes are generated in the merged beam and measured in the photodetector. This "fringe detector" is connected to an atomic clock. The velocity of the mass is measured by the time taken for each optical fringe to pass the detector, and the acceleration is the change in the velocity (Figure 2).

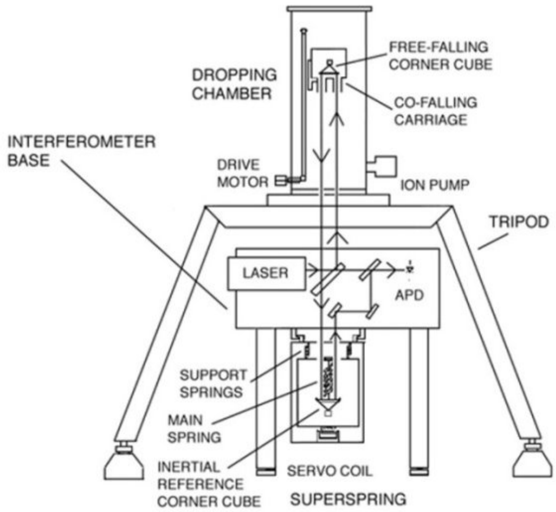

Figure 2. The schematic for the FG5 absolute gravimeter (courtesy of Micro-g Solutions, Inc.).

For each drop, the meter provides a time and distance measurement pair that can be solved numerically for acceleration. Repeated drops are performed to reduce noise in the measurement through averaging, and are normally performed in "sets." Sets can be organized in several ways, but commonly they are groups of drops (each drop spaced 10 s apart) that are performed at regular intervals. Statistics are generally performed on sets instead of the entire data set to help resolve changing environmental factors. Quiet sites require 30–56 hours of observations and noisy sites 70–100 hours.

Precise relative meter (discussed in Section 2.2) measurements are made at different heights above the floor to determine the vertical rate of change of gravity (the vertical gravity gradient) at that location. This measurement is made using a special tripod with an upper and a lower baseplate with a constant separation between them. This value of the vertical gravity gradient is used to transfer the gravity value to either the floor or a height of 1 m above the floor. The measurements are routinely corrected for lunar and solar attraction, ocean loading, polar motion, atmospheric pressure, and system/floor response. Corrections can also be made for soil moisture, snow cover, lake levels, or ground water variations if known.

The FG5 is capable of achieving a 1 μGal (0.001 mGal) measurement accuracy, but environmental and experimental factors probably limit accuracy to ~2 μGal. This accuracy is nearly one part per billion of the total field. Two μGal correspond to the gravity change resulting from 6 mm of elevation change. This level of accuracy allows the measurement of very small changes in gravity resulting from local changes in nearby masses such as ground water, atmospheric fronts, or magma movement associated with volcanic activity.

In addition to the superior accuracy, the falling body meters have a few advantages over relative meters. There is no instrument drift, there are no tares (abrupt changes in reading), and none of the calibration errors associated with relative meters are applicable. The disadvantage is the long occupation time required for a reading. This problem is partly overcome with a ballistic or a "rise and fall" absolute gravimeter, one of which is now manufactured by Micro-g Solutions. It is a more compact meter, with a shorter free-fall cylinder, capable of making as many as 100 drops per minute. Instead of only dropping the mass, this meter launches the mass upward from the bottom of the cylinder and tracks both its rise and fall with the laser interferometer. Thus, even with a shorter chamber, the mass spends more time in free-fall than in the FG5. The accuracy is comparable to the FG5, although probably somewhat less accurate in practice. Because of the rapid data acquisition rate, this meter is a candidate for use in dynamic environments such as in marine or airborne surveys.

2.2 Relative Gravity Meters

Most gravity meters in use today measure relative gravity, or the difference in gravity between two locations. It is far simpler to design a sensor that is quite sensitive over a range of several thousand mGal than over a range of a million mGal. Most of these meters are based upon the principle of a mass on a spring, somewhat like a bathroom scale. If a mass is suspended from a spring, the spring will stretch until it exerts a sufficiently large, upwardly directed force to exactly oppose the downward force of gravity. One can measure the force exerted by the spring through knowledge of the size of the mass, the elongation of the spring, and the spring constant. Such a system can easily detect changes in gravity from one location to another by the change in elongation of the spring. In the next section, we describe the suite of sensors in use that are variations of this design.

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*http://www.bel*lgeo.com/ [This website belonging to Bell Geospace, Inc. provides a good description of how the Bell UGM meter works and information on using the gradient components for data interpretation.]

Biographical Sketch

Vicki Childers, received her Ph.D. from Columbia University's Lamont-Doherty Earth Observatory in 1996 in geophysics. After graduation, she received a National Research Council Postdoctoral Fellowship at the Marine Physics Branch of the Naval Research Laboratory in Washington, DC. She now works for NRL with John Brozena as a geophysicist. Her working group at NRL specializes in the broad area of airborne geophysical surveying. They recently completed seven field seasons of gravity and magnetic measurements over the Arctic Ocean, and a sea-surface topography and littoral geodesy experiment in the Gulf of Mexico.