The Gravity of Geophysics

A recent article in *Reviews of Geophysics* examined terrestrial techniques for measuring changes in gravity over time and their application to the geosciences.

A FG5 absolute gravimeter measuring ice mass changes in Kulusuk, East Greenland. Credit: Olivier Francis

By Michel Van Camp, Olivier de Viron, Arnaud Watlet, Bruno Meurers, Olivier Francis, and Corentin Caudronon 13 November 2017

Volcanoes, glaciers, tectonic activity and ocean dynamics all have an effect on the Earth's gravity. A recent review article (http://onlinelibrary.wiley.com/doi/10.1002/2017RG000566/full) in *Reviews of Geophysics* described techniques for measuring changes in gravity over space and time. The journal's editors asked the authors some questions about developments in this field and its application to the geosciences.

In simple terms, what is gravity and how does it vary?

Gravity literally brings us down to the ground. As many people learn in high school, "standard gravity" near the Earth's surface is about 9.8 meters per second squared. But this is an average; gravity actually varies in both space and time. As the Earth is not a perfect sphere, this and a range of other influencing factors, such as the local density of the crust and altitude, mean that gravity is stronger in some places than others. Then factors such as fluctuations in Earth's rotation and tides, changes in ground water content, underground movements of magma, or vertical land movements mean that gravity changes over time.

Gravity (*g*) depends on the location on Earth; the time; the relative positions of the Moon, the Sun and planets; the climate system; and the mass distribution. For example, ice mass changes and fluid motions in volcanic systems influence the value of g as well as Earth's deformations and mass redistribution associated with large earthquakes. Credit: Michel Van Camp

By measuring changes in gravity over time, what can be learned about the Earth and different processes?

Monitoring changes in gravity over time provides information on deformations of the solid Earth and changes in the distribution of mass. This can be related to their geophysical causes such as tectonic and volcanic activity, past and present ice-mass changes, tides and the dynamics of the oceans. Hence, such data have a range of applications.

For example, gravimetry has proven useful on volcanoes, where combining gravity and deformation measurements has permitted discrimination between gas, water and magma intrusion, assessing voids opening or magma density changes associated with degassing.

How do you measure these changes in gravity over time?

The science of measuring this is known as "gravimetry" and two techniques coexist: absolute and relative.

Superconducting (blue) and absolute (black) gravimeters measuring at Conrad Observatory, Austria. Credit: Olivier Francis

Using absolute gravimeters, you repeatedly drop a mass in a vacuum chamber, measure its positions over time, and infer gravity from these data. These free-fall instruments are subject to wear, and are heavy and cumbersome, but this is the only way to accurately measure the absolute gravity value.

Using relative gravimeters, you measure a force to keep a test-mass still, counteracting gravity. Those instruments drift, which requires calibration to correct, and makes it unusable to determine the absolute value of gravity, but they are effective at monitoring gravity changes.

Presently, absolute instruments are used to perform campaign-style surveys, usually providing one gravity value after measuring for dozens of hours. On the other hand, relative gravimeters can measure continuously for years at a same place, or perform surveys such as measuring for just a couple of minutes.

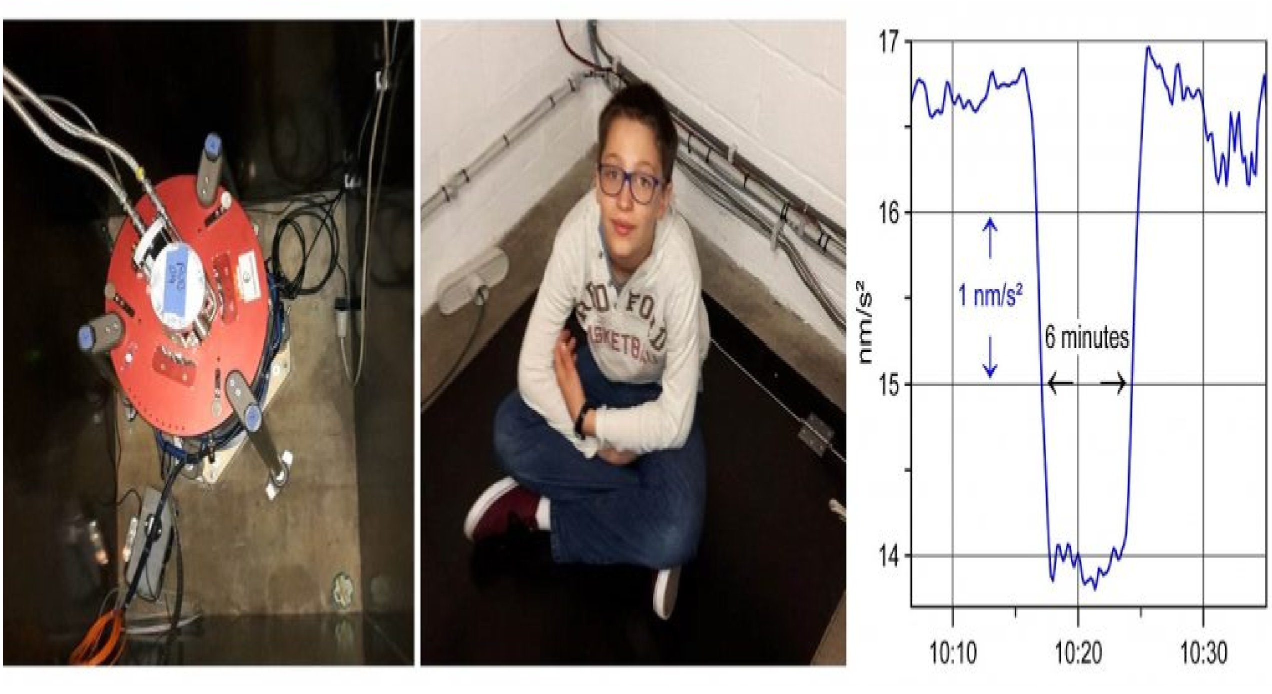
However, both types of terrestrial gravimeters are generally cumbersome, expensive (typically US$ 100,000-300,000 for relative instruments and US$ 500,000 for absolute ones), tricky to use, and require continuous power supply, which limits their contribution to Earth study.

How has technology advanced in recent years?

In recent years, our understanding of exactly what existing instruments measure, and how to get the most interesting science has strongly improved. Absolute atom gravimeters have been developed since the 1990s. Field cold-atom gravimeters are coming and should facilitate the deployment of absolute instruments, as they do not experience wear and because they will be lighter and smaller.

Microelectromechanical systems (MEMS) are also being developed as a gravimeter. These are microscopic mechanical devices, such as those present in smartphones. Presently, the noise level of MEMS is too high and their ability to measure location-dependent gravity variations is still to be demonstrated. However, those light instruments could revolutionize air- and sea-borne gravimetry; for example if such a device could be installed on a drone. They could also be deployed as a dense array around specific structures such as volcano, hydrothermal or karst systems.

Today's instruments can achieve a high level of accuracy. For example, a superconducting gravimeter can detect the gravitational effect of a child sitting 1 meter above the instrument. This is the equivalent of one millimeter in the ground water content.



Left: A superconducting gravimeter installed in a shaft at the Rochefort station, Belgium. Center: A 13-year old boy, weighing 45 kilograms, sat with his navel 1 meter above the instrument. Right: The gravitational effect of the boy sitting for 6 minutes: his mass induced a decrease in gravity of 0.28 billionth of g. Credit: Royal Observatory of Belgium/Van Camp et al, 2017 (http://onlinelibrary.wiley.com/doi/10.1002/2017RG000566/full), Figures A4d and A7

Are there any limitations to this technology?

Gravity is an integrated quantity, which means that a unique value results from the actions of many masses around the instrument, close or very far away, and a pervasive problem in gravimetry is that surface gravity measurements do not provide the measure of the mass distribution within the subsurface. By combining different geophysical exploration techniques and by applying appropriate signal processing, in many cases it is possible to discriminate the signature of the investigated phenomenon from the other contributions to gravity.

How might this technique develop further in the future?

Hopefully the next generation of gravimeters (atom and MEMS) will be more transportable, and may be less expensive if more instruments are produced. The ideal instruments would be cheap absolute gravimeters able to monitor continuously, with a precision equivalent to 10^{-11} g at a period of one minute. Such low-consumption gravimeters should weigh no more than a few kilograms and be easy to operate. That way, it will be possible to deploy arrays of gravimeters to understand the functioning of volcanoes, specific hydrogeological and hydrothermal systems, or post-seismic and post-glacial relaxation.

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