Recording Belgium's Gravitational History

Instruments at Belgium's Membach geophysical station set a new record for monitoring gravitational fluctuations caused by storm surges, groundwater fluctuations, and the Moon's tidal pull.

This doorway leads to the underground seismic monitoring station near Membach, Belgium. A superconducting gravimeter at this station has measured tiny fluctuations in Earth's gravitational field continuously for more than 22 years, setting a world record. Credit: Michel Van Camp

By Michel Van Camp, Olivier Francis, and Thomas Lecocq 29 December 2017

Deep beneath the surface of a Belgian forest, a silver-colored sphere of niobium metal floats in a vacuum that is only slightly warmer than the temperature in outer space, suspended by a magnetic field that exactly balances the force of Earth's gravity. Small fluctuations in the gravitational field pull and tug on the sphere, shifting its position ever so slightly, perturbing the magnetic field and sending electrical signals to nearby sensors.

This has been going on for the past 22 years—a new world record for the longest continuous gravitational measurement in the same location using this type of instrument. What's more, it's also the longest levitation of a superconducting mass.

The niobium sphere, about the size of a ping-pong ball, is encased in a metal cylinder, which in turn is attached to vacuum lines and a tank of liquid helium that serves as a refrigerant. As long as the temperature inside the container is kept below 9.2 K, niobium's superconducting transition temperature, magnetic field lines flow around, rather than through, the sphere, keeping it suspended in the center of its little chamber. Niobium wire coils, also kept at this low temperature, offer no resistance to the electrical current that flows through them, producing the perfectly stable magnetic field that levitates the niobium sphere.

This otherworldly setup is the basis of an instrument called a superconducting gravimeter (http://www.gwrinstruments.com/pdf/principles-of-operation.pdf) (SG). The SG measures fluctuations in Earth's gravitational field with a sensitivity far greater than previously possible using older instruments, which used reference weights attached to mechanical springs. For more than 2 decades, the SG in Belgium has faithfully recorded mass shifts caused by groundwater movements, the weight of storm surge water on the surface, and other phenomena that affect the nearby gravitational field [*Van Camp et al.*, 2017].

A Record for Longevity

Fig. 1. (left) The superconducting gravimeter C021 (made by GWR Instruments) resides inside a dewar of liquid helium (blue) in the Membach underground station in eastern Belgium (50.6085°N, 6.0095°E). (right) The instrument sits at the end of a 130-meter-long gallery, 48 meters underneath the surface. Credit: E. Coveliers, ROB.

Last September, the SG C021, an instrument located at the Membach seismological station in eastern Belgium, set records for the longest continuous time spent measuring gravity variations using a single SG in the same place, as well as the longest superconducting levitation of an artifact (Figure 1). On 18 September 2017, this instrument, which began operation 4 August 1995, had monitored gravity changes continuously for 8,081 days—22 years and 45 days. The previous record (8,080 days) was held by the SG T020, which measured at the Metsähovi station, Finland, from 10 August 1994 to 23 September 2016.

In 1995, currents were injected into the superconducting coils, causing the sphere to levitate. More than 22 years later, the currents persist.
The SG measurement principle is based on monitoring the levitation of a 4-gram superconducting niobium sphere. As far as we know, no object has ever been levitated for such a long time. In 1995, currents were injected into the superconducting coils, causing the sphere to levitate. More than 22 years later, the currents persist. This isn't new physics—in theory, a superconducting current can flow forever—but it is at least worthy of a place in the "cabinet of curiosities" of solid-state physics.

Relative and Absolute Measurements

Best practices in the science of gravity measurement require maintaining reference stations where gravity is monitored continuously for the long term. Operating high-quality observatory stations such as Membach at the state of the art has given scientists a thorough knowledge of the instrument. The resulting excellent measurements have proven useful in retrieving elusive geophysical and geodetic (https://eos.org/research-spotlights/antarctica-gets-a-new-gravity-map) signals.

On average, one absolute gravity measurement (https://eos.org/editors-vox/the-gravity-of-geophysics) is performed every month at the Membach station to complement the SG data, which measure changes in gravity. Absolute gravity is measured by repeatedly dropping a test mass inside a vacuum chamber and tracking its free fall using a laser interferometer.

These numerous absolute data points, combined with data from the SG, enabled the study of the uncertainties associated with the setup of an absolute gravimeter (AG) [*Van Camp et al.*, 2005].

The SG provides voltage variations (caused by the movement of the sphere), which are then calibrated into an acceleration expressed in nanometers per square second (nm/s^2) or microgals (1 μGal = 10 nm/s^2, or one billionth of the standard gravitational acceleration *g*). In 1996, Membach scientists compared data from the SG C021 with an FG5 ballistic AG, determining the calibration factor at the parts per thousand level [*Francis,* 1997]. This precision is required to assess solid Earth tidal models, which simulate the Moon's and Sun's gravitational effects on the solid parts of Earth.

Signal Drift or Geophysical Trend?

The gravimeter's sensitivity to signals is defined using a mathematical transfer function, which can be experimentally determined from the size of the sensor's response to specific signals of known strength. The first determination of an SG transfer function was performed in Membach [*Van Camp et al.*, 2000]. SGs drift by a few billionths of *g* per year. We determined this tiny drift by comparing the SG C021 to the frequent AG measurements [*Francis,* 1997].

We had originally assumed that the SG instrumental drift was linear; even then, we could separate the instrumental drift from actual geophysical trends. Later, when more AG and SG data became available, *Van Camp and Francis* [2007] found a nonlinear, exponentially decreasing drift of the SG, most likely caused by the aging capacitance bridge, magnetic variations, gas adsorption onto the surface of the levitating sphere (which floats in a small amount of residual helium), and/or helium gas pressure variations within the sensing unit, which is kept immersed in liquid helium.

From Evaporating Dew to Earthquakes and Storm Surges

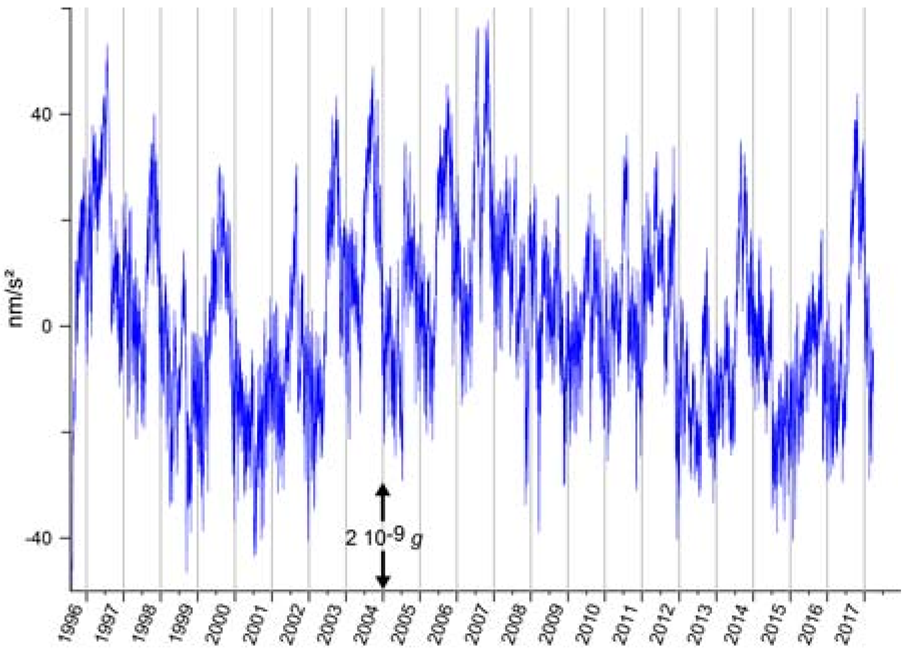

Fig. 2. This 22-year time series shows gravity changes monitored by SG C021, after correcting for instrumental drift, tidal, polar, and atmospheric effects. What remains is essentially due to hydrogeological effects. For example, during the summer, gravity increases because there is less groundwater above the instrument. The long-term variations remain poorly understood.

Long-term fluctuations in gravity records remain poorly understood (Figure 2) despite their importance for geodesists. Long-period gravity changes are most likely induced by climatic or hydrogeological variations. Membach was one of the first SG sites where a comprehensive hydrogeological investigation could clearly show and quantify the influence of changes in groundwater within the unsaturated zone [*Van Camp et al.*, 2006]. The effect is about 50 nm/s² (5×10^{-9} *g*) over the course of a year.

Using rainfall modeling at the Vienna and Membach stations, *Meurers et al.* [2007] improved solid Earth tidal analysis by 10%. The Membach SG is also able to measure the diurnal evapotranspiration (https://eos.org/research-spotlights/deforestation-effects-as-different-as-night-and-day) from the deciduous forest above the station: *Van Camp et al.* [2016] identified average daily changes in gravity smaller than 1 nm/s² (10^{-10} *g*), equivalent to a depletion of 1.7 millimeters of water per sunny summer day, which is at the limit of the resolution of terrestrial gravity measurements in the time domain.

On the large end of the scale, after a large earthquake, seismic waves interfere and cause Earth to ring like a bell at frequencies between 0.3 and 20 mHz. The spectra of Earth's bell-like normal vibrational modes provide valuable information on the structure of the planet. SGs outperform the outstanding long-period STS-1 model seismometers at vibrational frequencies below 10 millihertz (mHz). For the lowest-frequency modes (below 1.5 mHz), correcting for atmospheric pressure effects can improve resolution still further. The Membach instrument could demonstrate that SGs could outperform the STS-1 seismometers [*Van Camp*, 1999]. In the same spirit of innovation, the SG C021 was the first to stream real-time data to the Incorporated Research Institutions for Seismology (IRIS (https://www.iris.edu/hq/)) seismic data center [*Van Camp et al.*, 2008].

Instruments at the Membach station, 200 kilometers away from the coast, successfully measured an increase in gravity of about 20 nm/s^2 associated with a storm surge in the North Sea.

Storm surges in the North Sea also affect local gravity by loading Earth's crust (https://eos.org/project-updates/on-the-rebound-modeling-earths-ever-changing-shape), depressing it as much as a few centimeters along the coastlines. Instruments at the Membach station, 200 kilometers away from the coast, successfully measured an increase in gravity of about 20 nm/s^2 associated with one such storm [*Fratepietro et al.*, 2006]. Such a wind-stressed effect was first observed along the Baltic Sea by an SG in Finland [*Virtanen and Mäkinen*, 2003]. In both cases, the phenomena were later confirmed using geodetic measurements from GPS.

Twenty-Two Years and Counting

Despite providing numerous results of time-varying gravity, the ever-young SG C021 is not willing to retire. Many scientific laboratories maintain an interest in the long-term monitoring of gravity. The staunch SG C021 is still contributing to numerous projects, including understanding long-period gravity variations (http://www.seismologie.be/en/research/gravimetry/crustal-deformations) and relative seismic velocity deviations (http://www.seismologie.be/large-mem/index.html) caused by groundwater changes [see also *Lecocq et al.*, 2017].

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Correction, 2 January 2018: An earlier version of this article incorrectly stated the effects of groundwater above the superconducting gravimeter on the gravitational field recorded by this instrument. This has been corrected.

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