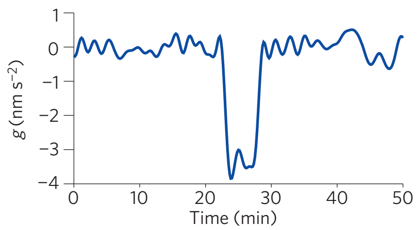
The slightness of gravimetry

Michel Van Camp and **Olivier de Viron** are attracted to the fluctuations in the Earth's gravitational pull.

When asked to give his age, the French humourist Alphonse Allais famously replied "I cannot, it changes all the time". This is all the more true for g, the gravitational acceleration felt near the Earth's surface, which varies in both time and space (between 9.78 and 9.83 m s^{-2}). These variations are a result of the gravitational attraction by the mass inside and around the Earth, centrifugal effects due to the Earth's rotation, the distance to the centre of the Earth, geographical latitude, the mass distribution in the Earth's interior, and the relative positions of the Earth, the Moon, the Sun and the planets. Precise determination of g is essential in several scientific domains. As geophysical processes are associated with deformations of the solid Earth and mass distribution changes in its climate system, monitoring local variations in gravity provides information on tectonic deformations, past and present ice-mass changes, tides, the dynamics of the oceans and the hydrosphere and the structure of the Earth[1].

Gravity surveys are also useful in geology and mineral exploration, and are indispensable for the determination of the geoid — the reference equipotential surface of the Earth's gravity field — and hence of altitude. In volcanology, gravity measurements complement deformation monitoring to discriminate between intrusions of lava, water or gas. In metrology, g is key in the new realization of the kilogram with the Watt balance experiment weighing electrical and mechanical powers[2]. Consequently, g plays a major role in state-of-the-art measurements of Planck's constant. Finally, gravimeters have also been useful in investigations of free oscillations of the Earth (global vibration modes excited by major earthquakes) through the monitoring of inertial acceleration[3].

Measuring local gravity is conceptually simple: one drops an object and measures the free-fall time over a given distance. However, before the 1960s, the best way of measuring g (with an accuracy of one part in 10^5) was by means of Kater's reversible pendulum. First introduced in 1817, this instrument (essentially a compound two-pivot-point



pendulum) enables a determination of g by measuring the pendulum's period of oscillation[1]. Realizing a free-fall experiment for determining g with sufficient precision — as physics students may experience — was practically impossible because it requires very accurate measurements of both distance and time. In 1971, ballistic absolute gravimeters based on optical interferometry became the new standard[1]; today, these enable an accuracy for g of 10^{-8} m s^{-2} or, as gravimetrists would say, 1 μGal. (The gal, named after Galilei, is the cgs unit of acceleration.) The working principle lies in repeatedly measuring the time and distance along a 20–30 cm path travelled by a freely falling mass in a vacuum chamber. In the 1990s cold-atom gravimeters were developed[4]; one of their advantages is that they allow for continuous measurements because they have no moving parts and, consequently, do not experience wear. Atom gravimeters are now being miniaturized to facilitate the portability of precise absolute gravimeters, useful for field studies.

Since the 1970s, the motion of satellites has been used to compute global models of the mean Earth's gravitational field[5]. In 2002, the Gravity Recovery and Climate Experiment (GRACE) twin satellites started providing information on the temporal variation of gravity, with a precision equivalent to a few kilograms per square metre on spatial scales of ~400 km at a sampling rate of once per month. The temporally constant part of the gravity field is now known at a level of 1 part in 10^6 with a spatial resolution that can reach 200 m in the best-covered areas by combining data from satellite and ground measurements.

In relative gravimeters, which only measure changes in g, a mass is prevented from falling by holding it and g is determined by measuring how much force is required to do so. Spring relative gravimeters are an example; they are portable devices that report gravity changes with respect to a reference. In superconducting gravimeters, a hundred times more precise and much more stable than spring instruments, a superconducting sphere is made to levitate in a magnetic field[6], resulting in a highly sensitive instrument with a drift of a few $10^{-9}g$ per year — spring instruments typically have a drift of 10^{-9}–$10^{-7}g$ per day. Superconducting gravimeters are also capable of measuring variations in g with a precision that is a hundred times better than that of absolute gravimeters for periods shorter than a day. In contrast to spring gravimeters, the most common mode of operation of superconducting gravimeters is continuous at a fixed location. The levels of precision achievable today — a few $10^{-11}g$ — are such that the effect of rain showers or the motion of a person operating the instrument are detectable (as seen in the plot after about 22 minutes when the operator sits above the gravimeter for 5 minutes).

When Newton realized that a falling apple obeys the same law as the Moon, could he have imagined that atoms play the same game[4], now verified with an accuracy of $10^{-9}g$? ❐

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