The FG5 absolute gravimeter: metrology and geophysics

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1. Introduction

The gravity force, which allows us to define the weight of an object, keeps us at the Earth's surface and is the origin of the free fall of a body. This force is proportional to the mass: $\vec{F} = m\vec{g}$, where $\vec{g}$ is the **gravity acceleration**. The magnitude of this acceleration is the **gravity** g, measured with a **gravimeter**. This is a physical quantity varying in time and space. Indeed, $\boldsymbol{g}$ depends, mainly, on the latitude, the mass distribution in the Earth's interior, the Earth's rotation (velocity and position of the rotation axis), and the relative positions of the Moon and the Sun, which cause the tides[1]. The determination of g is essential in several areas of the scientific research. In **geophysics**, one measures the gravity variation to study tectonic deformations [1], the post-glacial rebound [2], the tides, the influence of the atmosphere and the hydrosphere, and the structure of the globe from the inner core to the Earth's crust. On the other hand, the analysis of the local variations of g presents numerous applications in **geology**. g is indispensable to **geodesy** for the determination of the geoid and therefore of the heights (the geoid represents the average level of the seas and their prolongation under the continents). Finally, in **metrology,** g enters in the determination of standards derived from the kilogram (ampere, pressure, force) and is to play an essential role in the new realisation of the kilogram [3][4]. In the international system of units, the kilogram is the only remaining base unit that still relies on a material artefact. This is unsatisfactory, especially because the stability of the kilogram prototype is not well constrained. The most promising approach is the Watt balance experiment that allows expressing the kilogram in terms of the meter, the second and the

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[1] The tidal accelerations due to the nearby planets are 10^4 (Venus) to 10^5 (Mars and Jupiter) times lesser than those from the Sun and the Moon. This is usually negligible, but it must be taken into account using high quality continuously recording gravimeters like the superconducting ones.

Planck's constant h, by equating mechanical and electrical power. The electrical power is measured in terms of the Josephson and quantum Hall effects, and it will allow one to link the unit of mass to the Planck constant.

First we present the last generation of absolute gravimeter (AG), the FG5 from Micro-g Solutions, Erie, Colorado, USA [6]. This is the most accurate and in fact, the only commercially available absolute gravimeter, which provides the value of g with an accuracy of 1 part in 10^9. Secondly, we describe the Watt balance experiment and briefly some other approaches aiming at redefining the kilogram. Then, we present the results of absolute gravity measurements performed in the Belgian Ardenne to measure intraplate crustal deformations. Finally, we provide some insights on the future of gravity measurements.

2. The FG5 absolute gravimeter

2.1 Principle of operation

The principle of the ballistic FG5 AG is to observe the free-falling of a repeatedly dropped corner cube reflector. This test mass is contained in a co-falling servo-controlled motor-driven drag-free chamber and falls over 20 centimetres in 0.2 second inside a vacuum chamber. The position of the mass is measured as a function of time by laser interferometry. One arm of a Mach-Zender interferometer traverses a path up to the free-falling retro reflector. This "test" beam is reflected back down to another corner cube contained in the proof mass of an active long-period seismometer (free period of ~60 s) which provides an inertial reference frame (Figure 1)[2]. The other interferometer arm ("reference" beam) recombines with the first test beam. As the object falls, interference fringes are formed at the optical output. The fringe signal is detected using an avalanche photo-diode and the time of occurrence of the fringes is measured by a rubidium atomic clock. The length standard is provided by an iodine-stabilised laser. The absolute gravity measurements are therefore directly tied to the time and length SI units.

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[2] To get such a spring, its length should reach about $l = gT^2/(2\pi)^2 \sim 1$ km. Instead, we use a "Superspring", a vibration-isolated device that electronically mimics a 1 km spring. The idea is that in a real spring, points on the spring near the bottom move almost like points at the bottom. A sensor detects differences between the bottom and the top of a 20 cm spring, and the top is moved to mimic the motion it would have in a 1 km spring.

A total of 700 time-position points are recorded over the 20 cm length of each drop. Drops can be produced up to every two seconds but in routine operation, the drops are repeated every 10 s, 100 times per hour. The average of 100 drops is a "set", which exhibits standard deviations of 40 to 150 nms^{-2} (or 4 to 15 µGal[3]) under normal conditions. Measurements usually consist of one set per hour with the average of several sets (usually 12 to 48) providing a "gravity value". The instrumental accuracy of the FG5 is about 1-2 µGal as reported by the manufacturer [6]. However, environmental effects, still imperfectly corrected, affect the gravity value in a wide frequency band (from minutes to decades). It is common to observe differences greater than 2 µGal with the same instrument at two different time interval (see e.g. Section 5), even only 24 h apart. The data acquisition software performs a least square fit of the trajectory data to the following function:

$$\begin{aligned} x_i &= x_0\left(1+\frac{1}{2}\gamma\tilde{t}_i^{\,2}\right)+v_0\left(1+\frac{1}{6}\gamma g_0\tilde{t}_i^{\,3}\right)+\frac{g_0}{2}\left(\tilde{t}_i^{\,2}++\frac{1}{12}\gamma\tilde{t}_i^{\,4}\right) \\ \tilde{t} &= t_i-\frac{(x_i-x_0)}{c} \end{aligned} \tag{1}$$

Where the three unknowns are *x0* (initial position), *v0* (initial velocity) and *g0* (*g* value at $x=0$). γ is the vertical gravity gradient and *c* is the speed of light. Methods to extract the gravity gradient and trajectory parameters simultaneously have proved difficult to implement as signal-to-noise levels are low. Therefore the vertical gravity gradient is measured using a relative spring gravimeter and usually equals about 3 µGal/cm. The finite speed of light gives a correction since the optical reference occurs at time $\Delta t(t)=L(t)/c$ after the light bounces off the dropped object, where *L(t)* is the path of the drop. The bias introduces an apparent shift of approximately -11 µGal in the gravity value for a 20 cm drop.

The final gravity value is obtained after applying correction for earth tides, ocean loading[4], local atmospheric effects (-0.3 µGal/hPa due to loading and mass attraction) and polar-motion effects[5].

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[3] 1 µGal = 10 nm s^{-2}

[4] The surface loading of the Earth due the weight of the ocean tides causes a time varying deformation of the solid Earth, which is called ocean tide loading. The vertical component of the ocean tide loading varies spatially and has a maximum of 12 cm peak to peak in Cornwall, but is less than 2 cm in Membach (Eastern Belgium). This ocean tide loading deformation is in addition to the Earth's body tide deformation, which is typically 40 cm peak to peak in mid-latitudes.

Presently, there are only some thirty of these instruments in the world and the Royal Observatory of Belgium owns the FG5-202 since 1996.

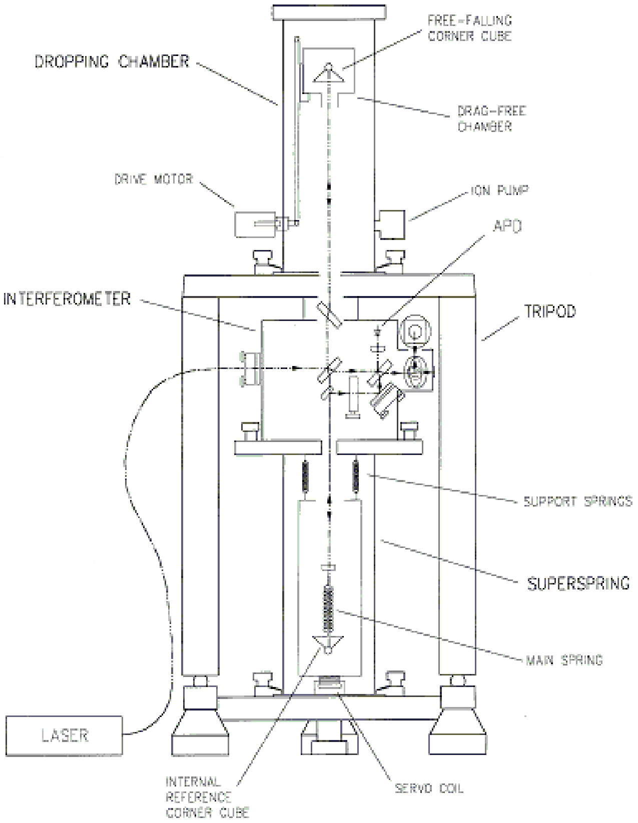

Figure 1. The FG5 absolute gravimeter: a corner cube reflector contained in a co-falling servo-controlled motor-driven drag-free chamber, falls over 20 centimetres in 0.2 second inside a vacuum chamber (the "dropping chamber"). The superspring is a vibration-isolated device, which provides an inertial reference frame. Presently there are only some thirty of these instruments in the world. For a colour photo, see e.g. http://homepage.oma.be/mvc/absolu.htm.

2.2 Control of the FG5

To ensure that the gravimeter remains in good working condition, it needs to be checked regularly at a reference station. For this reason, measurements are made at the reference

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[5] Free of forcing, a body tends to rotate around its principal moment of inertia. In response to a given excitation, the rotation axis can be moved. The rotation axis then oscillates around the main inertia axis: this is the polar motion. The main component of this motion is the Chandler wobble: the pole describes an ellipse of some tens of meters with a period at 14 months. This motion is mainly induced by the interaction with the atmosphere and the oceans. As the rotation axis is changed, the value of the centrifugal acceleration varies; those variations can be measured by AGs and SGs (amplitude of about 10 µGal peak to peak).

Membach Geophysical station (near Eupen [7]) before and after each measurement campaign in the field. In this station, a superconducting gravimeter (SG) GWR-C021 [8] continuously records the gravity with a resolution of 0.1 μGal. The fundamental component of a SG consists of a hollow superconducting sphere that levitates in a persistent magnetic field. A vertical displacement of the sphere is compensated by a feedback voltage, which is proportional to the gravity changes. The GWR SG provides only relative gravity measurements and the most common mode of operation is continuously at a fixed location. Collocated observations by a SG and an AG then can be used to eliminate uncertainties in the observed gravity variations due to instrumental effects as the SG and AG are completely different in instrumental design and working principle. Thus we can check the AG data over time by determining whether any observed offsets in the AG are due to instrumental problems or to actual changes in gravity [7]. As high accuracy reference instrument, the Belgian FG5 AG also participates in numerous international comparisons [9][10]. For example, at the "Bureau International des Poids et Mesures" (BIPM, Sèvres, France) or at the "Swiss Federal Office of Metrology and Accreditation (METAS, Bern, Switzerland)" laboratory, where a Watt balance is currently under development [4].

3. Redefining the kilogram: the Watt balance experiment

The kilogram is the only remaining base unit of the International System of Units (SI) whose definition is based on a physical artefact rather than on fundamental properties of nature. This artefact is the international Prototype Kilogram, also named "K" ("Grand K"), which consists in a cylinder of platinium-iridium alloy kept at the Bureau International des Poids et Mesures (BIPM) in Sèvres, France. This current definition is quite limiting, especially because:

1. The prototype is not perfectly stable and the amount it changes cannot be known perfectly: there is no "perfect" reference against which to judge it. However, long-term studies of the differences between selected 1 kg prototypes and K indicate that the long-term variation of the kilogram could be as much as 5 parts in 10^9 per year [11][12].
2. The value of the national copies cannot be monitored at the highest level of accuracy without being compared directly with K. The fact that a single artefact provides traceability for the entire mass scale world-wide presents a major logistic and resource

problem. Notice that most national measurement institutes hold only one (on a total of about 77) official copy of the kilogram (Belgium holds the No 37).

To prepare the SI for the increasing needs of science and technology, a replacement of the kilogram based on fundamental constants is needed. A new definition should be considered if the expressed relating mass and fundamental constants reach a relative uncertainty of less than 1 part in 10^8 [5].

We focus here on the Watt balance experiment that aims at monitoring the kilogram by equating mechanical and electrical power. As the electrical power is measured in terms of the Josephson and the quantum Hall effects, the unit of mass can be linked to the Planck constant.

The experiment is performed in two parts (Figure 2). Consider a coil suspended from one arm of a balance. The coil is immersed in a horizontal magnetic flux Φ. The current I in the coil exerts a vertical force on the conductor which is balanced against the weight F_m of the test mass m:

$$F_m = mg = -I \cdot \frac{\partial \Phi}{\partial z} \tag{2}$$

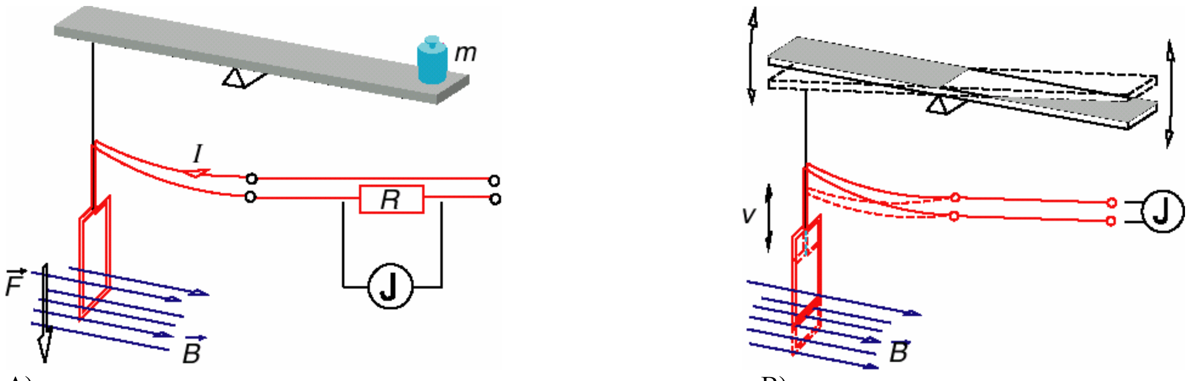
where g is the local acceleration due to gravity. In the second part of the experiment, the coil is moved at a constant velocity v in the vertical direction through the flux and the voltage U induced across the coil is measured, being

$$U = -\frac{\partial \Phi}{\partial t} = -\frac{\partial \Phi}{\partial z} \cdot \frac{\partial z}{\partial t} = -\frac{\partial \Phi}{\partial z} \cdot v \tag{3}$$

at the location of the weighing. Combining (2) and (3), we eliminate the flux gradient $\partial \Phi / \partial z$, geometrical factor difficult to measure, and we obtain:

$$U \cdot I = m \cdot g \cdot v \tag{4}$$

The experiment allows the comparison of the watt realized electrically to the watt realized mechanically. This requires measuring the gravity acceleration[6] g, which is done using an AG. The Royal Observatory of Belgium collaborates with METAS by bringing its experience in gravity measurements.



A)

B)

Figure 2. The Watt balance. A) static mode: the electromagnetic force acting on the current I carrying coil is balanced against the weight mg of the test mass. B) Velocity mode: the coil is moved in vertical direction through the magnetic field B and the induced voltage U is measured.
One obtains: $U\,I = m\,g\,v$. U and I are determined using the Josephson and the quantum Hall effects $\Rightarrow m\,g\,v \sim f_j\;,\,h$ where f_j is the Josephson's frequency and h, the Planck's constant. g is measured using an AG.

Watt balance experiments are currently pursued at three institutes: the National Physical Laboratory (NPL, U.K.), the National Institute of Standards and Technology (NIST, U.S.A.) and METAS (see [3][4]). Two new projects are announced at the Bureau National de Métrologie (BNM, France) and at the BIPM. In the case of BNM, gravity will be monitored by an atomic gravimeter (see Section 6) whereas the former ones use their own FG5 AG.

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[6] The *gravity acceleration* depends on the arrangement of the terrestrial and extraterrestrial masses, as well as on the Earth's rotation. It can not be mistaken as the acceleration due to the *gravitational attraction*, only due to mass attraction.

3.1 A possible new definition of the kilogram based on the Planck constant

The voltage U is measured against a Josephson[7] voltage standard and the current I from the voltage drop across a resistance calibrated against a quantum Hall[8] resistance standard. Therefore, (4) becomes:

$$m = \frac{1}{g \cdot v} kh \tag{5}$$

where k is a constant and h, the Planck's constant [5]. Using a Watt Balance, Williams et al. [13] obtained the best measurement of the Planck's constant in 1998, with an uncertainty of 8.7 x 10^{-8} and a numeric value of 6.62606891 x 10^{-34} J s.

If the Watt balance experiment reaches the necessary precision of 1 part in 10^8, first one should have to check the stability of K. Then, one could naturally redefine the kilogram in such a way that the value of h is fixed (such a reasoning was already applied to define the meter, where c had to be fixed). According to Taylor and Mohr [14], the new definition of the kilogram could be as follow: "*the kilogram is the mass of a body at rest whose equivalent energy equals the energy of photons whose frequencies sum to* 135639274 x 10^{42} Hz". This definition results from the well known Einstein relation $E = mc^2$ and the relation $E = h\nu$ valid for the energy of photons. The Watt balance could be a practical realization of the kilogram, like an iodine stabilized He-Ne laser is a practical realization of the meter.

3.2 The other approaches

3.2.1 The voltage balance

The electrostatic force acting between the plates of a capacitance is compared with the weight mg of the test mass m. With the present techniques, this approach does not promise to reach an uncertainty below 1 part in 10^7. The main problems are the high voltage required in

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[7] Josephson effect: If a thin insulated barrier between two superconductors is cooled to 4.2 K and exposed to electromagnetic radiation of frequency f, then the DC voltage across the junction V_j assumes discrete values $V_j = nfh/2e = nf/K_j$, where K_j is the Josephson constant, n an integer, h the Planck constant and e, the electronic charge. For predicting this effect, Esaki, Giaever and Josephson were awarded the Nobel Prise in 1973.

[8] Quantised Hall Effect: the Hall resistance measured in silicon MOSFETs at low temperature and high magnetic fields is quantised: $R_H = h/ie^2 = R_k/i$ (R_k is the von Klitzing constant and i an integer). It was discovered in 1980 by G. Dorda, M. Pepper and K. von Klitzing, this latter were awarded the Nobel Prize in 1985.

the experiment (10-100 kV), the voltage and frequency dependence of the capacitance and its mechanical imperfections [5].

3.2.2 The superconducting magnetic levitation

Like the Watt balance project, this method relates the kilogram unit to the Josephson and quantised Hall effects. Here a superconducting body is levitated in a magnetic field generated by a superconducting coil. The current required in the coil is proportional to the load of the floating element. The most important problems to overcome in this experiment are due to horizontal force components on the trajectory of the levitated object, to the distortion of the object under levitation, to obtain a perfect diamagnetic floating body [5].

3.2.3 The Avogadro project

While the three previous approaches aim at defining the kilogram using the equivalence between mechanical and electrical energy, the internationally coordinated Avogadro project attempts to define the kilogram based on a fixed number of atoms of silicon [5][15]. The mass of a sphere of silicon is related to its molar mass and the Avogadro constant by the equation:

$$m = \frac{M_m}{N_A} \times \frac{V}{v_0} \tag{6}$$

where m is the mass of the sphere, M_m the molar mass of the silicon isotopes measured by spectrometry[9], N_A the Avogadro constant, V the volume of the sphere measured by interferometry and v_0 the volume occupied by a silicon atom, measured by x-ray interferometry. The practical realization of this definition relies on the calculation of a value for N_A from an initial value for the mass of the sphere. The value N_A is then fixed and used subsequently to give the value for the mass m of the sphere. Apart from the problem of measuring N_A with a relative uncertainty of 1 part in 10^8, another complication is the growth of oxides of silicon on the surface of the spheres, which needs to be monitored.

The Planck and Avogadro constants are related by the relative atomic mass of the electron, the square of the fine structure constant and the Rydberg constant. At this present time, these

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[9] The Institute for Reference Materials and Measurement (IRMM) in Geel, Belgium, is the only one in the world which can measure the isotope ratios (and therefore molar mass) of silicon with a sufficiently small uncertainty.

constants are not exactly known and hence the Avogadro experiment has not yet provided *h* exactly [14].

3.2.4 The ion accumulation approach

Like the previous one, this strategy is to relate the mass of a fundamental particle to the kilogram by counting a large number of identical atoms. This approach involves the accumulation of a known number of gold atoms Au^{197} [16]. The number of ions collected is related to the ion current required to neutralise them, which is measured using quantum Hall resistance and Josephson voltage.

4. Measuring crustal deformation using a FG5 absolute gravimeter

Using this instrument, we have observed at the Membach station a small trend in the gravity of (-0.6 ± 0.1) µGal/year for more than 7 years (Fig. 3). It indicates that the station is perhaps going up by about 3.0 mm/year, which seems to be confirmed by the (2.7±0.2) mm/year uplift observed by continuous GPS performed 3 km away from the Membach geophysical station [7]. Further inspection of Figure 3 indicates that SG observations agree with those from the AG at the µGal level and also shows a quasi-annual signal in the continuous SG gravity observations most probably and mainly due to local hydrological variations. The ~5 µGal peak to peak amplitude varies significantly from year to year, depending on the meteorological context. The rainfall around Membach is uniformly spread over the entire year but the gravity decreases in winter as the evapotranspiration is reduced. The inverse relationship may at first seem surprising as one would expect gravity to increase with an increase in water mass in the ground beneath the instrument. However, the Membach laboratory is in fact located within a 140 meter long tunnel cut into the side of a hill. The SG is located 49 m below the surface. This means that the water mass is above, not below, the instrument thus making gravity decrease. Further, given that the instrument is buried at such a distance, the water evaporates before it has time to percolate down beneath the instrument.

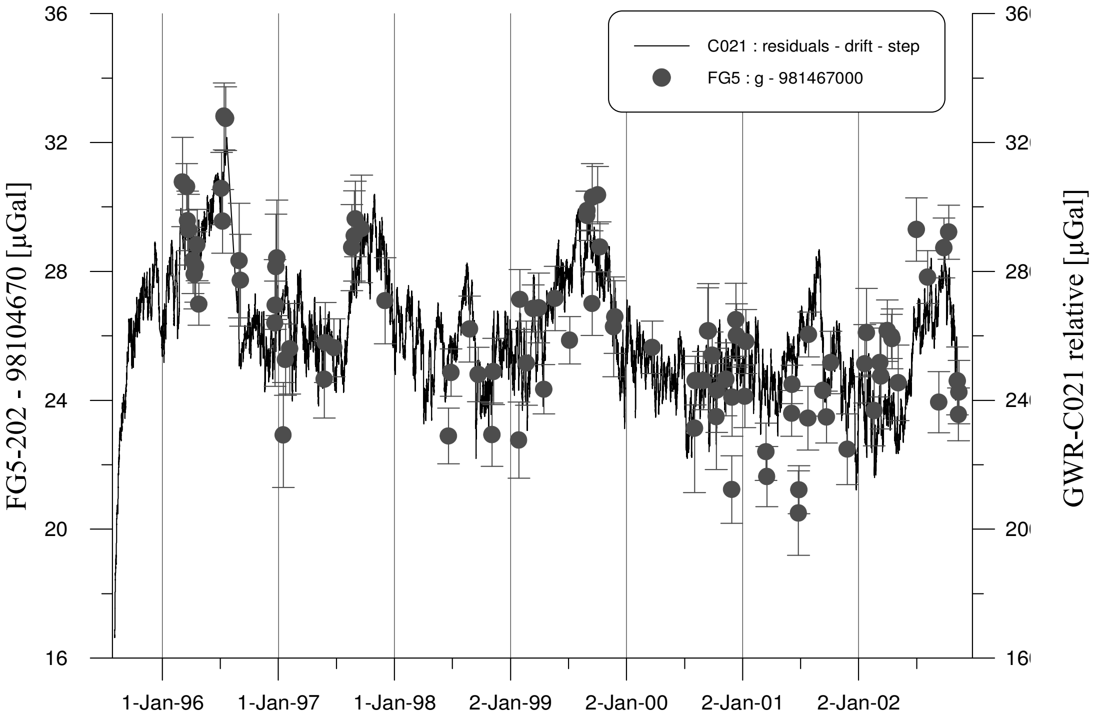

Figure 3. Comparison between gravity measurements of the SG C-021 and the AG FG5-202. The Earth tides, ocean loading and atmospheric effects, and polar motion have been removed. The SG C-021 instrumental drift of 4.3 μGal/year was evaluated by taking the difference between the residuals of the SG C-021 and of the AG FG5-202. AG error bars are 1 σ. The initial exponential decrease from August to December 1995 is due to the SG C-021 setup. What remains in these corrected SG residuals, from March 1996 to November 2002, is a geophysical trend, mainly linear and we estimate its slope at (-0.6 ± 0.1) μGal/Year.

In order to confirm this uplift and to estimate its wavelength, we are performing semi-annual AG measurements along an 8-station profile across the Ardenne and the Roer Graben since 1999. This present deformation could be linked to the active faults in the Ardenne and/or bordering the Roer Graben (this is an important parameter to assess the not negligible seismic hazard); to the possible volcanic Eifel plume or to the Fennoscandia post-glacial rebound [1]. Along this profile, at the Jülich station, we observe there a gravity change of (3.7+/-1.3) μGal/year related to a subsidence of more than 1 cm/year, caused by water pumping [17]. This prevents us to measure tectonic deformations at that location, but this strong signal acts as a test bench, with valuable applications in hydrogeology. In the other seven stations, at this present time, there is no detectable gravity rate of change larger than 1.8 μGal/year (which is equivalent to a vertical deformation of 9 mm/year). This long-term experiment shall be carried out up to 2009 at least; then we should be able to constrain any possible long-term trend with accuracy better than 0.5 μGal/year.

AG measurements are also performed in Oostende once a year. The goal is to determine vertical land movement at the tide gauge. Thus, the FG5-202 takes a part in the European Sea Level Service (ESEAS) which aims at monitoring the mean sea level.

5. The future

Here we briefly describe three new approaches under development. First, the compact cam-driven AG: the test mass is placed on a cart whose vertical motion is defined by the shape of a cam that rotates with a velocity around a horizontal axis [18]. This instrument uses 20 mm of free fall 200 times a minute (respectively 20 cm and maximum 30 times for the FG5).

Another approach is the atom interferometer based on a fountain of laser-cooled atoms to measure *g*. An atom is placed into a superposition of two spatially separated atomic states; each state is described by a quantum-mechanical phase term, which will interfere with one another when they are brought back together. Gravity acts on the moving atoms and distorts the phase of the matter waves. This changes the interference pattern, which are detected using laser resonance fluorescence. Comparing atom and FG5 AGs, Peters et al. [19] obtained the best confirmation of the equivalence principle between a quantum and macroscopic object.

The last technique comes from space with projects such as GRACE (Gravity Recovery and Climate Experiment [20][http://www.csr.utexas.edu/grace]. It consists in twin satellites launched in March 2002, which are able to map the Earth's gravity fields by making accurate measurements of the distance between the two satellites. The expected precision is one thousandth of a FG5, but the satellites cover the whole Earth and will be used to estimate global models for the mean and time variable Earth gravity field approximately every 30 days.

6. Conclusions

The first ballistic FG5 AG was brought into service about 10 years ago. The accuracy of this AG model, based upon advanced metrological standards monitored with great care, is now approaching 1 part in 10^9 (1 μGal). This allows numerous applications in geophysics, geodesy, geology and metrology, especially in the Watt balance experiment, aiming at redefining the kilogram, in which measuring *g* at a level of a few part in 10^9 is a key factor.

Presently some instrumental variations still dominate. Close collaboration between the FG5 manufacturer and users, and the laboratories developing other ballistic and atomic AGs, will allow one to reach the μGal level in a near future. Moreover, the modelling of the parasitic environmental effects (groundwater, atmosphere, tidal effects…) needs to be improved. The Royal Observatory of Belgium and METAS actively participate to these two challenges.

7. Acknowledgments

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