V. ГЕОДИНАМИКА

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ABOUT TIME VARIATIONS OF GRAVITY

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Advances in gravity instumentation have allowed for the determination of the absolute acceleration of gravity to a precision of 3-5 μGal and observations of tidally driven changes in gravity on the order of nanogals. With observations of gravity and changes in gravity at these levels of precision we are able to investigate problems such as the resonance of the earth's liquid inner core, discriminate between the various ocean tidal models, understand the effects of atmospheric pressure loading on gravity observations, and perhaps measure ice mass changes in Greenland. In this paper, we report on some of our results using absolute and superconducting gravimeter data. We describe a project to establish a site for international comparisons of absolute gravimeters in Luxembourg.

О ВРЕМЕННЫХ ВАРИАЦИЯХ СИЛЫ ТЯЖЕСТИ

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Успехи в развитии приборов для измерения силы тяжести позволяют определять ее абсолютную величину с точностью до 3–5 мкГал и приливные изменения силы тяжести с точностью порядка наногал. Имея столь высокоточные наблюдения силы тяжести и ее изменений, мы теперь можем исследовать такие задачи, как резонансы в жидком внутреннем ядре Земли, уточнение модели морских приливов, влияние атмосферного давления на измерения силы тяжести и, возможно, определение изменений массы льда в Гренландии. В данной работе мы приводим некоторые результаты по измерению абсолютной силы тяжести с помощью гравиметров, основанных на явлении сверхпроводимости. Описывается проект по созданию пункта для международных сравнений абсолютных гравиметров в Люксембурге.

Introduction

We have had the good fortune to have Vladimir Keilis-Borok visit our countries many times. We are sincerely grateful to him for the always stimulating and pleasant discussions about fundamental geophysical problems that he inspired. As a testimony of our admiration for his scientific work, we are extremely pleased to be able to dedicate this overview of results obtained by our team in the field of high precision gravimetry, not only here in Belgium and Luxembourg but also outside Europe.

Gravimetry is a research field, which was born when Galileo Galilei discovered the laws governing an object's free-fall at the Earth's surface and the isochronism of the pendulum oscillations (between 1582 and 1604). About one century later, the first experimental pendulum measurements were performed by Picard and Richer (1668–1672).

More than three centuries of difficult and often slow progress brought us to the threshold of sub-milligal precision for gravity experiments undertaken at the time of the International Geophysical Year (IGY, 1957–1958). Now, owing to the extraordinary advancements in electronics and in time and length standards, new absolute instruments capable of achieving microgal accuracy (since around 1990) are common. In addition, thanks to the invention of the superconducting gravimeters we have become accustomed to speaking in terms of nanogals (10^{-12} of the gravity) when measuring the tidal variations of gravity. We have been fortunate to have the opportunity to work with both kinds of instruments and wish to report here on some of our results.

1. Absolute free-fall instruments

The principle of free-fall absolute gravimeters is to measure the acceleration of a falling corner cube reflector, itself contained in a co-falling, servo-controlled, motor-driven, drag-free chamber. The corner cube falls inside a vacuum chamber over a distance of only 20 centimetres, taking approximately 0.17 seconds. One arm of a Michelson interferometer provides a length standard while the corner cube attached to the falling mass forms the movable arm of the interferometer. The timing of the resulting interferometer fringes is measured by an atomic clock. Drops can be produced every two seconds which allows for a determination of the acceleration of gravity to a precision of 3 to 5 μGal.

The new generation free-fall type absolute gravimeter, the AXIS-FG5 (currently the Microg-FG5) represents an important improvement over the previous JILAG type gravimeters. In the FG5, the reference corner cube is integrated into a seismometer proof-mass of an active inertial reference, the Superspring, which isolates the measurements from seismic noise and reduces the measurement errors down to the order of a few milligals. Hundreds of consecutive drops are combined to make one "run" after which an instrumental levelling is carried out. Several runs are performed on each station lasting from one to two days. The length standard is provided by an iodine-stabilised laser that is a practical realization of the SI definition of the meter. Thus no calibration is required. The instrument has a long-term stability of 2×10^{-11} per year. The time is measured by a rubidium atomic clock, which means that the absolute gravity determinations are tied to absolute standards. With this instrument the accuracy of the determination of gravity at a single station is estimated to be about 1 to 2 μgals with a precision of ± 1 μGal (0.01 μm s^{-2}).

TABLE 1. Examples of precision obtained in our determinations of g for different sites

STATION	g value (microgal)	Standard deviation (microgal)	Drop-to drop standard deviation (microgal)	Year
BOULDER (USA)	979 622 841.9	0.8	7.6	1998
BRUSSELS (Belgium)	981 128 649.2	3.1	31.4	1996
WALFERDANGE (Luxembourg)	980 963 953.3	0.7	10.9	1998
KULUSUK (Greenland)	982 337 191.7	3.0	18.1	1999

Comment. Boulder and Walferdange are very quiet sites (laboratory conditions) where one can attain precisions of better than 1 microgal. The Brussels standard deviation is typical of the results one can expect in an urban environment. Kulusuk is a remote station far from anthropogenic activities, however, the measurements are performed in the field inside a portable tent where temperature variations are difficult to control.

2. Fine structure spectrum in tidal gravimetry

The interpretation of the various tidal effects experienced on and inside the Earth's body requires a broad multidisciplinary approach including Celestial Mechanics, Solid Earth Physics and Oceanography. In the next sections we outline the different 'steps' required in understanding tidal observations.

The first step, Astronomy: Celestial Mechanics describes the orbital movements of the Earth around the Sun and of the Moon around the Earth with such a high precision that the attraction potential exerted by these two bodies (including also a small contribution by the planets of Venus and Jupiter) can be described by a series development of some 10.000 harmonic terms whose frequencies are known exactly to eight digits and whose amplitudes are know exactly to six.

Tidal perturbations due to this luni-solar attraction, exerted on the global Earth are the only existing geophysical phenomenon where the acting forces are known to us, a priori, with a very high accuracy.

The number of components to be taken into account in the development of the tidal potential for the analysis of data is of course a function of the quality and length of the recording. At the time of the IGY, 386 terms appeared to be sufficient while, today, in the year 2000 not less than 10.000 accurately known frequencies are used in the computer programs for Earth tide analysis. The length of the observational record also determines which of the numerous waves can be separated: only six from one month of data, while the long series of fourteen years completed with the cryoscopic superconducting gravimeter at Brussels has allowed for the correct recovery of 31 diurnal, 23 semi-diurnal, 4 terdiurnal tides, i.e. not less than 58 tidal waves.

A registration of tidal effects (gravity, tilt, or strain) can be analysed to a very high precision by a least squares method where the frequencies are frozen. The result obtained for each wave is the amplitude A and the phase α of a tidal vector $\mathbf{A}$. However the corresponding "theoretical vector" computed for the totally rigid and oceanless Earth which is the only model considered in Celestial Mechanics has a well defined amplitude not equal to A and having a zero phase. Moreover, in the case of strain the amplitude is strictly equal to zero.

As a matter of fact the analyses of observations give amplitudes augmented in the case of gravity, diminished in the case if tilt variations, and non-zero in the case of strains while all waves exhibit nonzero phases.

The second step, Geophysics: To explain the discrepancies between celestial mechanical theory and observations, one has to change the rigid Earth model (described above) to a deformable viscoelastic model of the Earth's interior. One immediately observes that viscosity could not explain all the phase lags, which often reach several degrees, principally at coastal stations and islands. Understanding this observation will require a third step.

The differences in the amplitudes, indeed, are explained to a large extent (but not completely) by the elastic properties of the Earth's interior. Taking for each wave the ratio of the observed amplitude A to the Celestial Mechanics amplitude one obtains a measure of the global elasticity of the Earth which is expressed in terms of the famous "Love numbers" h and k.

This "amplitude factor" is

$$\delta = 1 + h - (3/2)k \quad \text{for gravity (vertical component)} \tag{1}$$

$$\gamma = 1 + k - h \quad \text{for tilt (horizontal components).} \tag{2}$$

Expressions for the six components of horizontal strains [1] are even more complicated. The vertical strain component depends on the radial derivative of the h Love number with an amplitude factor defined as

$$\eta = ah' + 2h \tag{3}$$

The Love numbers can be calculated theoretically for any rheological model of the Earth's interior [2]. The observed δ and γ amplitude factors of the sectorial semi-diurnal waves fit reasonably well with the modeled amplitude factors for observing stations distant ($>$ 1000 km) from any ocean, but the agreement between the model and observations diverge more and more when approaching a coast [3]. On the contrary, because the tesseral diurnal tides are generally weak in most of the oceans, the amplitude factors of these waves fit the model ones in a more or less satisfactory way. Oceanic corrections are small so that γ and δ factors reveal one of the most interesting and important perturbations due to inertial tesseral oscillations excited in the fat Earth liquid core. Well before the geophysical discovery of the core, the existence of a resonance reaction of a suspected liquid core had been already demonstrated theoretically, independently and simultaneously in 1895, by Th. Sloudsky [4] in Russia and by Hough in the U.K. It is often referred as the Poincare effect on the basis of his brilliant paper published in 1910 (see [5]).

The resonance frequency was known to be very close to the sidereal frequency of the rotation of the Earth ($15.041°h^{-1}$). We now know that it is $15.076°h^{-1}$, a result obtained by stacking VLBI measurements of the Earth rotation parameters with diurnal tidal amplitudes obtained with superconducting gravimeters (ours in Brussels and two others in Strasbourg and Cantley). No tidal wave has exactly this frequency but three waves of large amplitude are more or less close, while only one wave, which unfortunately has very small amplitude, ψ_1 has a frequency very close to the sidereal rotation frequency. Table 2 shows how their observed tidal factors fit the values computed on the basis of an Earth model with a liquid core.

TABLE 2. Diurnal waves and the liquid core resonance

Wave	O_1 (lunar)	P_1 (solar)	K_1 (luni-solar)	ψ_1 (solar)
Frequency, $^{-1}$	13.943°	14.959°	15.041°	15.082°
Tilt amplitude (EW)	0"00478	0"00212	0"00672	–
Observed γ	0.676 ± 0.008	0.713 ± 0.005	0.754 ± 0.002	–
Modeled γ	0.695	0.705	0.736	–
Gravity (nanogals)	35098	16318	48796	413
Observed δ (1)	1.1572 ± 0.00008	1.1572 ± 0.0002	1.1376 ± 0.00006	1.2326 ± 0.00078
Observed δ (2)	1.1568 ± 0.00009	1.1517 ± 0.0002	1.1367 ± 0.0007	
Modeled δ	1.1528	1.1477	1.1324	1.2800
Astronomical Correspondence	13.66 days nutation	Semi-annual nutation	Precession	Annual nutation

Comment. Tilt: mean of 3 stations in Belgium and Luxembourg: $\gamma = 1 + k - h$ (~1960–90) using Verbaandert-Melchior quartz horizontal pendulums; Gravity: (1) superconducting gravimeter at Brussels: $\delta = 1 + h - 3/2k$; (2) Walferdange underground Laboratory (1974–1997); Models from [1].

The amplitudes obtained for a perfectly elastic Earth model corresponds to a vector $\mathbf{R}(R, 0)$ with zero phase. It is advisable to consider the vectorial difference

$$\mathbf{A} - \mathbf{R} = \mathbf{B} \tag{4}$$

and investigate the geographical distribution of the amplitudes B and phases β of this residual vector. The amplitudes are generally of the order of a few microgals. On islands, amplitudes can reach up to 10 microgals while the phases can be in any one of the quadrants.

The third step, Oceanography: The oceans which cover the bulk of the Earth's surface are subject to tides of variable, and often large, amplitude, and large phase with respect to the astronomical potential. The periodic displacements of huge amounts of water exert a variable attraction on the observing ground based instruments and, at the same time, periodic deformations of the Earth's mantle under the load exerted by these masses. These perturbations have exactly the same frequency as the Earth's body tides.

Today we are fortunate to have at our disposal several different oceanic models for the twelve principal tides, derived from satellite altimetry with remarkable precision.

Using the technique of Green's functions [6] one may obtain at any point on the Earth's surface and for every tidal wave a loading attraction vector $\mathbf{L}(L, \lambda)$ and correct accordingly the observed data. Table 3 summarizes some of our results for the main lunar semi-diurnal tide, M_2.

The comparison of vectors $\mathbf{B}$ and $\mathbf{L}$ is performed by calculating the correlation between their corresponding projections: $B\cos\beta$ with $L\cos\lambda$ and $B\sin\lambda$ with $L\sin\lambda$. We found very high correlations (Table 4) verifying, without a doubt, the assimilation of the residues, B, into the oceanic tidal effects. Particularly impressive results have been obtained on small islands in the South Pacific Ocean and the large island Madagascar where tidal gravimeters had been installed by one of us and (at Kerguelen) by M. Bonatz (Table 5).

TABLE 3. Principal semi-diurnal lunar wave M2 corrected for oceanic attraction and loading

Corrections according to	$\delta = 1 + h - 3/2k$ amplitude factors and phase	
	Europe (20 stations)	South America (34 stations)
Oceanic model FES95.2	1.1607 ± 0.0003 $0.00° \pm 0.03°$	1.1603 ± 0.0012 $-0.33° \pm 0.05°$
Oceanic model CSR3.0	1.1636 ± 0.0007 $-0.12° \pm 0.03°$	1.1607 ± 0.0012 $-0.38° \pm 0.07°$
Earth Model	1.16257 0.00°	

Comment. The Earth model is the inelastic non-hydrostatic from[2].

Final step: Perhaps provisional. After having removed the contribution of the Earth's elasticity from the tides, we can now subtract the contribution of the oceans :

$$\mathbf{X}(X, \chi) = \mathbf{B}(B, \beta) - \mathbf{L}(L, \lambda) = \mathbf{A}(A, \alpha) - \mathbf{R}(R, 0) - \mathbf{L}(L, \lambda). \tag{5}$$

We could call $\mathbf{X}$ the final "residue" if it corresponded to the noise in the observations. Our task should be completed if this were indeed so. However the amplitudes X are often still larger than the instrumental noise and consequently could be the result of inaccuracies in the models. We need to look further for something that may have been neglected or forgotten in the modeling.

TABLE 4. Correlation coefficients between observed residue B and calculated oceanic load L

Wave	In phase component cosine		Out of phase component sine
	h	Coefficients	Coefficients
Q_1	36	0.97 ± 0.01	0.86 ± 0.04
O_1	289	0.83 ± 0.02	0.82 ± 0.02
P_1	27	0.93 ± 0.03	0.95 ± 0.02
K_1	26	0.97 ± 0.01	0.91 ± 0.03
N_2	206	0.92 ± 0.01	0.92 ± 0.01
M_2	289	0.93 ± 0.01	0.94 ± 0.01

TABLE 5. M_2 wave tidal vectors observed in some islands

Station	B	β	L	λ	X	χ
Apia (Samoa)	13.2	$-27°$	8.3	$-11°$	5.9	$-49°$
Papeete (Tahiti)	0.5	102°	1.0	94°	0.5	$-94°$
Kerguelen	5.3	196°	4.7	196°	0.6	196°
Antananarivo	4.1	52°	4.3	57°	0.4	$-64°$

Comment. The amplitudes B, L, and X are given in microgals.

As the wavelengths of the tides are large (e.g. 20.000 km for the diurnal waves and 10.000 km for the semi-diurnal waves at the equator) it would appear that local tectonic anomalies could not play any significant role in altering the magnitudes of the tidal deformations.

We considered the idea that large tectonic features, such as provinces of high heat flow, might have an effect on the tides there. We developed this proposal notably with V. Keilis-Borok [7], obtaining a high correlation coefficient (0.60) between the component $X \cos \chi$ (which is directly related to the model) with local heat flow [8]. This result seems to indicate that high heat flow may be an indicator of a more fundamental phenomenon. Unfortunately, despite our findings, these results have not been convincing for several of our colleagues.

3. Importance of atmospheric loading

After Earth tides, atmospheric pressure effects are the most dominant signals in a superconducting gravimeter time series. Gravity is affected by the atmosphere in three ways. First, there is the temporal change in atmospheric mass. Second, is the vertical deformation of the Earth's crust from the excess mass, and third, there is the change in the Earth's gravitational potential. Of these effects, the change in mass affects gravity the most; however, the change in gravity from the deformation of the Earth is also measurable. The pressure variations correlate with gravity changes with an admittance of about -0.3μGal mbar^{-1} at non-tidal frequencies (1992). For long time series, changes in local gravity are fit to changes in local pressure to empirically determine the admittance relationship. Atmospheric pressure varies at frequencies from hours to years and so must be carefully removed from a gravity time series before interpreting gravity changes in terms of geophysical or other environmental effects.

Atmospheric pressure effects are routinely removed from gravity time series using the single admittance factor described above. This process leaves long-period residuals of a few μGals and short period (< 1 day) residuals of about a μGal. The long-period residuals are due to the neglect of very distant pressure systems and the short-period residuals are due to changes in the horizontal scale of local pressure systems.

Atmospheric pressure/gravity admittances calculated by a least-squares fit of pressure to gravity have been observed to have a geographical and seasonal dependence [9]. Frequency dependent admittances have also been observed.

The dependence of the pressure admittances on site, season, and frequency reflect the temporal and spatial variations in the atmosphere and how the Earth and ultimately the measurement of gravity on its surface changes in response to these variations. For example, the atmosphere expands and contracts with temperature without any accompanying change in surface pressure. There will be however an effect on gravity and hence the gravity/pressure admittance because the mass distribution of the atmosphere has changed.

These conclusions indicate that a physics based model of the relationship between pressure and gravity rather than a least-squares fit may be more appropriate for correcting a gravity time series for atmospheric pressure effects.

Various analyses of the physical relationship between atmospheric pressure and gravity have been presented in the literature. The first used a standard atmosphere applied as a column load centred on the gravimeter, a half-space approximation for the Newtonian attraction, and a spherical-elastic Earth model to determine the load induced deformation. Admittances derived based on a spherical Earth model with a thin atmosphere. That work was extended by modeling the regional and global pressure variations. van Dam and Wahr [10] took this one step further and used global surface pressure grids to model the deformation-induced effects of atmospheric pressure on gravity measurements. The Newtonian attraction was modeled using an infinite plane assumption for the distribution of atmospheric mass. These analyses, while all advancing our ability to model the effects of atmospheric pressure variability in gravity, all neglect the complicated horizontal variability of the atmosphere at varying heights. Merriam [11] was the first to address this issue by modeling the atmospheric density change with height using the hydrostatic assumption and prescribed vertical temperature gradients. van Dam and Francis [work in preparation] will improve on the work of Merriam by using atmospheric pressure observations at different heights above the surface of the Earth.

4. Using gravity and GPS to infer Ice mass changes in greenland

Climate research indicates that global warming is occurring and will probably continue to occur for the next several decades. One consequence of a global warming scenario is a global sea level rise that would be expected from 1) the thermal expansion of the near surface ocean water and 2) the melting of the Antarctic and Greenland ice sheets and continental glaciers.

Determining the relationship and feedback mechanisms between climate, sea level, and ice mass changes has been difficult because of the lack of appropriate data. It is not even clear, for example, whether changes in the Greenland and Antarctic ice sheets over the last century have caused sea level to rise or have caused it to fall.

We are currently involved in an ongoing geodetic project to measure changes in the vertical position and surface gravity at bedrock sites along the southern edge of the Greenland ice sheet. The long-term goal is to use these measurements to constrain ice mass changes in the southern third of the ice sheet and to eventually contribute useful data to understanding climate variability and its relationship to long-term sea level trends and ice mass changes.

The principle of using geodesy to measure present-day ice mass changes (or any surface load for that matter) is relatively straightforward. First, imagine that you have a positioning instrument or a gravimeter on bedrock at the edge of the Greenland ice sheet. If the ice sheet undergoes significant melting, the Earth's crust in the vicinity of the ice sheet will experience an immediate uplift. If the uplift is large enough, it can be measured by a positioning instrument or a gravimeter. Three millimetres of uplift without associated mass changes causes a gravity change of 1 μGal.

The first question is "Are the crustal motions from the ice sheet large enough to be observed with contemporary geodetic techniques?" Results from satellite radar and airborne laser altimeter observations of ice surface elevations indicate that the ice in the southern third of Greenland, has been changing at a rate of anywhere between $+200$ and -200 millimetres per year of equivalent water thickness. If we assume that the ice is changing uniformly within, say a 500 km radius of our bedrock location, we find that for an elastic Earth model, crustal displacements would be about 1–2 % of the ice mass change or on the order of ± 1 mm yr^{-1}. Contemporary geodetic techniques can certainly measure crustal deformation rates of this magnitude within a few years.

The experiment, then, seems simple enough. We deploy positioning or gravity instruments to bedrock locations around the Greenland ice sheet, we collect data for a few years, analyse those data to determine long-period trends, and then interpret those trends as constraints on the ice mass variability. Unfortunately, there is a catch in this seemingly simple experiment. The interpretation of the vertical deformation signal will be complicated by the fact that in addition to the elastic crustal motions caused by present day changes in ice mass, the observed deformation signal will also contain a viscoelastic contribution caused by past changes in ice load. The viscoelastic deformations are called the Glacial Isostatic Adjustment (GIA).

Viscoelastic deformations in this region are likely to be relatively large. Using a viscoelastic Earth model and the Ice-3G ice load history, the viscoelastic crustal uplift predicted at the southwestern edge of the ice sheet is estimated to be about 3.5 ± 2.5 mm yr^{-1}. However this signal can easily be a factor of two smaller or larger depending on our choice of Earth model, lithospheric thickness or ice load history. Hence, the viscoelastic crustal motions from past melting might be significantly larger than the elastic crustal motions due to present day melting and must be accurately determined and removed from the data before the observed signal can be interpreted in terms of a present day ice-mass change.

The issue of separating the elastic crustal motions due to present day melting from the GIA was first addressed by Wahr et al. [12]. In that publication the authors demonstrated that by making measurements of both gravity and vertical crustal motion at a bedrock site, the elastic and viscoelastic signals could be separated. The viscoelastic crustal motions are related to the viscoelastic changes in gravity via a proportionality constant that is independent of the choice of Earth or ice model. Hence collocated observations of crustal motions and gravity changes can be linearly combined to provide information on present day changes in ice mass, independent of GIA.

The gravity changes expected are approximately 1 μGal yr^{-1}. To observe changes of this order of magnitude, a very precise instrument with long-term stability is required. We have chosen the FG5 absolute gravimeters for our gravity observations. The instrument has a footprint of about 2m$\times$2m and weighs approximately 500 kg, including accessories such as the electronics, a heat pump, and a tent for outdoor measurements.

For both GPS and gravity, the most effective way of determining a secular signal is to make continuous observations so that these non-secular terms can be identified and removed. This can be done with GPS, by installing a permanent receiver. It is not practical, however, to make continuous absolute gravity measurements over time periods longer than about a month or so. The wear and tear on the instrument is too great. Thus, we have installed two permanent GPS receivers in Greenland but only make gravity measurements over a period of 1–2 weeks once every year, and it is the accuracy of our gravity measurements, not that of the GPS vertical coordinate, that is the limiting factor in our ability to separate the elastic and viscoelastic crustal deformations (see above). From our estimates of the accuracy levels we can achieve with these instruments, we must make gravity observations every year for the better part of a decade.

5. The walferdange underground laboratory of geodynamics (WULG) and the GRAVILUX project

In 1968, J. Flick and P. Melchior established the Underground Laboratory of Geodynamics at Walferdange (Luxembourg) with the installation of quartz horizontal pendulums of the Verbaandert-Melchior type. The quality of the site, as demonstrated by the registrations of the instruments (see Table 2), led to an expansion of the equipment housed in the laboratory. Several gravimeters (1970), long-base water tubes (mercury, 1980; magnetic, 1986; interferometric, 1989; capacitive, 1990), horizontal extensometers (long quartz tube, 1971, Ozawa superinvar, 1971, King-Bilham, 1972) and, a three meter quartz vertical extensometer (1971) were added over the next 30 years. This last experimental instrument gave surprisingly good results for determining the amplitudes and phases of the main tidal waves [1] which themselves depend on the radial derivatives of the elastic Love number h (equation (3)).

A classical seismological station was also established in the Laboratory (Sprengnether, 1973; Lennartz 3D short period, 1987; broad band Geofon, 1994; Russian long period, 1996) and, more recently, regular radon measurements have begun in cooperation with the University Centre of Luxembourg (1993).

One of the main objectives of the laboratory has been to organise tests and comparisons of high sensitivity tidal instruments in a highly stable environment. Various type of equipment from China, England, Finland, France, Germany, Russia, Iceland, Japan, Spain have been installed there for limited periods of time for evaluation.

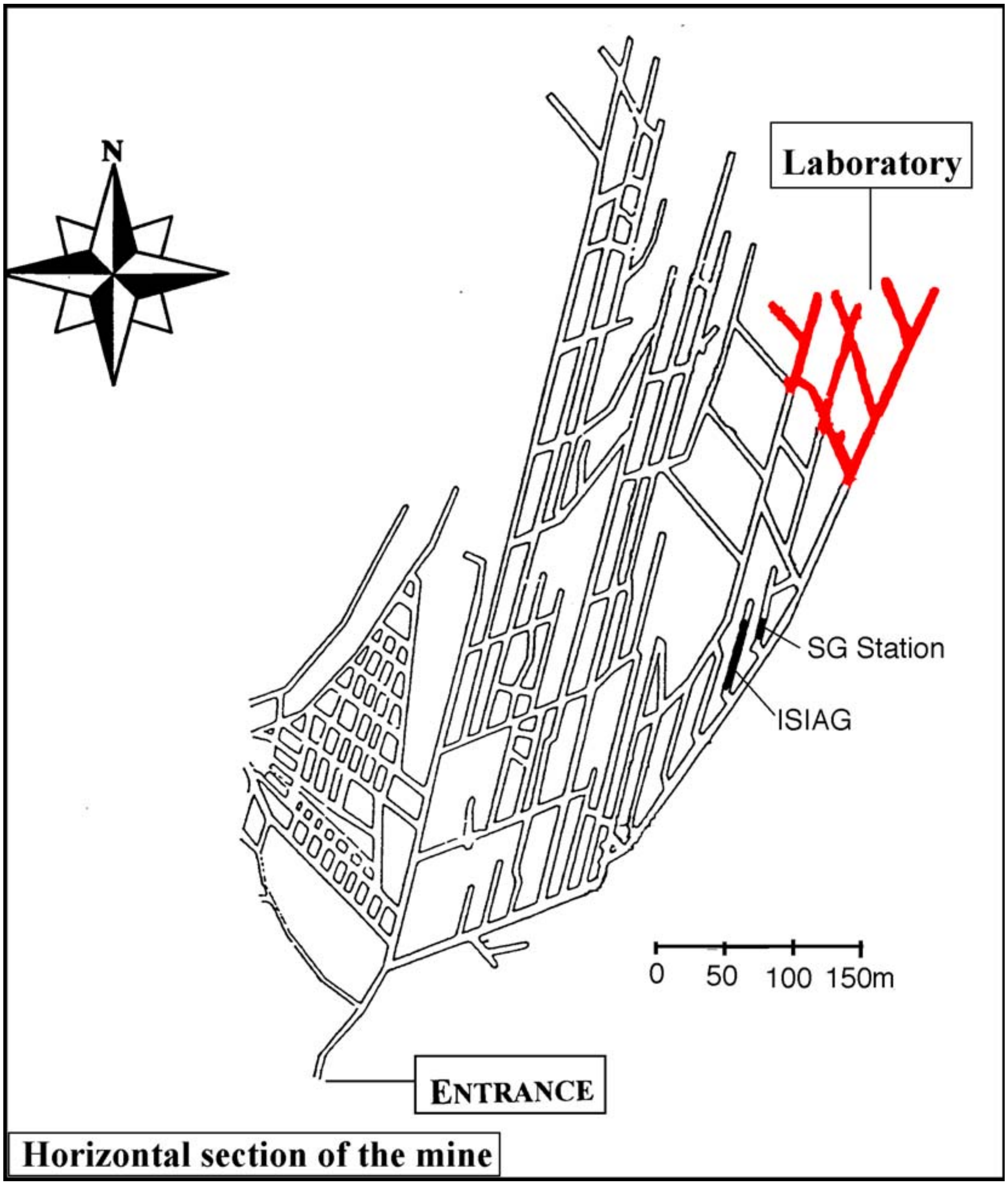
One of the most recent experimental tests conducted there was the installation of an AGI Dual Axis Resistive Bubble type tiltmeter in 1998 which has been proposed as a tool for monitoring volcanoes in active areas as well as for monitoring the stability of hydroelectric dams [14,15]. The tests have demonstrated that, in the underground laboratory (i.e. in extremely stable conditions), better performances than those quoted by the instrument manufacturer could be realised (the main tidal waves have been satisfactory derived from the registrations).

After 30 years of continuous and productive activities and considering the exceptionally good ambient conditions for high precision work and the high quality of the results obtained to date, the Luxembourg Ministry of Scientific Research decided in 1994 to increase support to the Laboratory by creating within the "Musee National d'Histoire Naturelle" (MNHN, director N. Stomp) a section dedicated to geophysics. The new scientific and technical staffs are hosted in a building acquired in the city of Walferdange, located only a very short distance from the Underground Laboratory.

Another important advance for geodynamic research within Luxembourg came when in 1998, the European Center for Geodynamics and Seismology of the Council of Europe (ECGS) jointly proposed with the MNHN, the "Institut Superieur de Technologie" (IST) and the "Administration du Cadastre et de la Topographie" (ACT), the establishment of a new project named GRAVILUX [16].

The broad aim of the project is to establish in the Laboratory a quiet gravity reference station that will allow for international comparisons of all absolute gravimeters at a seismically quiescent site in Europe becoming also a gravity reference site where temporal changes in gravity are continuously monitored.

To achieve this, two stations in neighbouring galleries were specially constructed and outfitted with power, UPS and Internet access: the smallest room ('SG station', 20m^2) will house the superconducting gravimeter (see Figure). The larger room ('ISIAG station', 150m^2), built in a dead end gallery, is large enough to accommodate as many as 15 absolute gravimeters operating simultaneously.



Horizontal cross-section of the Walferdange Mine (Grand Duchy of Luxembourg)

The acceleration of gravity at the surface of the Earth varies in time and space due to mass changes above and below the Earth's surface and changes in the height of that surface. Hence, absolute gravity observations can be used to constrain the geoid, to calibrate local gravity networks and to measure small crustal deformations such as those associated with post-glacial rebound, sea level, tectonics and environmental loading. In addition, they may also be used to monitor magmatic intrusions on volcanoes, changes in local hydrology, or changes in the ice mass of glaciers and ice sheets.

Being absolute instruments, these gravimeters cannot really be calibrated. Only some of their components (such as the atomic clock or the laser) can be calibrated by comparison with known standards. The only way one currently has to verify their good working order is via a simultaneous intercomparison with other absolute gravimeters of the same or even of a different model. Intercomparisons of this type are difficult to arrange which is why they have only officially been organised every 4 years by the Bureau International des Poids et Mesures (BIPM). This time scale is not sufficient for most users as most also regularly deploy their instruments for field observations.

In the case of regular field deployments, the users must be sure that there isn't an offset in their measured values of gravity caused by instrument malfunction. To be sure that an instrument is indeed in good working condition, the instrument needs to be regularly checked by measuring gravity in a place where gravity is well known. But as mentioned above, gravity at any given location will change with time due to Earth tides, ocean or atmospheric loading effects, or water table variations. So, gravity changes of the reference station must be carefully monitored in time. The best way to achieve this with enough precision is to continuously measure the gravity variations by means of a superconducting gravimeter. Those relative gravimeters operate by measuring the voltage required to maintain the position of a levitating sphere in a magnetic field. The field is produced by an electric current caught in a coil at the temperature of the liquid helium. At that temperature (about 4°K, i.e. -269°C), the current circulates without any resistance and produces a very stable magnetic field. Superconducting gravimeters reach a precision of a few nanogal (10^{-12} ms^{-2}), i.e. one thousandth of a billionth of the mean gravity on the surface of the Earth on diurnal and semi-diurnal periods by integrating over 2 or 3 years.

In 1997 and 1998, absolute gravity observations were undertaken in the Underground Laboratory by one of us using the FG5-202 absolute gravimeter (see Table 1). The precision (set standard deviation) of the measurements is about 1 microgal. The drop-to-drop scatter (mean standard deviation) is between 7.8 and 10.0 microgal. (For comparison, the drop-to-drop scatter is 21.4 microgals and 7.8 microgals at the BIPM and Table Mountain Gravity Observatory (TMGO), respectively, for the same instrument). This was the lowest value observed by the Royal Observatory of Belgium team with that instrument in all of 1997, confirming the quality of the WULG as a quiet "gravimetric" site. (It is interesting to note that at the time of the 1997 observations, the electronics of the FG5-202 had been not yet upgraded with the fast data rate card. And, in 1998, the superspring was not perfectly tuned due to electronic problems. We would thus expect even better performance with the new FG5).

In 2000, our staff has been increased by two geophysicists and is expected to engage two additional technical engineers in 2001. The instrumentation to support the project includes a superconducting gravimeter, which is currently being built an absolute gravimeter, which will be purchased in 2001 and other ancillary equipment necessary to support research (3 GPS receivers, a spring gravimeters, absolute barometers etc.)

Given that the aim of this paper is to dedicate the results of our personal work to Vladimir Keilis-Borok , the References have been limited to some of our most recent papers where tribute has been paid to all those who contributed to the progresses of this area of research (see [3, 17]).

REFERENCES

1. *Melchior P.* The Tides of the Planet Earth. 2nd Edition. Pergamon Press. 1983. 641 p.
2. *Dehant V., Defraigne P., Wahr J.M.* Tides for a convective Earth // J. Geophys. Res. 1998. Vol.104. P.1035–1058.
3. *Melchior P., Francis O.* Comparison of Recent Ocean Tide Models using Ground-Based Tidal Gravity Measurements // Marine Geodesy. 1996. Vol.19. P.291–330.
4. *Sloudsky Th.* De la rotation de la Terre supposée fluide à son intérieur // Bull. Soc. Imp. Nat. Moscou. 1895. Vol.9. P.285–318.
5. *Melchior P.* Theories of Polar Motion from Tisserand to Poincare (1890–1910) // Inter. Astronomical Union. Colloquium 178. 1999. Cagliari.
6. *Francis O., Dehant V.* Recomputation of the Green's functions for tidal loading estimations // Bull. Inf. Marées Terrestres. 1987. Vol.100. P.6962-6986.
7. *Yanshin A.L., Melchior P., Keilis-Borok V.I., De Becker M., Ducarme B., Sadovsky A.M.* Global distribution of tidal anomalies and an attempt of its geotectonic interpretation // Proc. 10th Int. Symp. on Earth Tides, Consejo Sup. Investigaciones Cientificas. Madrid. 1986. P.731–756.

8. *Melchior P.* A continuing discussion about the correlation of tidal gravity anomalies and heat flow densities // Phys. Earth Planet. Inter. 1995. Vol.88. P.223–256.
9. *van Dam T.M., Francis O.* Two years of continuous measurements of tidal and non-tidal variations in gravity in Boulder // Colorado. GRL. 1998. Vol.25. P.393–844.
10. *van Dam T.M., Wahr J.M.* Displacements of the Earth's Surface due to Atmospheric Loading: Effects on Gravity and Baseline Measurements // J. Geophys. Res. 1987. Vol.92(B2). P.1281–1286.
11. *Merriam J.B.* Atmospheric pressure and gravity // Geophys. J. Inter. 1992. Vol.109. P.488–500.
12. *Wahr John M., Han D., Trupin A.* Predictions of vertical uplift caused by changing polar ice volumes on a viscoelastic Earth // Geophys. Res. Lett. 1995. Vol.22. P.977–980.
13. *Melchior P., Francis O.* Proper Usage of the ICET Data Bank - Du bon usage de la Banque de Donnees ICET, Comparison with theoretical applications on Earth Models, Proceedings of the XIIIth International Symposium on Earth Tides Eds. B. Ducarme and P.Paquet, July 22-25, 1997, Bruxelles. 1998. P.377–396.
14. *d'Oreye de Lantremange N.* AGI-712 Resistive Bubble Type Tiltmeters tested in the Underground Laboratory of Walferdange // Bull. Inf. Marées Terrestres. 1998. Vol.129. P.9953–9962.
15. *d'Oreye de Lantremange N.* Long- and short-base tiltmeters for active area monitoring // Compterendu of the 86th Journées Luxembourgeoises de Géodynamique. 1999. P.12–17.
16. *d'Oreye de Lantremange N., van Dam T., Francis O.* An International Reference Station for Intercomparison Absolute Gravimeters (ISIAG) in Walferdange, Luxembourg: The GRAVILUX Project // Bureau Gravimétrique International, Bulletin d'Information. 2000. Vol.86. P.27–36.
17. *Melchior P.* Tidal Interactions in the Earth Moon System, IUGG General Assembly Vienna, 1991 // "Union Lecture" at the invitation of the President of the Union, V. Keilis-Borok - IUGG Chronicle 210. 1992.