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French gravimetry organization and its instrumental park

S. Merlet, N. Le Moigne, G. Pajot Métivier, J-D. Bernard, F. Littel, J-P. Boy, S. Rosat, G. Gabalda, L. Seoane, S. Bonvalot, C. Champollion, A. Mémin, M. Maia, O. Charade

The Action Spécifique Gravimetry of the French Research Infrastructure Epos-France is based on a mutualized national instrumental park offering scientific teams a range of measurement resources and services for the gravity field studies. It is driven by an office which aims to manage all activities in the field and runs the park. The range of instruments includes absolute and relative gravimeters of different classes and technologies. It allows covering a vast array of applications with which, among other things, it maintains the French observation networks, the "measurements" component of the Service National d'Observation Gravimétrie in France.

Introduction

Epos-France is a research infrastructure (RI) in the field of solid Earth, dedicated to observation. Its aim is to advance knowledge of the Earth system in all its diversity and complexity. Gravimetry research and activities take part to the RI through the Action Spécifique Gravimetry (ASG). The complexity and level of performance of the instruments used in this domain make them relatively expensive sensors, both to purchase and to maintain. Moreover, some institutes and research teams do not require the permanent availability of instruments. As a consequence, researchers have organized themselves to buy and share instruments in common. Launched in the mid-1990s, the national park is the result of decades of investments by French teams in the acquisition of gravimetric measurement equipments for academic research and the establishment of reference networks. It responds to numerous fundamental or applied research applications in geodesy, geophysics, geology, hydrology, oceanography and metrology. The paper presents the organization, its objective and missions to detail the park of instruments it manages.

The objectives and the subsequent organization

The main objectives of the French organization are to :

- federate the French community around national measurement resources in gravimetry, absolute and relative, continuous and repeated,
- maintain and make available to the scientific community, reliable, metrological instrumentation, traceable to the SI and modern, meeting the needs of users,
- exchange expertise in the acquisition, processing and exploitation of gravity measurements,
- maintain the Networks of Repeated and Permanent Observations of Service National d'Observation (SNO) Gravimétrie,
- support research and development activities in the field of terrestrial gravity measurement,
- integrate and promote the work carried out by the user community, both within the framework of national infrastructures and within the framework of gravity observation strategies promoted by international organizations (in particular : Association Internationale de Géodésie (AIG) and Comité Consultatif des Masses et Grandeurs associées of the Comité International des Poids et Mesures (CIPM-CCM)).

To achieve this, the organization is based on the National Instrument Park (PIN) PGravi and measurement sites, and is structured around the following three issues: i) Temporal monitoring; ii)

Metrology and iii) References & Imaging, as summarized in figure 1. The SNO Gravimétrie includes contributions to:

- the international scientific services of IAG, including the central offices of the Bureau Gravimétrique International (BGI) and the International Geodynamics and Earth Tide Service (IGETS),
- the monitoring of the observation networks: the Permanent Gravity Network (RPG) and the Repeated Gravity Networks (RRG). The RPG is composed of five multi-instrumented stations in France, four of which collocate absolute measurements with measurements of temporal variations in gravity using permanent superconducting gravimeters. The RRG is divided in four parts : the RRG tide gauge (four stations), the RRG Polar (five stations), the RRG calibration line (three stations) and the RRG collaborative (four stations).

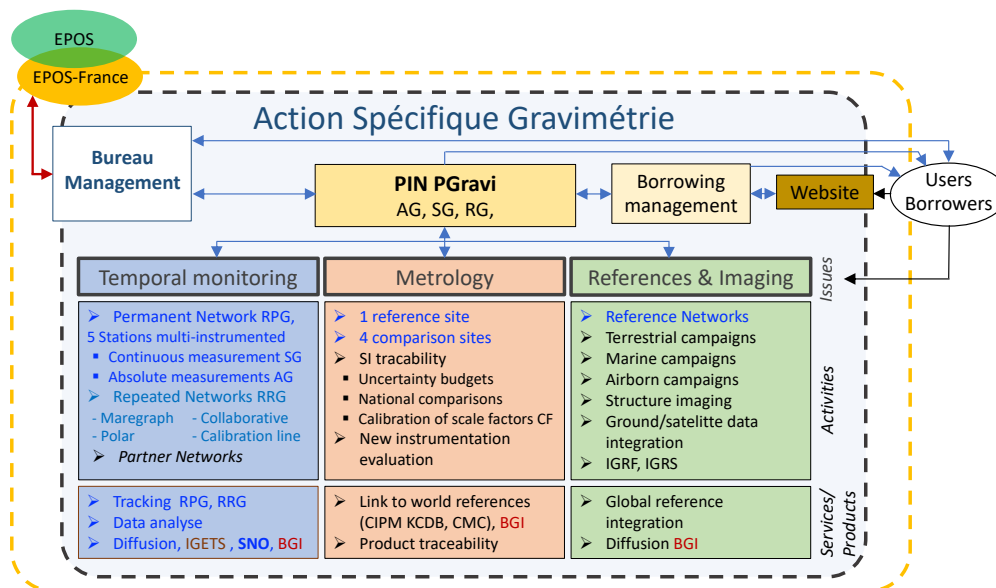


Fig. 1. Schematic of the French organization and management of its instrumental parc PGravi, of Epos-France research infrastructure. AG: Absolute Gravimeter, SG: relative Superconducting Gravimeter, RG: Relative spring Gravimeter, CF: Calibration Factor, RPG: Permanent Gravity Network, RRG: Repeated Gravity Network. SNO components are shown in blue.

The ASG is led by Institut National des Sciences de l'Univers of Centre National de la Recherche Scientifique (CNRS-INSU) through a consortium of research laboratories most involved in the acquisition and implementation of gravimetric measurement resources. It is run by a single office. The coordinator, also in charge of the PIN PGravi provides the link between the technical part of the park and the scientific aspects. He interacts with members in charge of the three issues of the ASG and the head of the SNO Gravimétrie, the BGI and IGETS, both in charge of collecting, validating and disseminating gravity data acquired with the means of the instrumental park. The technical park manager is in charge of all technical and budgetary aspects. He is the main contact for users on technical hardware, software and logistical issues. PGravi instruments are available to the national scientific community. Their use is governed by a charter. Borrowing requests are made exclusively via an online website.

As part of the innovative developments underway in the field of quantum sensors, the instruments of the PIN PGravi enable the ASG to work with manufacturers from national research and

metrology laboratories to develop and validate new generations of gravimetric sensors that can be easily used by operators. The new measurement possibilities offered by these new instruments mean that both users and designers need to work together to make the most of the new potential of quantum sensors.

The instrumental park

The instrumental park is made up of absolute and relative gravimeters of different classes and technologies. These different sensors can measure spatial or temporal variations in gravity with accuracies ranging from a few 10^{-8} g to a few 10^{-11} g. They are used in laboratories for characterization, calibration, instrumental monitoring or comparison, as well as for permanent or semi-permanent measurements. Some are used in the field while others are dedicated to continuous monitoring of gravity variations.

The absolute gravimeters

Absolute gravimeters (AG) are the metrological references guaranteeing the traceability to the SI of the measurements made with all the gravimeters of the park, and therefore the quality of the resulting products.

The absolute measure of gravity is to observe an object falling in a vacuum. The trajectory, and therefore the positions of the object over time, gives access to an acceleration in m s^{-2} . Providing a ruler and a clock linked to the SI definitions, make the measurement absolute. The principle is represented in figure 2. The first type of instrument measures the free fall of a corner cube relatively to another reference one isolated from ground vibrations, using a Michelson optical interferometer as displayed on figure 2 b). The displacement of the corner cube along the equiphase planes causes the scroll of interference fringes measured by an avalanche photodiode (APD). The optical distance difference between the two arms of the interferometer is a function of $1/2gt^2$. The quantum gravimeters use free-falling cooled cloud of atoms as a test mass. Its acceleration is measured by atom interferometry which exploits the wave-like nature of matter and the possibility of manipulating 'atomic waves' with lasers. It allows to create an atom interferometer, displayed on figure 2 c), such as the Mach-Zehnder optical one [1]. This measurement is equivalent to measuring the position of the atoms at three instants of their fall using a ruler whose accuracy is linked to the knowledge of the wavelength of the lasers as represented on figure 2 d). According to the size of the vacuum chamber, these instruments measure at least one time per second. Moreover being absolute, it can measure continuously. To reject ground vibrations, ones combine an isolation platform and a seismometer whereas other stands directly on the ground and use an accelerometer [1]. The second type is adapted for field measurement and first for laboratory.

PGravi has five such instruments of different technologies:

- 2 Absolute corner-cube gravimeters - Micro-g LaCoste FG5X #206 and FG5 #228
- 2 Absolute matter-wave gravimeters - Exail AQG-B01 and AQG-A01 (field and laboratory instruments respectively)
- 1 Absolute matter-wave gravimeter - CAG (experimental laboratory metrology instrument)

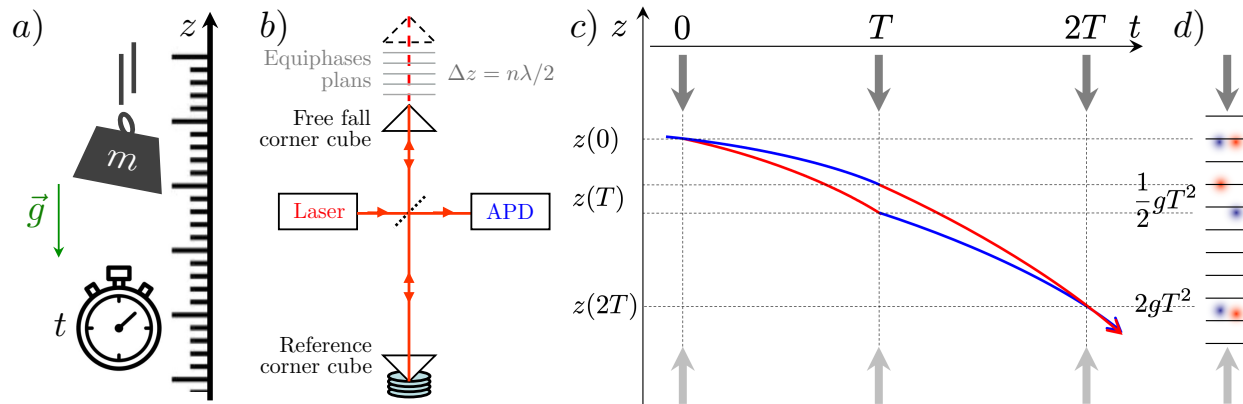


Fig. 2. Absolute Gravimetry measurement principles. a) general principle, positions (z_i) and associated time (t_i) of a mass free falling are measured with a ruler collinear to z and g , and a clock, b) free fall corner cube gravimeter principle (APD: avalanche photodiode), c) spatial and temporal representation of an atomic interferometer driven by three laser pulses (in grey) separated by a duration T , and d) the actual arrangement of the laser beams in the vertical direction in which the atoms in blue and red, fall freely.

FG5 mechanical parts allow for a free fall each 3 s [2]. Usually, operators perform one free fall every 10 s or more during 100 shots each hour to take care of the instrument. According to international comparisons results, these instruments allow for accuracy in between 30 nm s^{-2} and 50 nm s^{-2} and sensitivity below 10 nm s^{-2} in 1 000 s. This class of AG is the most used in the world. They are generally used in laboratories but with protections and with stable temperature, they can also be used outdoor. Movable, they are used for absolute determinations of gravity for reference networks, such as ones of the SNO Gravimétrie RPG and RRG or to monitor temporal variations. They are also used to calibrate the scale factors of relative instruments and to monitor the drift of superconducting relative gravimeters (SG) [3]. These instruments generally perform 20 measurements per year, half of which are on the SNO RPG and RRG networks.

AQG-A01 is the prototype developed by muquans for first tests which lead the company to develop the thermalized B version for on field applications [4]. AQG-B01 is still assessed in conjunction with the manufacturer which is now part of Exail. It exhibits accuracy between 100 nm s^{-2} and 150 nm s^{-2} and can reach sensitivities better than 10 nm s^{-2} after 3 000 s of measurement [4]. Whereas the FG5 can be used on the field with some protection and under stable temperature conditions, the AQG-A01 operate in laboratories and the AQG-B01, thank in part to its temperature regulations, is fully designed for on the field applications [5]. The Cold Atom Gravimeter (CAG) is a laboratory standard developed at LNE-SYRTE, it only works in climatized room or where temperature is stable such as in mines or tunnels [6]. After participating to several international comparisons since 2009 [7], the studies carried out have made possible to bring its accuracy at the 20 nm s^{-2} level and to reach sensitivity of 0.5 nm s^{-2} after 10 000 s [8]. Current developments aim to push back the now well-known limits and make the instrument automated for absolute continuous measurement in the 10^{-10} range, both in term of accuracy and stability.

Due to their complexity and fragility, the FG5, AQG-A01 and CAG are difficult to use by inexperienced personnel. They are 'loaned' in the form of measurement campaigns carried out by park staff in charge of these instruments. On the contrary, AQG-B01 has been acquired to be loaned and used by all and any geophysicist wishing to have access to an absolute and/or continuous measurement for their studies. An initial loan experiment was carried out in early 2023 [5] for a gravity campaign in Guadeloupe, the followings are in preparation. Temporal continuous

acquisitions of 6 or 12 months are for exemple planned for RRG maregraph measurements and others for continuous monitoring and/or mapping in hydrology domain. Before shipping the AQG, a half a day training session is organized to discover the instrument and allow borrowers to put it back into operation, alone, for their application.

The absolute gravimeters are nationally compared and one of them takes part to international comparisons after being prepared and metrologically evaluated at the French National Metrology Institute LNE facilities (see fig. 3). Other French institutes owners of absolute gravimeters are invited and also take part to the national comparison, moreover, they can easily access to RPG stations to check the capabilities, or simply the proper functioning, of their instruments before and after their measurement campaigns. According to the number of AG involved, such comparisons are organized in one of the four RPG stations. They are also an opportunity to determine the calibration factor (CF) of the SG of the RPG stations with different sensors.

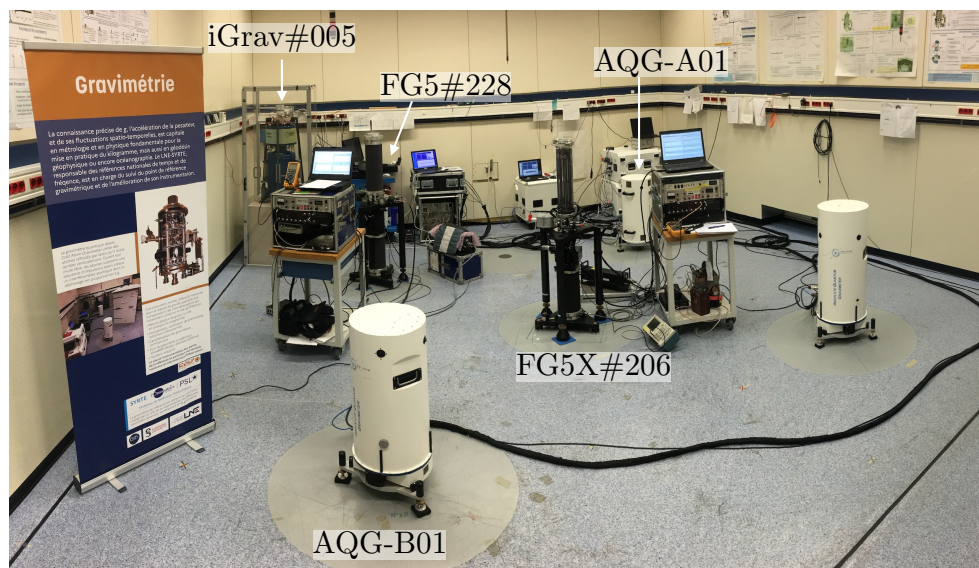


Fig. 3. Comparison of four PGravi absolute gravimeters and an invited AQG at the gravimetry reference station RPG TRAP at LNE. This comparison in 2022 was also the opportunity to test previous SG iGrav#005 calibration factor determinations, previously only performed with the CAG.

The relative gravimeters

The principle of relative gravimeter is to hold a mass in a fixed position, subject to gravity and an adjustable force in the opposite direction. The feedback required is directly proportional to a gravity variation. The force that compensates gravity is obtained with a spring or superconducting magnetic field. The scale factor of these sensors then have to be periodically measured. Also, as the efficiency of the involved force evaluates the sensor response drift.

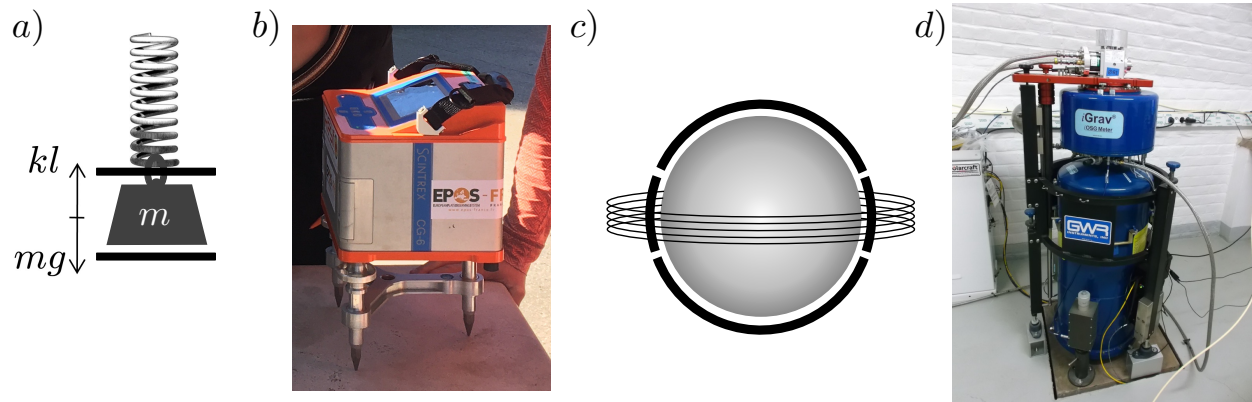


Fig. 4. Relative gravimeters and principles. a) General principle, the weight of a mass is balanced by a spring force kl . Bold black lines are the capacitance bridge. b) Picture of a Scintrex CG6 gravimeter, a spring gravimeter (RG) based on a) principle. c) Same picture than a) with a levitating superconducting sphere as a mass, and coils to generate the counterpropagating force. Bold black lines are the capacitance bridge. d) Picture of iOSG#023, a superconducting gravimeter based on c) principle.

Spring gravimeters The principle and an example of Scintrex CG-6 spring gravimeter [9] are displayed on figure 4 a) and b). They are very compact and easy to use, moreover, technology allow the manufacturer to improve each new version making them smaller and, above all, lighter which make these sensors extremely suitable for on field campaigns. The main disadvantages are linked to the spring which is sensitive to temperature variation and its stiffness evolves with the age of the sensor. To remove the drift during a mapping, repeated measurements on a or several stations are necessary. These instruments are mainly used for cartographic surveys, to be linked to absolute measurements, but also to determine the vertical gradient of gravity, which is necessary for absolute measurements. PGravi has now six of such Scintrex spring gravimeters, three of last version CG6 and three of previous version CG5. This class of instruments, easily used by most of geophysicists, are the most widely borrowed sensors of PGravi. The five sensors, the last being just received, were immobilised for 180 weeks in 2023, i.e. 70% of the time, for 65% of on field missions and 12 % for teaching, the remainder having been dedicated to manufacturer maintenance and calibrations. It represents more than 40 loans which durations vary from a day to close to two years. Some requests include from one to four sensors. The goal of the loan differ from missions and borrowers applications, and instruments travel all over the world. The park technical personal calibrate the scale factor of the sensors with the calibration line of the SNO RRG network and assesses the proper functioning of the instruments before they are sent out for loan. If requested, a training session is organized for the borrower.

Continuous superconducting gravimeters Figure 4 c) and d) displays an example of superconducting gravimeters and a detail of the sphere, levitating in the superconducting magnetic field [10]. Although these instruments operate at cryogenic temperatures (4.2 K) in order to maintain the superconducting state of the Niobium sphere, the latest improvements allow the use of helium gas, which the instrument liquefies. The technology which could be a disadvantage is indeed a force as these sensors offer a better sensitivity on gravity measurements and a low drift that after one or two year is quite linear. These gravimeters manufactured by GWR are installed at sites to monitor continuously during months, the variations of the gravity field. PGravi equips four

sites in France with such instruments, the Strasbourg Gravimetric Observatory for several decades (see fig. 5) and the other sites from 2011. These instrumented sites are part of the RPG of SNO Gravimétrie, and as the superconducting gravimeters are permanently installed there, they can not be borrowed. The scale factor of these instruments and the monitoring of their drift are ensured by periodic absolute measurements with AG.

PGravi has two types of these instruments:

- 2 GWR iOSG : #023 at Strasbourg (STJ9 station) and #024 at Rustrel (RUST station)
- 2 GWR iGrav : #002 at Larzac (LARZ station) and #005 at Trappes (TRAP station)

As well as being a national contribution to world monitoring of temporal variations in gravity, carried out from a set of permanent observatories housing superconducting gravimeters, the instruments and the stations in which they are continuously measuring, allow for local stations available for users to check and control their instruments.

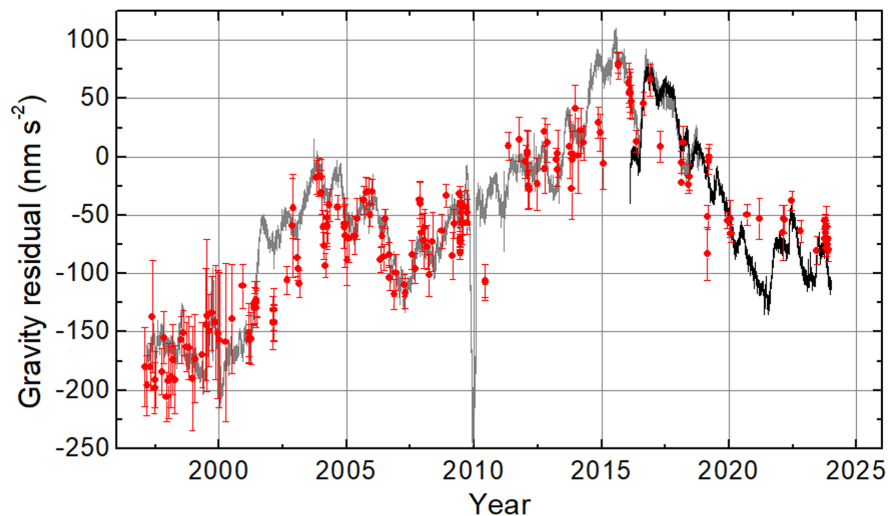


Fig. 5. Continuous gravity measurement corrected from tides, atmospheric and polar motion effects at RPG STJ9 station since 1997 with, in gray superconducting gravimeter C026 which has been replaced by iOSG#023 (in black). The drifts are corrected by absolute measurement of gravity close to the instrument with AG FG5#206 ungraded in FG5X, AG measurement are represented in red.

Summary

Table 1 summarizes the features and some characteristics of the fifteen PGravi instruments.

Type	Name	Technology	ν (Hz)	U (nm s ⁻²)	σ_g (nm s ⁻²)	Applications	Environmental conditions	Share / movable	Localisation / gestion
AG	FG5X-206	FFCC	0.1	30-50	10 @ 10 ³ s	Local absolute measurement, SG monitor	Laboratory and on the field (with low temperature variations)	Yes with operator / movable	Strasbourg
	FG5-228				3 @ 10 ⁴ s				Montpellier
	AQG-A01	FFCA Atom Interferometry	2	200	10 @ 4.10 ³ s	Local absolute reference	Laboratory with small temperature variations	No	Toulouse
	AQG-B01			100 (150 outside)	3 @ 2.10 ⁵ s	Local absolute measurement, SG monitor	Laboratory and on the field (0°C ; 40°C)	Yes after training / very movable	Montpellier / Trappes ...
	CAG			3	20	10 @ 36 s 0.6 @ 2.10 ⁴ s	Metrological reference, Local absolute measurement, SG monitor	Laboratory environment with very low temperature variations (1°C)	No / Movable to other places with operators
RG	3 CG5	Spring	6	NA	10 @ 50 s	Survey, links between stations, vgg evaluation	On the field (-35°C ; 45°C)	Yes / Extremely movable	Paris / Montpellier
	3 CG6				5 @ 200 s				
SG	iOSG-023	Superconductivity	12	NA	0.1 @ 600 s	Local continuous gravity monitoring	Laboratory / Observatory	No, RPG are accessible for instrumental check and comparisons of AG	Strasbourg
	iOSG-024								STJ9
	iGrav-002								Rustrel RUST
	iGrav-005								Larzac LARZ Trappes TRAP

Tab. 1. Table of PGravi instruments with some features, capabilities, characteristics and applications. AG: Absolute Gravimeter, RG: Relative spring Gravimeter, SG: relative Superconducting Gravimeter, vgg: vertical gravity gradient, U : uncertainty and σ_g : stability in an averaging time (values are given as example of obtained sensitivities, they differ with respect to noise during the measurement and so according to environmental conditions), NA: Non Applicable, RPG: Permanent Gravity Network.

Data

As indicated in the PGravi charter, data acquired with PGravi instruments must be available for public access via the ASG, no later than three years after the start of the measurement campaign. For long missions, this embargo period may be extended to a total of four years following a specific request from the borrower to the park manager. Both relative and absolute data have to be transferred to BGI which is responsible for archiving, validating and distributing the gravity measurements acquired worldwide. A DOI provided by BGI is assigned to dataset or networks and soon, also to AG instruments and networks. The measurements can be accessed at <https://bgi.obs-mip.fr/gravity-databases/>, where they are classified according to type: terrestrial relative data, obtained with RGs and absolute data, obtained with AGs. For AG data, BGI and BKG have continued their effort to restore the international Absolute Gravity database AGRV. A new web interface is accessible on-line at the above mentioned link. AG data will contribute to the International Terrestrial Gravity Reference System & Frame ITGRS/ITGRF [11]. In addition, PGravi absolute measurement data from the SNO observation networks are also accessible on the SNO database (<https://gravimetrie.epos-france.fr/recherche/service-national-dobservation->

[gravimetrie/](#)) as raw data and other data products from the superconducting relative gravimeters (SG) which makes all the data accessible. In the future, links to access to data will also be accessible via EPOS when a Thematic Core Service (TCS) [12] dedicated to Gravimetry will be created and validated.

Conclusion and prospects

The french instrumental park PGravi is composed of 15 instruments, absolutes and relatives of different class and different technologies, allowing measurements down to the 10^{-11} g level, for various applications, from on field mapping to static continuous monitoring. They are used for national survey services and shared for users that can loan them from request for different scientific projects all over the world. The absolute instruments are the cornerstones of PGravi as they allow for traceability to SI of the products obtained with the PGravi instruments. They allow to maintain the French observation networks, the "measurements" component of the SNO Gravimétrie in France and contribute to the realization of observation campaigns or networks. Data obtained with PGravi sensors are freely accessible via BGI, IGETS and SNO databases. The park include personal highly involved to perform measurement, maintain the instruments, prepare them for missions and loan and assist the borrowers in their projects. Moreover these activities, they evolve with technology improvements. The staff looks for, develop or help to the development of new sensors with manufacturers.

In the future, less requested old generation spring gravimeter CG5 may be adapted for continuous gravity measurements applications for which a superconducting gravimeter would not be adapted, for the mission duration, the place and environment or quite simply budget reasons. For this purpose also, the acquisition of a Micro-g Lacoste g-Phone X [13] is also under consideration without taking priority over the rejuvenation of PGravi instruments. According to the evolution of the national missions, services and requests of borrowers, the range of instruments will also evolve. The acquisition of new dual absolute quantum sensor allowing for gravity and vertical gravity gradient measurements [4] is also studied. The budgets requested to acquire this higher cost instrument, and the associated prospects, also lead to a wider reflection rising to which on the interest of onboarded sensors based on quantum technologies [14]. National and European strategies are interested, or could be interested, in facilitating the multiplication of quantum sensors on the ground, in networks and onboard. The budgets required for such a wide instrumental park could be envisaged within the creation of an European Research Infrastructure in order to pool resources and infrastructure such as the PGravi park, to share quantum instruments with the goal of improving the products that EPOS could make available once TCS Gravimetry is operational.

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