SPACE ACCELEROMETERS FOR MICRO AND NANO SATELLITES
Fundamental Physics and Geodesy missions from MICROSCOPE, GOCE and GFO return of experience

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ABSTRACT

ONERA's department of Physics has developed for 50 years high performance accelerometers for space science. In 2017, the CNES MICROSCOPE mission, proposed by the Observatoire de la Cote d'Azur and Onera, showed outstanding results in fundamental physics. Thanks to the accelerometers, it delivered the best result ever on the test of the Equivalence Principle, cornerstone of the General Relativity. In 2013, the ESA GOCE mission, embarking 6 electrostatic accelerometers, gave the best Earth gravity map. More recently, the two JPL GFO satellites were launched and delivered results for the Geodesy community following 15 years of measurement with GRACE.
For future missions, taking advantage of our laboratory legacy, a more compact accelerometer is under development for science on board microsatellites or nanosatellites. After an overview of the performance achieved in the last decades, the presentation will focus on future developments addressing geodesy and fundamental physics on small satellites or nanosats.

1. INTRODUCTION

Building on a legacy dating back to 1964, the department physics has since been developing space accelerometers with increased sensitivity and performance. This improvement allowed envisaging space applications to Fundament Physics and Geodesy.
The first accelerometer flight in 1975 embarked a three-degrees of freedom accelerometer with a spherical test-mass (Figure 1) on the CNES Castor (D5B) satellite [1]. On a 270km-1270km elliptical orbit, CACTUS measured the non-gravitational accelerations applied to the satellite due to Earth and Sun radiation pressure or the Earth residual drag at 10^{-9}m/s² level.
The success of this flight helped to go further on studies for Geodesy applications. The ARISTOTELES ESA program aimed at measuring accurately the gravity gradients. For this purpose at the end of the 80's, a new accelerometer called GRADIO [2] was developed with 6-degrees of freedom acceleration output. The core of the accelerometer comprised here a parallelipedic test-mass (Figure 1) which is electrically connected through a 5µm diameter gold wire. This configuration has several advantages with respect to CACTUS totally free test-mass: maintains a more stable electrical voltage on the test-mass, prevents patch field to move as in the free CACTUS rotating test-mass, delivers angular accelerations. Even if the program of ARISTOTELES was cancelled in the 90's, it helped to develop a new generation of accelerometer. The first flight of this second generation of accelerometers was performed with ASTRE [3] in 1996 on board the NASA Columbia shuttle thanks to an ESA program. After the flight success, it flew again on the shuttle in 1997. ASTRE was a degraded version of GRADIO with similar resolution than CACTUS and sufficient high range to sustain the shuttle environment.
Then, a series of accelerometers[4] were developed as STAR for the CHAMP mission and SuperSTAR for the GRACE mission, respectively 10^{-9}ms^{-2}Hz$^{-1/2}$ and 10^{-10}ms^{-2}Hz$^{-1/2}$ resolution. Derived from ASTRE with improved resolution, these accelerometers were embarked on 500kg satellite class.
This paper details the application on such mini-satellites which leads to develop the highest accurate geodesy mission, GOCE, developed with a GRADIO type accelerometer from 2000 to 2018. This experience leads to give confidence on the technology which was adapted to a microsatellite mission of

CNES, MICROSCOPE [5], aiming at testing the foundation of the general relativity to one part over 10^{15} in 2016.
Today, this technology is derived to study smaller configuration that should equipped nanosatellites or mini-satellites to test physics in space or follow the NASA GRACE program.

Figure 1: Cactus accelerometer core (Left); GRADIO type accelerometer core (right)

2. PRINCIPLE OF OPERATION

The principle of operation of the accelerometer is based on the electrostatic control of a test-mass (TM) about its 6 degrees of freedom. The test-mass is submitted to electrostatic forces (F), to parasitic forces (Fp) and to the gravity.

$$\frac{d^2x_E}{dt^2} = \frac{1}{m}F + \frac{1}{m}F_p + g(x_E) \qquad (1)$$

With x_E the coordinates of the TM in the Galilean frame.

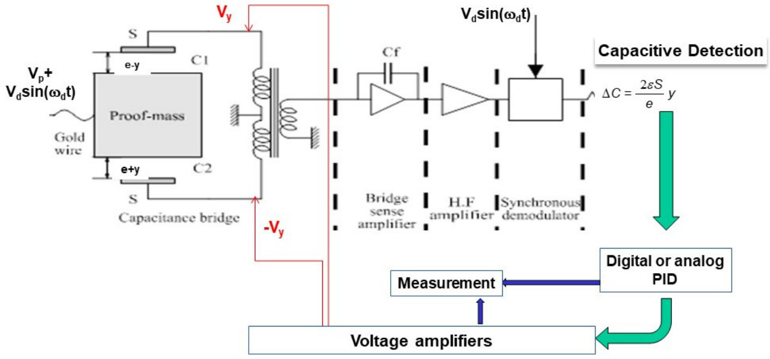
The satellite is submitted to external force (F_{ext}) like the drag, to propulsion thrust (F_{th}) and to gravity:

$$\frac{d^2x_{SE}}{dt^2} = \frac{1}{M_{sc}}F_{ext} + \frac{1}{M_{sc}}F_{th} + g(x_{SE}) \qquad (2)$$

With x_{SE} the coordinates of the spacecraft in the Galilean frame.
When the TM is at the CoG, the acceleration measurement a_y is inferred from the measurement of the voltages applied on the electrodes and thus:

$$a_y = \frac{1}{m}F = -\frac{1}{m}F_p + \frac{1}{M_{sc}}F_{ext} + \frac{1}{M_{sc}}F_{th} \qquad (3)$$

In case of the accelerometer is not at the CoG, the TM is submitted to Earth gravity gradient and to the angular motion of the satellite, that generates an inertia gradient: additional terms have then to be considered in equation (3).
The electrostatic forces are expressed as in Figure 2 for one degree of freedom. When the TM is servo controlled, its residual motion is very small (nano-meter to pico-meter). With a DC voltage Vp, applied on the TM and opposite voltages Vy on each electrode surrounding the TM (Figure 2), then the electrostatic force is at first order linear in Vy and Vp.
The parasitic forces can be due to gradient of temperature between the two opposite sides of the TM (radiometer effect or radiation pressure) or to contact potentials that generates additional electrostatic forces. A detailed description is performed in the case of the MICROSCOPE mission in Reference [6].



$$F = F_1 - F_2 = \frac{1}{2}\left[\frac{\partial C_2}{\partial y}\left(V_y - V_p - V_d \sin(\omega_d t)\right)^2\right] - \frac{1}{2}\left[\frac{\partial C_1}{\partial y}\left(V_y + V_p + V_d \sin(\omega_d t)\right)^2\right] \qquad a_y = F/m \sim -\frac{2\varepsilon_0 S}{me^2} V_p V_y$$

Figure 2: Control loop of one TM degree of freedom

3. OBTAINED RESULTS

3.1. In Geodesy

ONERA has delivered 10 accelerometers in the period [2000-2017] and integrated in mini-satellites. The first one on the CHAMP satellite for a GeoForschungsZentrum (GFZ) mission dedicated to Earth gravity and magnetic mapping. CHAMP was launched by Kosmos-3M in Plessetsk and followed a quasi-circular polar orbit (87.3°) at 454km of altitude from 2000 to 2010. A GPS receiver gave the precise orbital position and was associated to the STAR accelerometer measuring the satellite non-gravitational forces. These measurements allowed establishing the best Earh's gravity field model at that time in 2002: Eigen-1s [7]. The spectral resolution of this model was about 10cm up to degree 30 corresponding to a 600km spatial resolution, thanks to the accelerometer reaching 3×10^{-9}ms^{-2} within the bandwidth [10^{-4}-10^{-3}] Hz. After 33 months of mission, this first Geoid was improved with different versions until the Eigein-3p model version which reached order 65 with a spatial resolution of 300km.

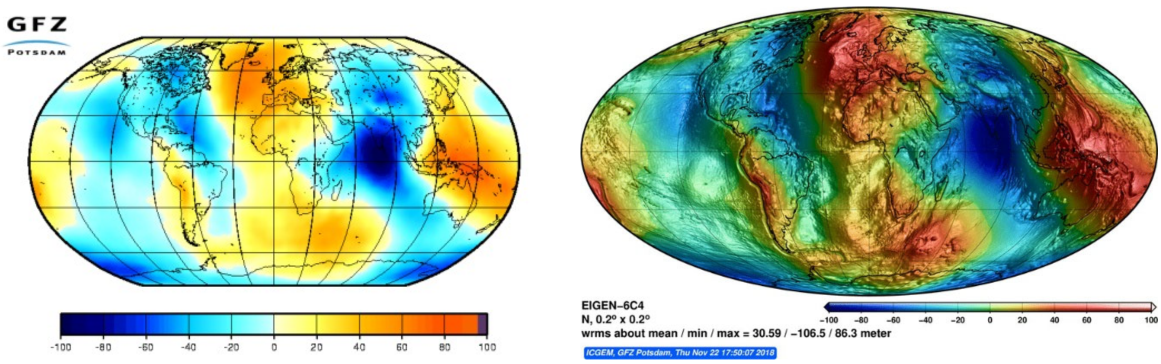


Figure 3: Left: EIGEN-1S Geoid (a=6378136.46, 1/f=298.25765) in meter [Credits http://op.gfz-potsdam.de/champ/results/grav/004_eigen-1s.html]; Right: Geoid undulation computed from the EIGEN-6C4 combined gravity field model (CHAMP, GRACE, GOCE) expanded up to a degree and order of 2190, Credits [8].

The success of CHAMP motivated the DLR to cooperate with NASA on the Gravity Recovery And Climate Experiment (GRACE an GRACE-Follow on, ie. GFO). The two GRACE mini-satellites were launched in 2002 about 200km apart on a polar orbit (89° inclination) at an initial altitude of 500km with a Rockot launcher from Plessetsk. Deorbited in December 2017 and March 2018, the mission was continued by the launch of the two satellites of GFO in May 2018 with a Falcon 9 from Vandenberg. GRACE and GFO are very similar and aims to map the Earth's gravity and its seasonal variations. These satellites embarked an improved version of STAR called SuperSTAR. The distance between the two satellites is evaluated by a micro-wave satellite to satellite tracking and complete in GFO by a laser ranging interferometer. This data added to the satellite non-gravitational forces measured by

SuperSTAR, to the orbit position by the GPS and to the star-tracker attitude measurement improved significantly the CHAMP performance. SuperSTAR had a resolution of 10^{-10}ms^{-2}Hz$^{-1/2}$. Beyond a better accuracy, GRACE program brought also an original exploitation of the geoid maps by observing their monthly variations and their link to climate, ocean circulation, ground water depletion and hydrology. Geophysics is also one application of GRACE missions to better understanding the Earth body.

The increased performance obtained with CHAMP and GRACE family mini-satellite and increased interest in Geodesy science from space data led ESA to launch the GOCE mission in 2009. The one-ton satellite placed at a 250km heliosynchronous orbit (96.5° inclination) comprised 6 accelerometers integrated by pair along the 3 axes (see Figure 4). The principle of operation is here quite different: the difference of accelerometer measurements of one pair give directly the gravity gradient once the angular effects are subtracted. Start tracker measurements combined to the angular accelerometer outputs allow determining the centrifugal and angular acceleration perturbing effects.

$$V(x,y,z) = \frac{GM}{r}$$

$$\vec{g}(x,y,z) = \vec{\nabla} V$$

$$grad(\vec{g}) = \frac{\partial^2}{\partial i \partial j} V = \begin{bmatrix} V_{xx} & V_{xy} & V_{xz} \\ V_{xy} & V_{yy} & V_{yz} \\ V_{xz} & V_{yz} & V_{zz} \end{bmatrix}$$

$$V_{xx} + V_{yy} + V_{zz} = 0$$

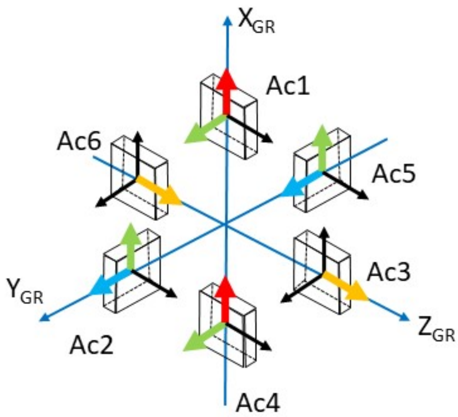


Figure 4: Electrostatic Gravity Gradiometer principle of measurement. 6 parallelipedic accelerometer test-masses are associated by pair along the 3 axes. The combination of 2 or 4 TM measurements determines the components of the gravity gradient matrix. In the schema, some examples of measurement combinations are colored with the same color as the corresponding matrix component.

In GOCE the accelerometer is the update version of GRADIO/ARISTOTELES with a digital control of the test-masses at the difference of ASTRE, STAR or SuperSTAR with analog control loop. In flight, thanks to the digital controller, it was possible to match alignments and scale factors and then to reach the outstanding resolution of about $(3\ to\ 6) \times 10^{-12}$ms^{-2}Hz$^{-1/2}$, almost two orders of magnitude better than GRACE.

3.2. In Fundamental Physics

Fundamental Physics in space is a particular domain asking for challenging performance and technologies. In 1999, ONERA in collaboration with OCA proposed to test the Equivalence Principle (EP) in space with the objective to improve the current accuracy by 2 to 3 orders of magnitude.
The MICROSCOPE mission relies on a 300kg and 2m^3 micro-satellite of the CNES MYRIADE line. The micro-satellite was launched in 2016 as a passenger of a Soyutz launcher in Kourou and placed on a circular orbit at 710km altitude. It was deorbited in 2018. The payload is composed of two differential concentric accelerometers [6] (see Figure 5). The first analyses performed in 2017 on only 7% of data allowed to claim that the EP is still valid at 2×10^{-14}, one order of magnitude better than current best experiments [5]. The performance of the accelerometer has reached a resolution of 10^{-11}ms^{-2}Hz$^{-1/2}$ with the help of the drag-free and attitude control of the satellite better than 10^{-13}ms^{-2} over 120 orbits (8.5 days) along the 3 axes. The drag-free and attitude control of the satellite about its 6 degrees of freedom made use of 2 star trackers hybridized with the angular acceleration outputs provided by the accelerometers and made also use of the science accelerometer outputs for the linear control. In 2022, a collection of papers have been submitted and should very soon been released giving the final result of the process of all data. This final analysis improveed the accuracy of the test by an additional one order of magnitude.

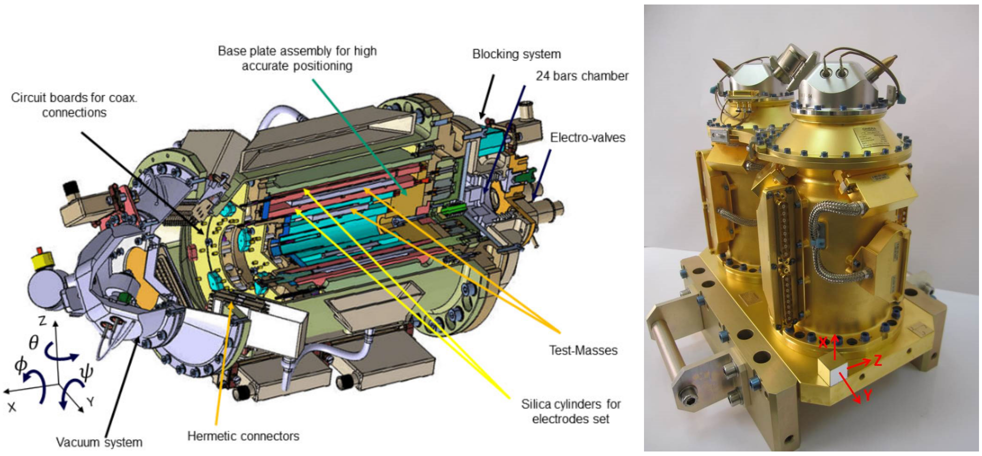


Figure 5: Left: Cut-off drawing of a differential accelerometer. Right: picture of the flight model mechanics with the two differential accelerometers mounted on a reference place that supports an optical cube for alignments.

4. FUTURE DEVELOPMENTS

The next generation of Geodesy mission have to deal with two aspects: the continuity of the measurements of the GRACE program survey of gravity seasonal change and the need for better accuracy of the spatial resolution.

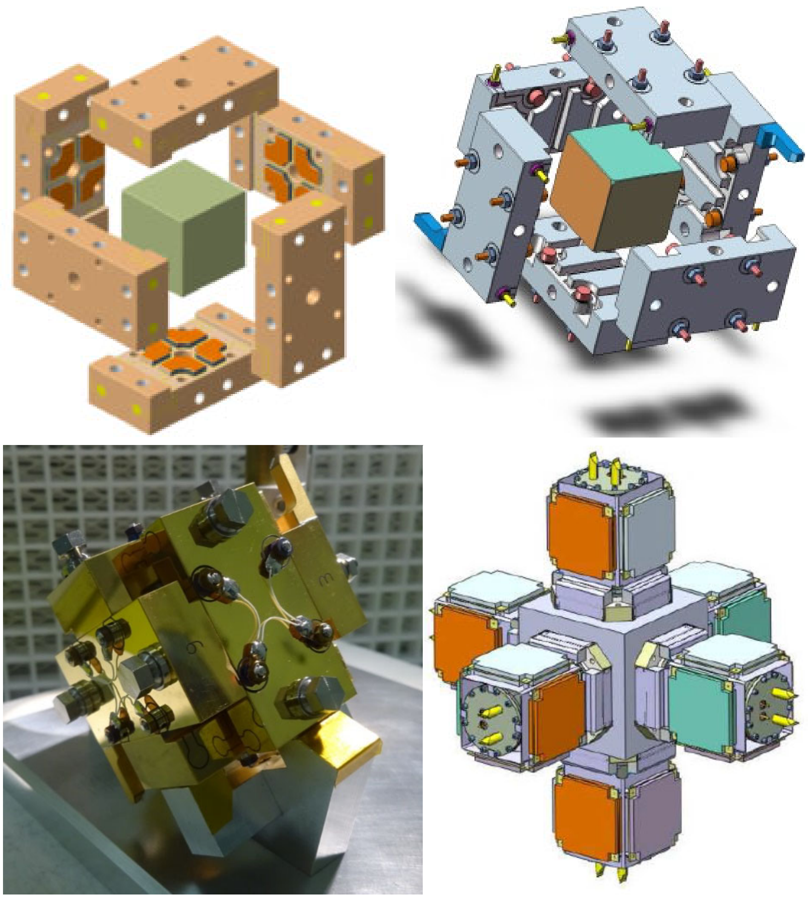


Figure 6: Top left Drawing of MicroSTAR accelerometer. Top right: Drawing of CubeSTAR accelerometer. Bottom left: CubeSTAR core prototype. Bottom right: Concept of a gradiometer with MicroSTAR or CubeSTAR acceleromete

An improved version of SuperStar has been developed (Figure 6). Unlike previous accelerometers, a cubic test-mass is used to have the same performance about the 3 axes. On GRADIO derived accelerometers, two axes were performants and the third one had its geometry adapted (reduced gap and increased area) to get a higher range needed for an operation on ground with high voltages. The advantage of ground operations is to test the wellness of the core even with a dedicated electronics in place of flight model electronics. The drawback is that only 2 axes can be used in orbit with full performances. With cubic test-masses, this is a true 3 axis accelerometers that can be tested in its flight configuration (during free-fall in Bremen for instance [6]).
This cubic test-mass can be produced at two scales as shown in Table 1 : MicroSTAR and CubeSTAR. The first one is directly inherited from SuperSTAR with two possible configurations: analog or digital controller. The performance can reach the GRADIO/GOCE accelerometer and is limited by the mechanical noise of the thin gold wire of tens of micrometer used to electrically connect the TM to a stable voltage. This limit in GRADIO/GOCE was also observed in TSAGE/MICROSCOPE [6], [10]. The second one uses a 30% smaller test-mass with lower voltages to simplify the electronics. The range is much higher and the performance consequently lower but the reduced volume may help to fit on a nanosatellite instead of mini or micro satellite. The electrode geometry of the CubeSTAR is also simplified with no redundancy at all for the TM control: reduce complexity to reduce the size and cost. The mechanical configuration could also enable the association of 6 accelerometers in a stable structure to form a gradiometer as shown in Figure 6.

Mission	Satellite Volume /Mass	Accelerometer Resolution	Volume / Mass / nominal power
CHAMP	4.3 (+4 for the boom) x 7.5 x 1.6 m^3 522 kg	STAR (1) 10^{-9} ms^{-2}_{rms}	2.4x2.4x2 L / 8.7kg / 2W + power conditioning (?)
GRACE	2 satellites: 3.1 x 1.9 x 0.7 m^3 432kg	SuperSTAR (2) Version 1997 10^{-10} $ms^{-2}Hz^{-1/2}$	2.3x2x1.8 L /7.6kg / 1.8W + 1.2x1.8x2.5 L / 6kg / 3.8 W For each SuperSTAR
GRACE-FO (GFO)	2 satellites: 3.1 x 1.9 x 0.8 m^3 600kg	SuperSTAR (2) Version 2013 $3x10^{-11}$ $ms^{-2}Hz^{-1/2}$	2.4x2.2x2.2 L / 8.9 kg / 5.7 W + 0.3x2x2.7 L / 1.5 kg / 4.7 W For each SuperSTAR
GOCE	5.3m x 0.9 m^2 1100 kg	GRADIO (6 TM = 1 instrument) $3x10^{-12}$ $ms^{-2}Hz^{-1/2}$	6x[1.6x1.6x1.9 L / 5kg / 0W] + 3x[2.5 x2.5x1.3 L / 5.4kg / 9.5 W] + 1x[3.5x2.2x1 L / 5.9 kg / 52 W] (includes digital controller)
MICROSCOPE	1.4x1x1.5 m^3 303 kg	T-SAGE (4 TM = 1 instrument) 10^{-11} $ms^{-2}Hz^{-1/2}$	3.8 x 3.5 x 1.8 L / 26 kg / 0 W + 2 x [2.7x1.7x0.9 L / 3.5 kg / 7.1 W] + 3x2.5x1.1 L / 5.5 kg / 11 W (includes digital controller)
Future mission	Micro or mini satellites	MicroSTAR $2x10^{-12}ms^{-2}Hz^{-1/2}$ ($10^{-10}ms^{-2}Hz^{-1/2}$ without digital controller)	2x1.6x1.6 L / 6 kg / 0 W + 2.5x2.5x0.7 L / 4kg / 8W + 3.5x2.5x0.7 L / 5kg / 8 W (includes digital controller)
Future mission	Micro or nano satellites	CubeSTAR 10^{-9} $ms^{-2}Hz^{-1/2}$	2 U / 3.5 kg / 2 W + 2 U / 1.5kg / 2.5W (1 U = 1x1x1 L)

Table 1: Summary table of the developed accelerometers and key interface figures (for the most accurate accelerometers, a digital controller is necessary for calibration)

In fundamental physics, measuring the acceleration with high accuracy allows to test the foundation of gravitation theories. MICROSCOPE showed that outstanding results could be obtained with a microsatellite and a dedicated accelerometer. The laboratory is studying future missions in interplanetary trajectories with MicroSTAR to test the frontier of the General Relativity [11]. At a smaller scale, one can envisage also to test Geodesy in a non-Newtonian theory of gravity [12] with a constellation of nano-satellites equipped of CubeSTAR.

The next step in future development should be to replace the gold wire used in the core of the accelerometer with a discharge device as performed in LISAPathfinder [13] to get access to even better performance.

5. CONCLUSION

ONERA department of Physics has developed, tested and delivered 15 accelerometers which have flown around the Earth in Geodesy and Fundamental Physics applications. From nano-g to pico-g resolution, the accelerometers had a major contribution in these fields with quite no equivalent instrument in the world. These accelerometers were first designed for mini-satellites with a fine control of the environment (ARISTOTELES, GOCE) and were adapted to operate in micro-satellite (MICROSCOPE). In the future, the laboratory is looking for smaller configuration to answer to the opportunities offered by nano-platforms doing valuable science and for more efficient configuration to answer to the Geodesy community. At a longer term, even high performance and interplanetary missions are envisaged on a micro or mini platform to go beyond General Relativity.

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