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CUBESTAR: A TINY SPACE ACCELEROMETER FOR EARTH OBSERVATION APPLICATIONS

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ABSTRACT

The New Space has opened opportunities for low cost space applications. ONERA is currently leading several cubesat/nanosat missions: CREME for the sun radiation monitoring, CROCUS for the study of electrostatic satellite charging, FlyLab a demonstrator of optical and radar systems. Our laboratory is giving some support to all these teams because of its long experience in space missions.

Indeed, the laboratory has been involved in all major space Geodesy missions by providing highly sensitive electrostatic accelerometer for more than 5 decades. Since the 70's, the resolution of the accelerometers has been improved leading to outstanding results with the ESA GOCE mission where the accelerometers exhibited a few $10^{-12} \text{m.s}^{-2}.\text{Hz}^{-1/2}$ resolution. Out of Geodesy application, the accelerometers developed in ONERA have allowed to test the Equivalence Principle on board the MICROSCOPE satellite at a level of 10-15, establishing in 2022 the best test ever made.

Taking advantage of this particular know-how quite unique in the world, the laboratory is studying the feasibility of measuring the Earth's Energy Imbalance (EEI) by a direct measurement of the acceleration exerted by the radiation pressure on the satellite. The current EEI budget is obtained by combining space measurement of radiometers and local temperature measurements of Oceans. But the combination from different sources gives rise to bias and uncertainties. The objective of the Accelerometer measurement is to solve these uncertainties.

A new accelerometer more compact, CubeSTAR, is under study in the laboratory in view of an utilisation in cubesats for science application. EEI characterisation or Geodesy mission with multiple cubesats may emerge as a costless alternative to 500-kg satellites.

In this presentation, from previous experiments, we will describe the preliminary design drivers of the accelerometer candidate with its potential performance and show how it may be used in different space applications.

Keywords: Accelerometer, Geodesy, Cubesats

1. PAST MISSIONS

Since the '70s, ONERA developed several electrostatic accelerometers used in geophysical and scientific missions. Thanks to the knowledge acquired during the last five decades, the performances have been improved to reach in the more recent years, tenths of pico-g accuracy.

1.1 CHAMP

CHAMP (for CHALLENGING Microsatellite Payload) is a German satellite dedicated to geophysical research. Launched on July 2000 from Plesetsk by a Russian COSMOS rocket, the mission was designed with a circular orbit at an altitude of 454 km and an 87.3° inclination. From 2000 to September 2010, CHAMP measured the Earth's magnetic field and gravity field. The Earth's gravity mapping was performed thanks to the High-Low tracking of the satellite orbit perturbations obtained by the GPS constellation combined with the precise STAR accelerometer measurement of the non-gravitational forces acting on the satellite (residual drag, solar and Earth radiation pressures and attitude manoeuvre thrusts).

1.2 GRACE

GRACE (for Gravity Recovery And Climate Experiment) is a German-American project composed of a pair of twin satellites and was the first NASA Earth System Science Pathfinder (ESSP) Program mission. The satellites were launched on March 17, 2002 from Plesetsk by a Eurockot launch vehicle on a quasi-polar orbit (89° inclination) at an altitude of 500 km. The mission, which ended in October 2017, had the two identical satellites flying on the same orbit and separated by a distance of 220 km. Like CHAMP, GRACE used high-low GPS satellite tracking and accelerometer surface force measurements. The novelty of GRACE was a low-low satellite to satellite tracking thanks to a precise K-band microwave ranging system measuring the inter-satellite distance with an accuracy around the millimetre. The accelerometer, named SuperSTAR, was similar to STAR in CHAMP but with a resolution better by one order of magnitude.

1.3 GOCE

GOCE (for Gravity field and steady-state Ocean Circulation Explorer) was an ESA mission launched on March 17, 2009 from Plesetsk by a Eurockot launch vehicle which ended in November 2013. The GOCE orbit was sun-synchronous, quasi-circular and quasi-polar (96.5°) with an altitude about 260 km. The satellite instrumentation comprised a three-axis gradiometer named EGG constituted of six electrostatic accelerometers similar to those of GRACE except for the proof-mass in PtRh10 alloy (denser), the larger gaps and the digital control-loops instead of the previous analogue circuits. This ensured a resolution in orbit of $3 \cdot 10^{-12} \text{ m.s}^{-2} \cdot \text{Hz}^{-1/2}$. The gravity gradient, the angular acceleration and the common acceleration were provided by the combination of accelerometers outputs. The mean output accelerations were used to control the ion thrusters to compensate the drag along the velocity vector. GOCE aimed to know with a better accuracy the highest spherical harmonics of the gravity field model.

1.4 GRACE Follow-On

GRACE-FO was launched on May 2018 with a Falcon 9 launch vehicle from Space X at an altitude around 490 km with an inclination of 89° (same as GRACE). This mission that aimed to ensure the continuity of the measurements performed by GRACE was planned for 5 years and is still operating today. The accelerometers were identical to those of GRACE with the same objective. The major improvement relied on the testing of laser-ranging interferometry to improve the satellite-to-satellite tracking measurements.

1.5 MICROSCOPE

Launched in April 2016 from Kourou and ended in 2018, MICROSCOPE (MICROSatellite à traînée Compensée pour l'Observation du Principe d'Equivalence, which means drag-compensated microsatellite for the equivalence principle observation) aimed to test the equivalence principle (EP), pillar of Einstein's general relativity. The mission demonstrated the non-violation of the EP with an unprecedented accuracy of 10^{-15} [1]. The satellite was issued from CNES's MYRIAD program and the measure performed by ONERA's T-SAGE instrument.

T-SAGE (Twin Space Accelerometer for Gravitation Experiment) was composed of two double accelerometers, both containing two pairs of coaxial and cylindrical proof-masses. These accelerometers were controlled by electrostatic forces which provided six-degree-of-freedom measurements also required for the drag-free and attitude control of the satellite. The proof-masses of the first differential accelerometer were made in the same platinum-rhodium (PtRh10) alloy, giving a reference measurement. The second differential accelerometer comprised two proof-masses of different materials, platinum-rhodium and titanium (TA6V) alloys, the titanium one being gold coated for electrical properties.

2. FUTURE MISSIONS

Today, future geodesy missions are in development with the space agencies in order to better know the Earth's gravity field and its seasonal variations. ONERA is involved in two missions, with ESA (Next Generation Gravity Mission – NGGM) on one hand, and with NASA (GRACE – Continuity) on the other. Together, these two missions constitute the Mass-change And Geosciences International Constellation (MAGIC).

On the same basis as GRACE, NGGM is a mission composed of a pair of two twin satellites, one following the other on the same orbit at a distance of 220 km. Initiated by ESA, the launch of the mission is planned for 2031 with an orbit around 400 km and an inclination of 70°. The novelty of NGGM is the development of a new accelerometer with the same principle as the previous missions but with a cubic proof-mass providing three ultra-sensitive axes and three true-angular accelerations instead of two with the parallelepipedal “flat” proof-masses of previous missions. The performance targeted is the same level as GOCE so $3 \cdot 10^{-12} \text{ m} \cdot \text{s}^{-2} \cdot \text{Hz}^{-1/2}$.

GRACE-Continuity design relies on the strong heritage of GRACE and GRACE Follow-On with quite no major changes. In particular the accelerometers will be the same (SuperSTAR). The launch is planned at the end of 2028.

3. THE ELECTROSTATIC ACCELEROMETER TECHNOLOGY

3.1 Measurement principle

The principle of the electrostatic accelerometer is based on the electrostatic suspension of a proof-mass to maintain it motionless. Since the proof-mass is at the centre of gravity of the satellite and is servo-looped motionless with respect to the surrounding electrodes, rigidly fixed to the satellite, any non-gravitational acceleration applied on the satellite will turn into an electrostatic force applied to the proof-mass. The required voltage applied onto the electrodes to control this electrostatic force constitutes an observable proportional to the non-gravitational satellite acceleration.

3.2 Design

Since the CACTUS mission in 1975, generations of electrostatic accelerometers were developed. Each accelerometer is basically composed of a mechanical unit (ASH – Accelerometer Sensor Head), an electronic unit (FEEU – Front-End Electronic Unit) and an Interface Control Unit (ICU). Regarding the NGGM mission and the three MicroSTAR accelerometers particular configuration needs, Figure 1 presents a schema of the organisation between units. All units are connected with harnesses and ASHs and FEEUs are thermally controlled in order to limit thermal noise.

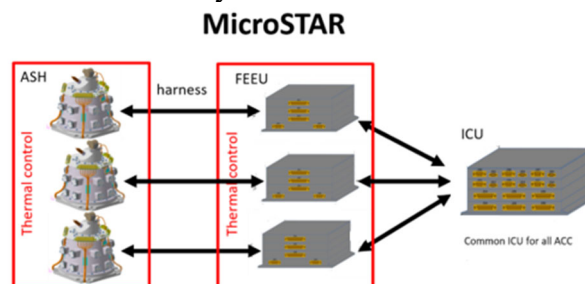


Figure 1: Subsystems links for the NGGM mission (MicroSTAR)

A cylindric, cubic or parallelepipedal proof-mass levitates in an electrode cage. It is polarised with a voltage applied through a thin gold or platinum wire of a few micrometre diameter. The electrode cage, represented in Figure 2, is composed of six electrode plates in Ultra-Low-Expansion Silica (ULE), machined, polished and gold coated, in order to delineate the electrodes. The electrode cage is maintained together by a stop cage which includes mechanical stops to limit the free-motion of the proof-mass. This mechanical core is protected and fixed by a housing and a sole plate that ensure the interface with the spacecraft, a good level of vacuum and provide a magnetic shielding. This assembly composes the mechanical unit.

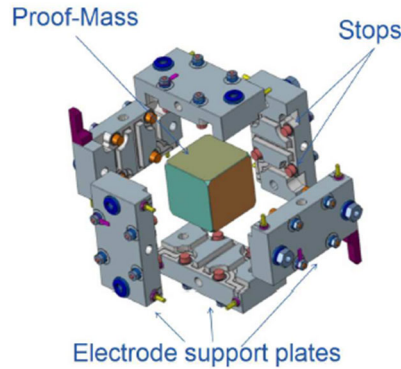


Figure 2: Electrodes cage for MicroSTAR

The FEEU detection and actuation functions feature low-noise components to servo-control and monitor each degree of freedom of the proof-mass with a high accuracy. The ICU provides the generation of the regulated power supply, the digital controller for the proof-mass servo-loops and the data and command data interface with the satellite.

3.3 Performance

In table 1 the different missions and the performance of the accelerometers are summarised.

Mission	Agency	Dates	Accelerometer	Performance	Field of study
CASTOR DB5	CNES/ONERA	1975	CACTUS	$10^{-8} \text{ m/s}^2/\sqrt{\text{Hz}}$	Geodesy
CHAMP	CNES/DLR	2000-2010	STAR	$10^{-9} \text{ m/s}^2/\sqrt{\text{Hz}}$	Geodesy
GRACE	JPL/DLR	2002-2017	SuperSTAR	$10^{-10} \text{ m/s}^2/\sqrt{\text{Hz}}$	Geodesy
GOCE	ESA	2009-2013	EGG	$10^{-12} \text{ m/s}^2/\sqrt{\text{Hz}}$	Geodesy
MICROSCOPE	CNES/ONERA	2016-2018	T-SAGE	$10^{-11} \text{ m/s}^2/\sqrt{\text{Hz}}$	Fundamental physics
GRACE-FO	JPL/Germany	2018-Today	SuperSTAR	$10^{-10} \text{ m/s}^2/\sqrt{\text{Hz}}$	Geodesy

Table 1. Previous missions performance summary

Regarding the future missions in study, the performances targeted are presented in table 2 below.

Mission	Agency	Launch targeted	Accelerometer	Performance	Field of study
GRACE-C	JPL	2027/2028	SuperSTAR	$10^{-10} \text{ m/s}^2/\sqrt{\text{Hz}}$	Geodesy
NGGM	ESA	2030/2031	MicroSTAR	$10^{-12} \text{ m/s}^2/\sqrt{\text{Hz}}$	Geodesy
MICROSCOPE 2	CNES	2030?		$10^{-14} \text{ m/s}^2/\sqrt{\text{Hz}}$	Fundamental physics

Table 2. Future missions targeted performance summary

These performances depend on various parameters such as the acceleration control range, the electronic components, the size, shape and material of the proof-mass, the ranges of its free motion in the electrodes cage or the gap between the proof-mass and the electrode plates for instance. Temperature sensitivity and parasitic forces on test-masses (patch effects or contact potentials, damping, outgassing...) also have to be considered in the budget for an optimal design.

For instance, Figure 3 presents the specification of the noise of the accelerometer MicroSTAR, in development for the NGGM mission.

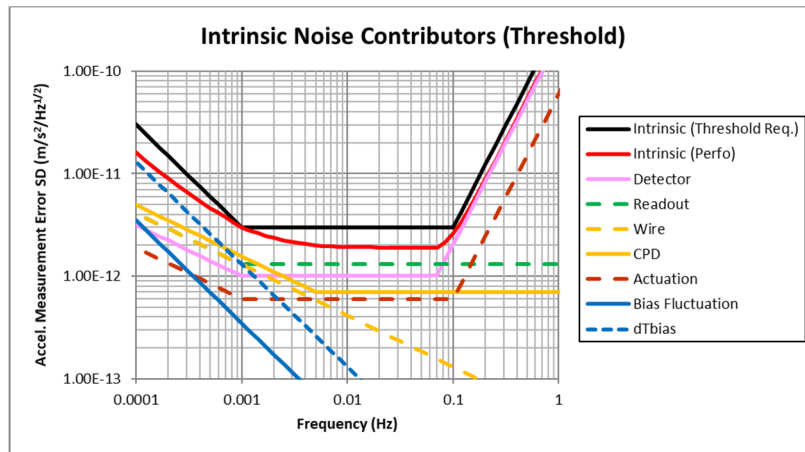


Figure 3: Noise specification for MicroSTAR (NGGM)

The main contributors of the error budget are the detector noise (in particular at high frequency), the damping of the wire, the thermal sensitivity of the bias (at low frequency), the measurement chain noise and then the contact potential noise (CPD), the actuation noise, and the bias fluctuation.

4. THE CUBESTAR ACCELEROMETER

CubeSTAR is an electrostatic accelerometer in development. The particularity of its design is the prime directive to fit the mechanical assembly in one cubesat unit (10cm*10cm*10cm) and the same goes for the electronics. The challenge resides in the reduction in size of all parts while keeping a good performance.

The mechanical core of CubeSTAR would be constituted of a cubic proof-mass featuring 2-cm sides in a light material surrounded by a six-ULE-plate cage. Plates are identical and include two electrodes. The stops cage is derived from MicroSTAR (NGGM mission) design. The aim of this assembly is to maintain the ULE plates together, to limit the free motion of the proof-mass in order to avoid any shock on the electrodes and to ensure the physical interface between the ULE core and the interface subassembly.

The main novelty resides in the mounting of the mechanical core on the interface. In CubeSTAR the sole plate is fixed in the middle of the core regarding the Z axis (the blue part in Figure 4). The objective is to reduce the thermal sensitivity between the interface and the core and to limit the temperature gradient thanks to the symmetry of the assembly.

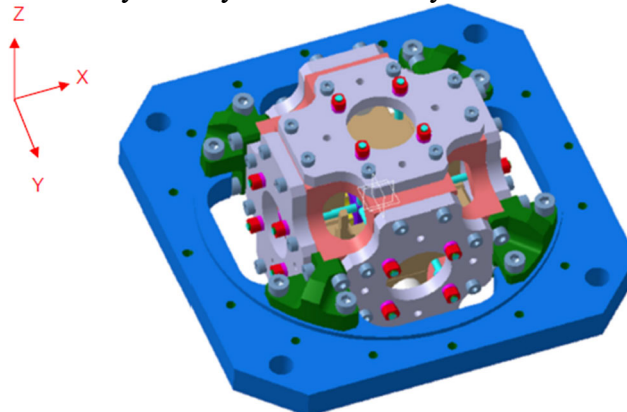


Figure 4: CubeSTAR mechanical core

The cubic proof-mass provides the same performance along the three axes. In the last estimations, the high-performance range of this accelerometer is $9 \cdot 10^{-4} \text{ m} \cdot \text{s}^{-2}$.

5. ELECTROSTATIC ACCELEROMETER AND CUBESATS

Geodesy and Earth's energy imbalance measurement are topics that still interest the scientific community. They allow to better understand how the Earth is evolving with its behaviour and its characteristics. Climate change is a central issue in this century's research and better knowing our planet will bring new solutions and a better knowledge of the future. In this part, the interest of a reduced electrostatic accelerometer will be presented.

5.1 Geodesy missions

Past and future missions such as GRACE or NGGM provide a better knowledge of the Earth's gravity field but with a limited recovering period. Indeed, a single pair of satellites will take time to cover the whole surface of the planet before coming back to a point already measured.

The interest of nanosatellites in this case is to cover more surface in less time by the means of constellations. The low cost of cubesats would allow to increase the number of satellites and to be more flexible on the mission's design. It is possible to put more satellites on a same orbit or to place pairs on different orbits with various inclinations in order to cover more surface over the same duration.

CubeSTAR, as a payload, would then measure the nongravitational acceleration over the satellite and provide a mapping of the gravity field.

5.2 Earth's Energy Imbalance (EEI) study missions

The Earth's energy imbalance (EEI) is the difference observed between the solar radiation incoming to the Earth and the total amount of radiation emitted by the Earth (the reflected solar radiation and the emitted thermal radiation). Its monitoring informs about our climate system and especially, the global warming of our planet. A deeper understanding of this mechanism will improve the knowledge about hydrological cycle, for instance, and estimate more precisely the future evolution of the climate.

Currently, the three radiative components of the EEI are individually studied using space radiometers with a high stability. In-situ measurements of the ocean heat content and space sea level monitoring complete this method; they offer an indirect information on the EEI. However, the combination from different sources gives rise to bias and uncertainties. Consequently, Mainguy (1985, [2]) proposed to complete these approaches by using space accelerometry with the ONERA BIRAMIS project. This new strategy offers the advantage of a direct measure (i.e. integrated value) of EEI. Following this idea, Hakuba et al. (2019, [3]) are defining the "Space Balls" mission.

Indeed, radiations from the Earth and the Sun apply an acceleration on the satellite, which is detectable with ultra-sensitive instruments. Equation 1 describes the radial acceleration $\overrightarrow{a_{rad}}$ produced by the Sun ($\overrightarrow{\xi_S}$), the Earth albedo ($\overrightarrow{\xi_A}$) and the Earth Infra-Red ($\overrightarrow{\xi_{IR}}$) radiations on a spherical satellite with a radius R and a mass M_{sat} .

$$\overrightarrow{a_{rad}} = \frac{\pi R^2}{M_{sat} c} (A_S * (\overrightarrow{\xi_S} + \overrightarrow{\xi_A}) + A_{IR} * \overrightarrow{\xi_{IR}}) \quad (1)$$

A_S and A_{IR} the mean coefficients of spectral pressure of the Sun (Sun radiation and Earth albedo) and of the Earth IR radiation. The contributors are represented in Figure 5.

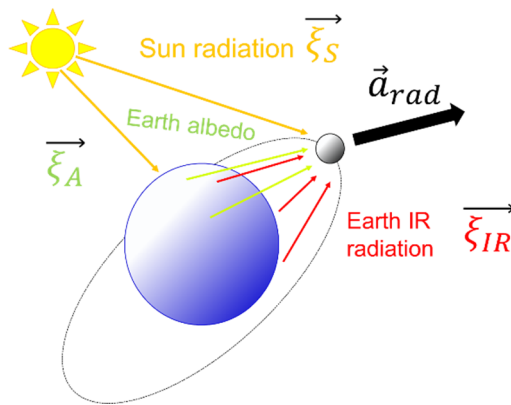


Figure 5: Contributions of radiations to the acceleration

Table 3 defines the acceleration corresponding to the type of radiation received by a spherical satellite of one-metre diameter with a perfectly absorbing coating.

Flux	GLOBAL MEAN (Wm^{-2}) ± UNCERTAINTY	derived acceleration (ms^{-2}) ± uncertainty
ISR	$340 Wm^{-2} \pm 0.01\%$	$1.8 \cdot 10^{-8} \pm 1.8 \cdot 10^{-12}$
RSR	$100 Wm^{-2} \pm 0.3\%$	$5.3 \cdot 10^{-9} \pm 1.6 \cdot 10^{-11}$
IR	$240 Wm^{-2} \pm 0.9\%$	$1.3 \cdot 10^{-8} \pm 1.1 \cdot 10^{-10}$
EI	$\sim 0.7 Wm^{-2} \pm 0.4 Wm^{-2}$	$3.7 \cdot 10^{-11} \pm 2.1 \cdot 10^{-11}$
EI	$\sim 0.7 Wm^{-2} \pm 0.1 Wm^{-2}$	$3.7 \cdot 10^{-11} \pm 0.5 \cdot 10^{-11}$

Table 3: Derived acceleration for radiations (ISR: Incoming Solar Radiation, RSR: Reflected Solar Radiation (albedo), IR: Infrared (emitted thermal radiation)) (from Hakuba et al., 2019 [3]).

Electrostatic accelerometers developed at ONERA achieve these expected performances for a given frequency (see Table 1 and 2). To increase their performance at long-term, a special care will be provided on their intrinsic bias. Indeed, the bias is stable in the frame of the accelerometer. By adding a rotation, the bias will rotate but not the external signal as shown in Figure 6. It will be possible to subtract the value of the bias and keep the external acceleration measured.

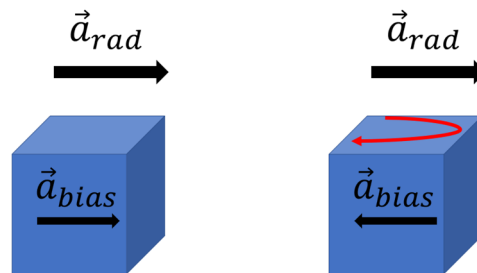


Figure 6: Bias rejection by rotation

In the first concept, the rotation will be applied on the satellite. The spacecraft has a quasi-spherical shape with a need to characterize precisely the surface properties in order to avoid confusing effects with perturbing forces. For symmetrical reason, the acceleration on a spherical satellite will be colinear to the illumination direction. The concept for the satellite shape is presented in Figure 8. It is composed of cubesat units joined together by solar panel and plates with a special coating in order to keep the same emissivity.

The second concept shown in Figure 78 involves to spin the accelerometer. An innovative idea would be to develop a rotative platform (Lenoir et al., 2013 [4]).

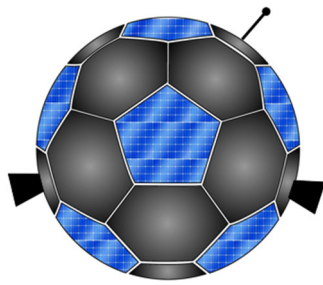


Figure 7: Spherical satellite concept (Space Balls [3])

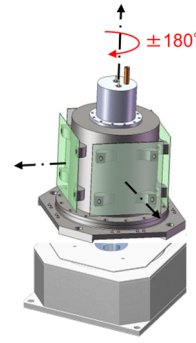


Figure 8: Bias rejection system with a turntable

CubeSTAR would be a main asset in this project thanks to its size and its performance. With an integration time of its measure of 100 seconds the performance level needed for this mission is estimated around $10^{-10} \text{ m.s}^2.\text{Hz}^{-1/2}$. Indeed, the integration allows to reach a level about $10^{-11} \text{ m.s}^{-2}.\text{Hz}^{-1/2}$.

6. CONCLUSION

With the heritage acquired during the last decades, electrostatic accelerometers appear to be an alternative to radiometers in the frame of the earth's energy imbalance and geodesy research. This technology has the advantage to be a passive system allowing local measurements, and provided along three axes. This last point is useful in order to discriminate parasitic contributors such as the atmospheric drag or the Sun radiation.

The challenges to be dealt with are ensuring a good acceleration resolution and efficiently rejecting the measurement bias. Regarding the spacecraft, a trade-off needs to be made, such as the choice of the coating or the shape of the structure so that the parasitic forces are limited and the instrument environment knowledge is as fine as possible.

Nanosatellites offer new perspectives and new solutions for the Earth observation research. Combining this new type of spacecraft with the electrostatic accelerometry brought by CubeSTAR would permit to afford new types of missions with higher time resolution, cheaper and with a better adaptability and the possibility for larger constellations.

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