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THE MICROSCOPE SPACE MISSION AND THE INFLIGHT CALIBRATION APPROACH FOR ITS INSTRUMENT

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Abstract. MICROSCOPE is a fundamental physics space mission which aims at testing the Equivalence Principle (EP) with an accuracy of 10^{-15}. The gravitational signal is measured precisely by a differential electrostatic accelerometer which includes two cylindrical test masses made of different materials. The accelerometer is on-board a drag-free micro-satellite which is controlled either Earth pointing or rotating about the normal to the orbital plane with a very stable angular velocity. The expected accuracy of the EP test could be limited by the inaccurate *a priori* knowledge of the instrument physical parameters associated to the instrument environment on-board the satellite. These parameters are partially measured or estimated by means of ground tests or during the integration of the instrument on the satellite. However, these evaluations are not sufficient and an in-orbit calibration is therefore needed to finely characterize the instrument and to correct the measurements. After the overall presentation of the MICROSCOPE mission and its scientific goal, this paper will focus on the accelerometer and will describe the specific procedures proposed for the in-flight instrument calibration.

Keywords: equivalence principle, gravity, MICROSCOPE, space fundamental physics, accelerometer, calibration

1 Introduction

The Equivalence Principle (EP) expressed by Einstein as a basis of its theory of General Relativity states the universality of free fall. It has been tested throughout the years by ground-based experiments with an increasing accuracy which reaches a few 10^{-13} (Schlamminger et al. 2008). The accuracy is limited by the noisy environment in the laboratory and by the strong local gravity. However, the unification theories which try to merge General Relativity and Quantum Mechanics expect a violation of the EP below this value (Damour et al. 2002). To go beyond this limit, it has been proposed to perform the experiment in space where noise is minimized and the duration of the free fall is not limited. This is the objective of the MICROSCOPE space mission which aims at testing the EP with an accuracy of 10^{-15} (Touboul et al. 2001). To achieve this goal, the payload of the MICROSCOPE satellite is a differential electrostatic accelerometer composed of two test masses made of different material. The accelerometer measures the difference between the gravitational accelerations of the two masses while their inertial motions are controlled identical and thus indicates whether there is violation of the EP or not. The accuracy of the experiment is limited by the inaccurate *a priori* knowledge of the instrument parameters. These parameters have to be better evaluated in orbit. A first estimation is in fact obtained by means of ground tests and during the integration of the instrument in the satellite. An in-orbit calibration is nevertheless necessary to correct finely the measurement and reach the objective of the mission.

After a general presentation of the MICROSCOPE space mission, the instrument is described. The interest of an in-flight calibration is highlighted and quantified. The calibration approach is then presented with its preliminary results.

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2 The MICROSCOPE space mission

For the MICROSCOPE space mission, a 200 kg dedicated satellite is developed by CNES within its MYRIAD program of micro-satellite. The Earth is the gravitational source of the EP test and the satellite will be injected on a quasi circular (eccentricity $< 5 \times 10^{-3}$) and heliosynchronous orbit, at an altitude around 810 km. The characteristics of the orbit ensure thermal stability and a reduced correlation between the EP signal and the gravity gradient. The duration of the mission is planned to be one year while the orbit period is about 6000 s. The time span of the measurement, not limited by the free fall, will be superior to 20 orbits.

The payload of the satellite is composed of two independent electrostatic differential accelerometers developed in our laboratory at Onera. Each differential accelerometer includes two test masses and measures the difference between the inertial accelerations of the two masses. One accelerometer is composed of two different masses (platinum/titanium) to perform the EP test and one is composed of two identical masses (platinum/platinum) to be used as a reference. The mass and power budgets of the payload lead to 35 kg and 40 W. The instrument thermal control is passive in order to respect the constraints of the micro-satellite.

The mass motions of the accelerometer are servo-controlled to follow the same orbit with a precision better than 10^{-11} m. This is made possible by the electrostatic actuation which forces the masses to remain concentric. Thus, the two masses undergo the same gravity field and a difference between the electrostatic accelerations applied to the masses will indicate a violation of the Equivalence Principle. The environment is maintained very steady limiting any perturbation and the System of Control of Attitude and Acceleration (SCAA) exploits the measurement of the accelerometer in order to make the satellite drag free along the three degrees of freedom: the surface forces and torques applied on the satellite are countered continuously by the thrust of the propulsion system. To this extent, MICROSCOPE represents a technical challenge.

Another advantage of performing the experiment in space is that the phase and the frequency of the signal to be detected are very well defined. The satellite pointing can be either inertial or spinning, each mode having its advantage. For example when the satellite is spinning, the signal frequency is increased and thus closer to the minimum of the noise of the instrument. The considered spin frequency is 1 mHz and therefore the signal frequency f_{ep}, sum of spin and orbital frequency, will be 1.2 mHz. In inertial mode, the satellite angular velocity is controlled null, limiting the effects of the centrifugal acceleration perturbations.

3 The payload of the mission

A differential electrostatic accelerometer is composed of two cylindrical and co-axial masses, each of them surrounded by cylindrical electrode parts. The two test masses have identical moment of inertia along their three axes in order to minimize the gravity gradient effect. The electrode parts are in gold plated silica in order to ensure the thermal stability. The sensor unit core is maintained under a vacuum better than 10^{-5} Pa thanks to an Invar tight housing and a getter material on top of the sensor unit. The only physical contact on the levitated proof mass is one $5\,\mu$m gold wire. The purpose of this wire is to control the electrical potential of the mass. This potential is composed of a constant part used to apply the actuation force and a sinusoid part used to detect the position of the proof mass. Control loops maintain the mass centered and motionless. The same electrodes are in charge of the measurement of the position of the mass through variation of capacitance and of the control of the six degrees of freedom of the mass with electrostatic forces.

The mechanical heart of the sensor is connected to the front end electronic unit linked to the interface control unit. The first unit corresponds to the analog functions such as the position detection while the second one corresponds to the digital control laws and the satellite interface. The satellite payload is operated in a finely stabilized temperature environment and protected from perturbations by a magnetic shield.

The operation of the accelerometer is similar along the six axes and hereafter detailed along the measurement axis which is the cylinder axis (X axis): when the mass moves along this axis, a variation of the recovering surface appears leading to a difference of capacitance between the mass and each electrode corresponding to an analog signal provided by the position detector. This signal is numerized and processed by the control loop laws in order to generate a voltage proportional to the acceleration of the sensor. This voltage is amplified and applied to the electrodes in order to keep the mass at the centre. The output of the control laws is used by the drag free system. The scientific measurement must have a better accuracy so it is picked up on the electrodes at the end of the loop in order to get a lower noise.

4 The in-orbit instrument calibration

4.1 *The accelerometer measurement*

In the case of a perfect instrument, the accelerometer measurement would be the acceleration applied on the proof mass to maintain it at the centre of the electrostatic cage, $\vec{\Gamma}_{App,k}$ (proof mass k) expressed by:

$$\vec{\Gamma}_{App,k} = \left(\frac{M_{gsat}}{M_{Isat}} - \frac{m_{gk}}{m_{Ik}}\right)\vec{g}(O_{sat}) + (T-I)O_k\vec{O}_{sat} + \frac{\vec{F}_{NGsat}}{M_{Isat}} - \frac{\vec{F}_{NGk}}{m_{Ik}} \tag{4.1}$$

Where M_{gsat} and M_{Isat} are respectively the gravitational and inertial masses of the satellite, m_{gk} and m_{Ik} are respectively the gravitational and inertial masses of the proof mass, O_{sat} is the centre of mass of the satellite, O_k the centre of the proof mass, T is the gravity gradient tensor, I is the gradient of inertia tensor, $\vec{F}_{NGsat}$ and $\vec{F}_{NGk}$ are the non gravitational forces applied respectively on the satellite and the proof mass. The semi differential quantity $\Gamma_{App,d} = \frac{\Gamma_{App,1}-\Gamma_{App,2}}{2}$ thus provides the EP violation signal defined as $\frac{1}{2}(\delta g(O_{sat}))$, with $\delta = \frac{m_{g2}}{m_{I2}} - \frac{m_{g1}}{m_{I1}}$. We define also $\Gamma_{app,d}$ such that $\Gamma_{App,d} = \Gamma_{app,d} + b_{1d}$, with the index "d" meaning differential and with b_{1d} the opposite of the differential non gravitationnal acceleration applied on the proof mass.

But the actual semi differential measurement in the measurement bandwidth along the X axis depends also on the instrument following parameters:

$$\begin{aligned}\Gamma_{mes,d} = \frac{1}{2}K_{1cx}\delta g_x(O_{sat}) + \frac{1}{2}\begin{bmatrix} K_{1cx} \\ \eta_{cz}+\theta_{cz} \\ \eta_{cy}-\theta_{cy}\end{bmatrix}^t \cdot [T-I] \cdot \begin{bmatrix}\Delta_x \\ \Delta_y \\ \Delta_z\end{bmatrix} + \begin{bmatrix} K_{1dx} \\ \eta_{dz}+\theta_{dz} \\ \eta_{dy}-\theta_{dy}\end{bmatrix}^t \cdot (\vec{\Gamma}_{res_{df}} + \vec{C}) \\ + 2K_{2cxx}(\Gamma_{app,d}+b_{1dx}) \cdot (\Gamma_{res_{df,x}} + C_x - b_{0cx}) + K_{2dxx}((\Gamma_{app,d}+b_{1dx})^2 + (\Gamma_{res_{df,x}} + C_x - b_{0cx})^2)\end{aligned} \tag{4.2}$$

Where K_{1cx} and K_{1dx} are the common and differential scale factors along the X instrument axis, θ_{cz} and θ_{dz} (respectively θ_{cy} and θ_{dy}) are the common and differential misalignment parameters along Z (resp. along Y), η_{cz} and η_{dz} (respectively η_{cy} and η_{dy}) are the common and differential coupling parameters along Z (resp. along Y), Δ is the test mass relative off-centring in the satellite frame and K_{2cxx} and K_{2dxx} are the common and differential quadratic factors along X, b_{0cx} is the common read-out bias along X. $\vec{C}$ is the drag free command, C_x its component along X. $\vec{\Gamma}_{res_{df}}$ is the drag free loop residue, $\Gamma_{res_{df,x}}$ its component along X. $\Gamma_{res_{df,x}} + C_x - b_{0cx}$ is in first approximation equal to the common applied acceleration ($\Gamma_{App,c} = \frac{\Gamma_{App,1}+\Gamma_{App,2}}{2}$) used by the SCAA to make the satellite drag free.

4.2 *The calibration process*

The EP parameter must be detected with a resolution of $8 \times 10^{-15}\,\mathrm{ms}^{-2}$ to reach the objective of 10^{-15}. Tens of group of errors sources including mechanical defects, thermal and magnetic effects have been identified. For each of them, specifications have been associated in order to reach the measurement accuracy. In equation 4.2, three groups of errors explicitly appear depending on: integration of the instrument in the satellite which refers to all the common mode parameters, differences between the two sensors characteristics which refer to all the differential mode parameters and the quadratic non linearities. The values by construction of these parameters are such that they lead to an error by far too large compared to the specified accuracy (Guiu 2007). That is why it is necessary to estimate some parameters in order to correct the measurement and thus reach the specified accuracy. The idea is to amplify the parameter effect using both the capability of the SCAA to force the motion of the satellite through its thrusters and the sensor servo-control to force the motion of the test masses (Guiu 2007). A specific process is proposed to calibrate each parameter:

- $K_{1cx}\Delta_x$ and $K_{1cx}\Delta_z$ by using the Earth's gravity gradient at $2f_{ep}$ as the calibration signal; $K_{1cx}\Delta_y$ by forcing (through the drag-free command) the oscillation of the satellite around its Z axis ($K_{1cx}\Delta_x$ and $K_{1cx}\Delta_z$ can also be calibrated in similar way),
- $\eta_{cz}+\theta_{cz}$ and $\eta_{cy}-\theta_{cy}$ by simultaneously forcing the oscillation of the satellite around the X axis of the instrument and the test mass respectively along its Z axis and Y axis, thus creating a Coriolis effect,
- $K'_{dx}/K_{cx} = (K_{dx} + 2K_{2cxx}b_{1dx} + K_{2dxx}(C_x - b_{0cx}))/K_{cx}$, $(\eta_{dz}+\theta_{dz})/K_{cy}$ and $(\eta_{dy}-\theta_{dy})/K_{cz}$ by forcing the oscillation of the satellite along the instrument X, Y, Z axis. We chose to estimate K'_{dx}/K_{cx} instead of only K_{dx}/K_{cx}, in order to include the biases in the parameter to be estimated and this way to correct the scientific measurement of their effect through the quadratic terms.

- K_{2dxx}/K_{cx}^2 by forcing (through the drag-free command) the oscillation of the satellite along the X axis of the instrument and by analysing the measurement at the double of the oscillation frequency,
- K_{2cxx}/K_{cx}^2 by estimating separately K_{21xx}/K_{11x}^2 and K_{22xx}/K_{12x}^2. To calibrate K_{21xx}/K_{11x}^2 (respectively K_{22xx}/K_{12x}^2) the drag compensation shall be locked on the sensor 2 (resp. 1) and the proof mass 1 (resp. 2) forced to oscillate along its X axis; the measurement 1 (resp. 2) is analyzed at the double of the oscillation frequency.

A standard duration of 10 orbits is selected for each calibration process. After one single round of calibration the data are reprocessed; each iteration improves the global accuracy as the assessment of all individual parameters benefits from the refinement of the other parameters that take part in the measurement equation. The performance of the calibration has been evaluated analytically. We see (table 1) that the calibration process satisfies the requirements for all parameters.

Parameters to be calibrated	Specification	Performance after calibration
$K_{1cx}\Delta_x$	$0.1\,\mu$m	$0.07\,\mu$m
$K_{1cx}\Delta_z$	$0.1\,\mu$m	$0.07\,\mu$m
$K_{1cx}\Delta_y$	$2\,\mu$m	$1.3\,\mu$m
$\eta_{cz} + \theta_{cz}$	1×10^{-3} rad	1.1×10^{-3} rad
$\eta_{cy} - \theta_{cy}$	1×10^{-3} rad	1.0×10^{-3} rad
K'_{dx}/K_{cx}	1.5×10^{-4}	3.5×10^{-5}
$(\eta_{dz} + \theta_{dz})/K_{cy}$	5×10^{-5} rad	1.5×10^{-5} rad
$(\eta_{dy} - \theta_{dy})/K_{cz}$	5×10^{-5} rad	1.5×10^{-5} rad
K_{2dxx}/K_{cx}^2	$250\,\mathrm{s}^2/\mathrm{m}$	$55.9\,\mathrm{s}^2/\mathrm{m}$
K_{2cxx}/K_{cx}^2	$14000\,\mathrm{s}^2/\mathrm{m}$	$581.5\,\mathrm{s}^2/\mathrm{m}$

Table 1. Analytical evaluation of the performance of the calibration process

5 Conclusion

The scientific data of the MICROSCOPE mission have to be corrected in order to reject inaccuracies of the instrument. Therefore, an in-flight calibration has to be performed. The relevant parameters to be calibrated have been determined and an appropriate calibration method has been proposed for each of them. The analytical simulation of the errors of the calibration process shows that the needed parameters of the instrument can be estimated with an accuracy that complies with the objective of MICROSCOPE. The next step of this evaluation is the development of a software which will include the satellite attitude and the drag free system. Such a calibration approach could be considered for other space missions exploiting ultra sensitive accelerometers.

Concerning the development of the instrument, the qualification phase has started as well as the procurements for the flight models. In parallel, the satellite definition that had suffered from difficulties in the propulsion system development is now being completed by considering thrusters similar to the GAIA satellite. And a launch in 2014 is expected.

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