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Two cylindrical masses in orbit for the test of the equivalence principle

Ratana Chhun, Pierre Touboul and Vincent Lebat

ONERA, BP-72
F-92322 CHATILLON CEDEX, FRANCE
email: ratana.chhun@onera.fr

Abstract. Two pairs of solid test-masses have been considered to perform in space the test of the universality of free fall with an accuracy of at least 10^{-15}. These cylindrical masses are precisely at the heart of the MICROSCOPE mission instrument comprising two differential electrostatic accelerometers. These masses shall exhibit material quality, shapes, positions and alignments in regard to stringent experimental requirements. Indeed the space experiment is based on the control of the two masses submitted to the same gravity acceleration along the same orbit at 810 km altitude with an accuracy of 10^{-11} m. Thus effects of Earth and satellite gravity gradients shall be contained as well as any other disturbances of the mass motions induced by their magnetic susceptibility or electrical dissymmetries, by outgassing of the materials or radiation emissivity. Furthermore, the electrostatic levitation of the two masses depends dramatically on the mass shapes and electrical properties in particular for the definition of the sensitive axes orientation. All these aspects will be presented from the mass characteristics to the space MICROSCOPE experiment performance.

Keywords. MICROSCOPE, Equivalence principle, accelerometer, gravity

1. Introduction

For a few decades several unification theories have risen to try and merge general relativity and quantum mechanics. These approaches all call out for the existence of a fifth interaction force (Damour *et al.* 2002, Fayet 2003). Such existence would translate into a violation of the basis of general relativity, the Equivalence Principle which stipulates that all bodies acquire the same acceleration rate in the same uniform gravity field regardless of inertial mass or intrinsic composition.

To this day the Equivalence Principle has been verified to a precision of a few 10^{-13} by ground-based experiments (Schlamminger *et al.* 2008). MICROSCOPE aims to test the Equivalence Principle to better than 10^{-15} (Touboul *et al.* 2001).

In order to attain such precision, the test will be performed in space. The space environment indeed offers several very favorable conditions compared to a ground-based experiment: among those, reduced vibrations from micro to nano level, a very long integration time, highly stable thermal conditions, modulations of the Earth gravity source in the instrument reference frame and the possibility to use a dedicated instrument with sufficiently limited range with a consequent very low noise.

2. Mission description

The MICROSCOPE space mission is now at the production level of the instrument, the satellite and the masses being specified and defined. In the experiment, two concentric test-masses will be placed on the same gravitational trajectory. By keeping the two masses concentric, they are ensured to follow the exact same free fall and to undergo the exact same gravitational field. Instead of trying to detect a difference of free fall trajectory between the two masses, the principle of MICROSCOPE consists in measuring the deviation of electrostatic forces necessary to maintain the two masses on the same orbit along the gravity field direction. A breaking of symmetry between the measured control accelerations, equivalent to the two masses motions, would translate into a violation of the Equivalence Principle. Following an inertial heliosynchronous orbit at an altitude of about 800km, the test is performed at the orbit plus the satellite spin frequency around the normal axis to the orbital plane. Two pairs of test-masses, constituting the two pairs of test-masses of two differential accelerometers, embark the CNES microsatellite for a double differential test, one pair of platinum-rhodium alloy masses and one pair of one platinum rhodium alloy and titanium alloy masses.

The launch of the MICROSCOPE microsatellite is scheduled for the end of 2012 and the mission duration is set to a minimum of twelve months. It will follow a quasi-circular orbit (with an eccentricity inferior to 5×10^{-3}) for a very well known measurement frequency. In order to ensure the mission performance requirements, the satellite will be equipped with twelve micronewton thrusters, a continuous drag-free compensation system and fine orbit and attitude control. It will also feature a passive thermal control.

Currently manufacturing the instrument qualification model, this paper will describe the overall design of the instrument with a focus on the test-masses and the various numerical models and geometry constraints required to reach the experiment performance, i.e. the 10^{-15} accuracy EP test.

3. Instrument description

The payload is composed of two sensor units; each one is composed of one pair of test-masses centered with respect to each other at better than 20 µm after integration. Each test-mass is at the core of an inertial sensor, one half of the differential accelerometer. The ensemble is integrated inside a highly insulated thermal case and a µmetal magnetic shield installed at the center of the satellite so that the orientation of the payload with respect to the star sensor piloting the drag-free and attitude control system is very stable.

The test-masses are cylindrical and their dimensions are designed to obtain spherical inertia properties, trade-off between practicability and relevance for the test, thus minimizing the gravity gradient effects. The two cylinders are concentric and coaxial in addition to having a common center of mass, thus mimicking the behavior of two concentric spheres, with a privileged sensitive measurement axis, the average cylinder axis.

Each test-mass is electrostatically levitated and maintained centered and steady inside its gold-coated silica cage by applying adequate voltages on the electrodes etched on the silica cylinders surrounding the test-mass, which are also used to sense its position and thus its displacement attempts along or around its six degrees of freedom. The only physical contact on the proof mass is a 5 µm gold wire used for charge control and for applying a sinusoid voltage for the capacitive sensing.

Each sensor unit core is maintained under a vacuum less than 10^{-5} Pa thanks to an Invar tight housing and a getter material on top of the sensor unit.

4. Measurement equation

The science measurements of one inertial sensor are the applied voltages needed to maintain the mass centered with respect to its electrode cage, to compensate for both

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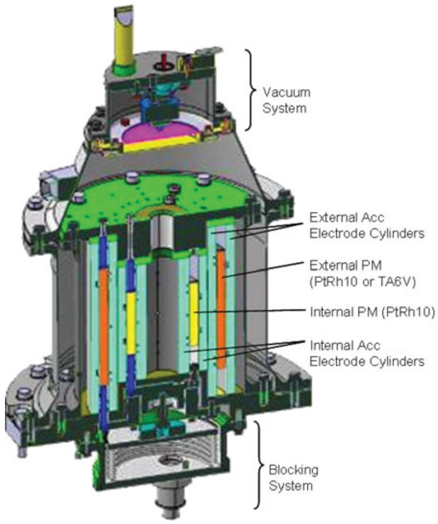

Figure 1. Cross cut view of the differential accelerometer, consisting of the sensor core of test-masses and electrode cylinders, the blocking mechanism below and the vacuum system above.

gravity and surface forces on the satellite. The differential measurement between the two inertial sensors is then expressed as follows:

$$\mathbf{\Gamma_{app,d}} \approx \left(\delta \cdot \mathbf{g}(\mathbf{O}_{\mathrm{sat}}) + ([T] - [In]) \cdot \mathbf{\Delta} - 2 \cdot [Cor] \cdot \dot{\mathbf{\Delta}} - \ddot{\mathbf{\Delta}}\right)$$

$\delta = m_{G2}/m_{I2} - m_{G1}/m_{I1}$ is the signal to be detected where m_G and m_I are respectively the gravitational mass and the inertial mass, Δ the excentering between the centers of mass of the two test-masses. At about 800 km high, $g(O_{\mathrm{sat}})$ is quite $8\,\mathrm{m/s^2}$, so in order to perform the test at 10^{-15}, the differential acceleration needs to be measured at a resolution better than $8 \times 10^{-15}\,\mathrm{m/s^2}$ at the test frequency. Thus, all other terms of the equation need to be weaker or very well known.

A great part of the error budget is then due to forces resulting directly from the test-masses design, material properties and manufacture.

5. Gravity gradients

The first disturbing effect due to the instrument defects is the effect of the Earth gravity gradient on the test-masses excentering. The Earth gravity gradient is considered uniform over the two masses and processed through the field tensor form. The Earth gravity gradient directly generates major components at DC frequency and at twice the measurement frequency and, due to the eccentricity, at the measurement frequency plus or minus twice the spin frequency of the satellite.

The test-masses relative centering specification is 20 µm but will not be sufficient to limit the Earth gravity gradient effect without an in-orbit calibration and data ground correction to 0.1 µm in the orbital plane and 0.5 µm along its normal through satellite controlled oscillations (Guiu *et al.* 2007).

A second disturbing gravity effect is due to the local gravity gradient of the satellite and the instrument itself, applied on the test-masses. To limit these effects, the masses dimensions are precisely selected, taking into account the fact that the masses actually feature flat areas for axial rotation control and holes at each end for motion limitation

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using dedicated stops. Equality of the moments of inertia are obtained around all axes at better than 10^{-4} and relative cross products of inertia inferior to 10^{-8}. Furthermore the homogeneity of the mass material is selected in relation. Moreover the satellite and the instrument are in addition designed to exhibit high stiffness and very good thermal stability to get very low disturbances at the measurement frequency due to environment conditions.

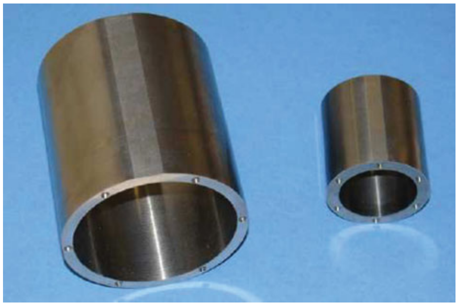

Figure 2. Test-masses featuring flat panels for axial rotation control and holes for displacement limitation.

Finite element models of the instrument on one hand and of the satellite on the other have been computed taking into account various mass motions and positions depending on temperature variations. For the instrument the model results in acceleration sensitivities due to the mass proximity environment thermal conditions of about 2.5×10^{-13} m/s^2/K. Combining the expected thermal environment stability at the measurement frequency of 1 mK, we can expect the instrument self gravity effect to be limited to 2.5×10^{-16} m/s^2. The satellite model shows likewise a satellite self gravity effect of about 10^{-16} m/s^2.

6. Magnetic field

The model for the magnetic field effect which we try so much to protect MICROSCOPE from, using two complementary shieldings, takes into account both the Earth magnetic field and the local magnetic sources, each of those having their own components at various frequencies but all add up to form a global magnetic field. The acceleration effect due to this global field is then $\mathbf{\Gamma}_m = \chi_m/(2\mu_0 \cdot \rho_m)\nabla\left[\mathbf{B}^2\right]$ where χ_m is the magnetic susceptibility of the test-mass material, ρ_m its density and μ_0 the magnetic permittivity in vacuum. χ_m/ρ_m is respectively limited to 1.4×10^{-8} m^3/kg for platinum mass and 1.6×10^{-8} m^3/kg for titanium mass thanks to the selection of the material.

The Earth magnetic field time variations along the MICROSCOPE orbit is derived from Oersted satellite data from which the components of the Earth magnetic field at the various frequencies considered in the global MICROSCOPE error budget, DC, the test measurement frequency, first multiples and random noise, are extracted.

The local sources are considered in a worst case approach as magnetic moments at 30cm from the masses: 1Am^2 at DC, 10^{-3}Am^2 at the test frequency and 0.04Am$^2/\sqrt{Hz}$ random noise.

The magnetic field attenuation due to the shieldings has been measured in CNES facilities and the magnetic field and magnetic field gradients over each test-mass volume has been computed using the FLUX3D software. The maximum acceleration effect at the measurement frequency in case of a purely inertial orbit is 2.08×10^{-16} m/s^2 and only 1.19×10^{-17} m/s^2 in case the satellite is also spinning.

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7. Shape dissymmetries and electrical effects

From the electrical point of view, each test-mass is surrounded by a number of gold-coated silica parts, two electrode cylinders, one inside and one outside the test-mass, but also two end disc plates which translate into two planar ring plates regarding the cylindrical mass ends and two sets of three finger stops whose purpose is to block the mass during launch and to limit the mass motion when there is no servo-control after retraction, located also at each end of the mass. These finger stops are at the same potential as the test-mass and sufficiently far away from it to consider that they do not induce any noticeable electrostatic stiffness.

The test-masses and the gold-coated electrode cylinders are all considered as equipotential conductors with limited patch effect thanks to motionless masses with respect to the conductive cages in regard. Since there is no relative displacement of the parts, we can only consider time and thermal variations at the test frequency of the difference of potential and not the DC patch. Not relying only on conjectured models, we also benefit for the evaluation of these disturbance sources from the behavior of previous space accelerometers either in laboratory or in orbit.

With perfect symmetry and coaxiality of all the cylinders and masses, there would then be no electrostatic pressure resultant applied on the mass. This is why the cylinder main symmetry defects must be kept to a minimum, such as cylindricity which translates into a combination of a cone and a barrel shape, or concentricity and coaxiality of the inner and outer diameters.

These defects create electrostatic biasing forces, stiffness and can modify the considered electrode force laws relation to the control electrical potentials. Care has been paid to verify deeply that the manufacturing accuracy of the parts are in agreement with the evaluation of these disturbances.

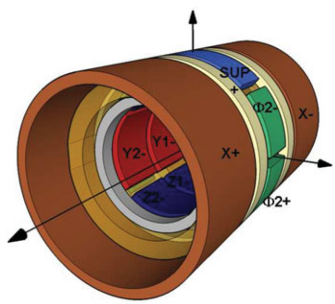

Figure 3. Electrode configuration : the electrode pairs, etched on gold-coated silica cylinders, control the six degrees of freedom of the encaged test-mass.

8. Emissivity and outgassing

We finally consider parasitic effects due to temperature gradients and residual pressure. A prototype model in laboratory under passive vacuum for two years demonstrates by daily measurements a residual pressure kept below 10^{-5} Pa.

With temperature gradients variations inferior to 2 mK/m verified on a thermal breadboard at the test frequency in the case of the satellite rotation mode, the radiometer effect modeled as $\Gamma_{\text{radio}} = 1/2 \cdot PS/mT \cdot \Delta T$ is limited to $\Gamma_{\text{radio}} < 10^{-16}$ m/s^2 at the test frequency.

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The outgassing effect depends on the mass material, its cleanliness and creates a difference of forces exerted on each side of the test-mass along any axis by variation of gas pressure induced by surface outgassing fluctuations and is kept below 10^{-17} m/s^2 thanks to the low temperature gradients inside the instrument core.

The radiation pressure model takes into account the emissivity and reflectivity of the mirror-like surfaces in regard in the case of MICROSCOPE and the multiple reflections of photons that would create a differential force on the test-mass resulting in the expression $\Gamma_{\mathrm{radia}} = 8/3 \cdot S\sigma/mc \cdot k\,(\epsilon_c, \epsilon_m)\, T^3 \Delta T$ where $k\,(\epsilon_c, \epsilon_m) = (1+\epsilon_m)(1-\epsilon_c)/(1-\epsilon_m \epsilon_c)$, function of the reflectivity of the test-mass and the cage. Since ϵ_m and ϵ_c are both very close to 1, the value of k can greatly vary from 0 to 2. In that respect, the model we consider is conservative and $k = 2$ for a disturbance of 1.2×10^{-16} m/s^2, still compatible with our needs.

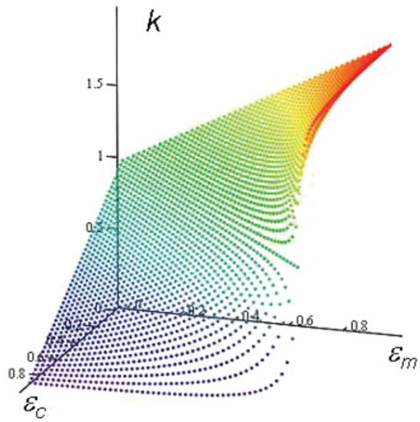

Figure 4. Correction factor of the radiation pressure model, function of the mass and cage reflectivities.

9. Conclusion

Mass geometry, material, magnetic susceptibility, surface outgassing, surface electrical and optical properties all have very mandatory requirements for the objective of the MICROSCOPE space mission, the test of the Equivalence Principle with an accuracy of 10^{-15}. All disturbing effects have been considered to evaluate the instrument performance limitation and to define in consequence the best payload configuration and satellite environment. The present production of the qualification model of the instrument confirms the possibility to meet all requirements. In the near future this instrument will be tested in drop tower and the flight models are foreseen to be delivered at the end of next year for the launch scheduled in 2012.

10. Acknowledgements

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