Objects in space get charged because of cosmic rays and solar wind. Charging is especially intense if the spacecraft passes over the so called South Atlantic Anomaly (once per orbit), as it is the case with the STEP and μSCOPE sun-synchronous orbits. Electric interactions effects are huge compared to the small gravitational signal to be detected in these experiments. For STEP a radiation sensor has been proposed in order to discard contaminated data [29], or else a 130 *kg* tungsten shield to reduce the flux of dangerous particles [30]. Another solution is to discharge each test cylinder, which in STEP and μSCOPE are levitated (by electrostatic forces in μSCOPE, by superconducting magnetic bearings in STEP). The solution chosen for μSCOPE is passive discharging (by means of a thin conducting gold wire), while the current solution for STEP is active electric discharging. The effect of the stiffness and damping of the wire in one case [42], and that of acting directly on the test masses in order to first measure the charge it has acquired and then to neutralize it, are serious matters of concerns in both experiments whose original design, being based on levitated test bodies, is naturally prone to electric charging.

To summarize, with the STEP experiment concept it is mandatory to operate at very low temperatures in order to achieve a high accuracy test of the Equivalence Principle. In turn, this choice has profound consequences in terms of the mission complexity, hence inevitably on its risks and cost. The μSCOPE variant of STEP at room temperature is severely limited by the radiometer effect and by a read-out system which does not exploit the differential nature of an Equivalence Principle violation signal. It is also worth recalling that a free fall experiment has been proposed for testing the Equivalence Principle inside a vacuum capsule to be released from a balloon at an altitude of 40 *km*, allowing a free fall time of 30 *s* [43]. The gravity detector to be used is a differential version (with zero baseline) of ISA–Italian Spring Accelerometer–built at IFSI–CNR in Rome and tested in the Gran Sasso Laboratory by measuring Luni-Solar tides. ISA is based on torsional spring suspensions and capacitive pick ups. At release inside the capsule ISA would be given a rotation rate of about 1 *Hz,* so as to modulate the signal of a possible violation of Equivalence at this frequency. The experiment can be performed also at low temperature. The expected sensitivity is of 1 part in 10^{14} at room temperature and one order of magnitude better at low temperature. This is competitive with the target of μSCOPE, with the additional advantages that the experiment can be easily repeated (to modify and improve the apparatus) and that suborbital flights are obviously much less expensive than free flyers, even if they need low altitudes.

7.2 The GG space experiment

In the case of GG the concentric test cylinders spin around the symmetry axis at a rather high frequency (2 *Hz* with respect to the center of the Earth) and are sensitive to differential effects in the plane perpendicular to the spin/symmetry axis (see Fig. 7, to be compared with Fig. 4). A cylindrical spacecraft encloses, in a nested configuration, a cylindrical cage and the test bodies inside it; the whole system has a dominant moment of inertia with respect to the symmetry axis and is (passively) stabilized by 1-*axis* rotation around it. The suspensions are all mechanical, and very weak, thanks to weightlessness. The test cylinders are weakly coupled, forming a mechanical system similar to an ordinary beam balance with the beam along the symmetry axis of the cylinder, and therefore sensitive to differential effects in the plane perpendicular to the beam. The weaker the coupling, the longer the natural period of differential oscillations of the test bodies, the more sensitive the system is to differential forces such as the one caused by an Equivalence Principle violation. The mechanical suspensions provide passive electric discharging of the test cylinders.

As shown in Fig. 7, an Equivalence Principle violation in the field of the Earth would generate a signal of constant amplitude (for zero orbital eccentricity) whose direction is always pointing to the center of the Earth, hence changing orientation with the orbital period of the satellite.

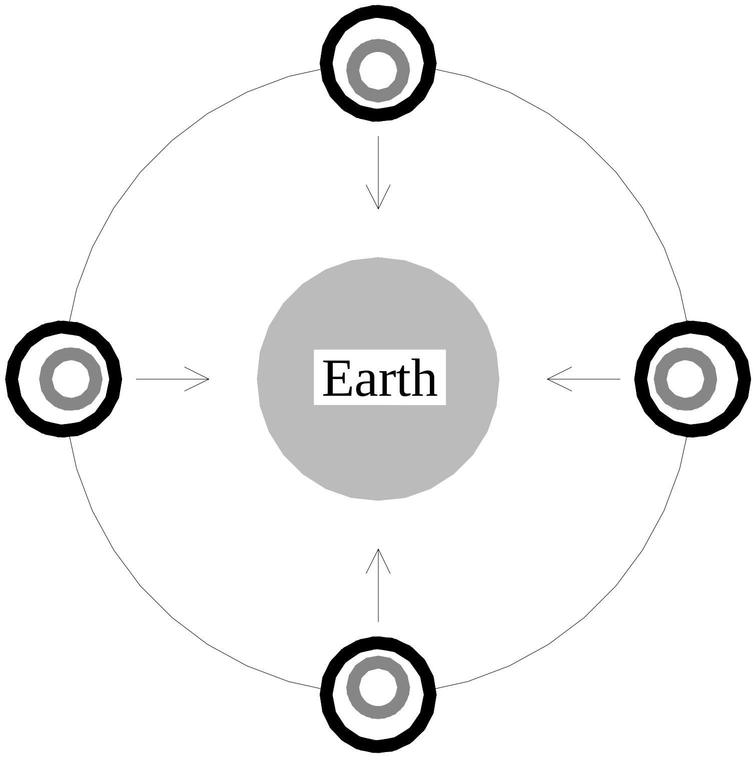

Fig. 7. – Section across the spin/symmetry axis of the GG outer and inner test cylinders (of different composition) as they orbit around the Earth inside a co-rotating, passively stabilized spacecraft (not shown). The centers of mass of the test cylinders are shown to be displaced towards the center of the Earth as in the case of a violation of Equivalence in the field of the Earth (indicated by the arrows). The read-out system (a capacitance bridge with plates located in between the test cylinders; not shown in figure) rotates at the same frequency as the test cylinders and the spacecraft, and therefore modulates the violation signal at this frequency (2 *Hz* with respect to the center of the Earth) (figure not to scale).

The read-out is made of 2 capacitance bridges (1 is for redundancy). In each bridge the two plates are placed half way in between the test cylinders, 180° from one another, and rotate with the system. Any differential force in the plane perpendicular to the spin/symmetry axis, as shown in Fig. 8, causes a mechanical displacement which unbalances the bridge and is transformed into an electric potential signal. A differential force in a fixed direction is modulated at the spin frequency of the bridge. The target of the GG experiment (10^{-17} in the Eötvös parameter η) requires to detect, at the orbiting altitude of the satellite ($\cong 500\ km$), a differential acceleration of $\cong 8.4 \cdot 10^{-15}\ cm\ s^{-2}$ yielding, in the GG system, a differential displacement of almost $10^{-10}\ cm$ amplitude. This mechanical displacement is transformed by the capacitance bridge (with the specific capacitances and gap of the GG system) into an electric potential signal of about 1 nV .

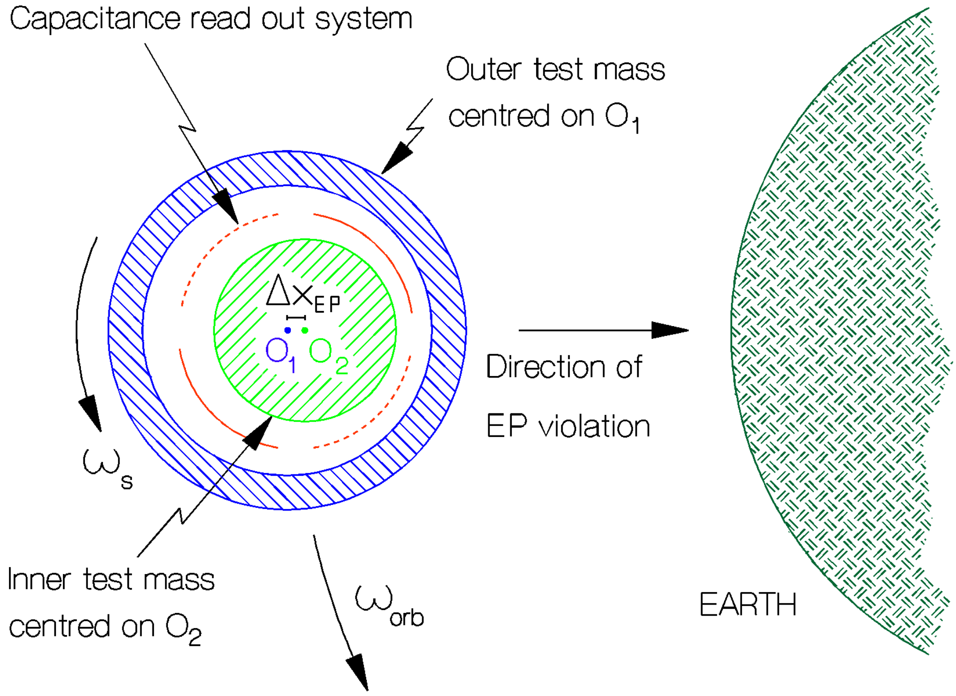

Fig. 8. – Section of the GG coaxial test cylinders and capacitance sensors in the plane perpendicular to the spin axis (not to scale). The capacitance plates of the read-out are shown in between the test bodies, in the case in which the centers of mass of the test bodies are displaced from one another by a vector $\Delta\vec{x}_{EP}$ due to an Equivalence Principle violation in the gravitational field of the Earth (e.g., the inner test body is attracted by the Earth more than the outer one because of its different composition). Under the (differential) effect of this new force the test masses, which are weakly coupled by mechanical suspensions, reach equilibrium at a displaced position where the new force is balanced by the weak restoring force of the suspension, while the bodies rotate independently around O_1 and O_2 respectively. The vector of this relative displacement has constant amplitude (for zero orbital eccentricity) and points to the center of the Earth (the source mass of the gravitational field); it is therefore modulated by the capacitors at their spinning frequency with respect to the center of the Earth.

As in an ordinary balance, the two arms can be adjusted (with PZT actuators) in order to reject forces acting in *common mode*, such as the inertial forces generated by air drag or by other non gravitational forces acting on the outer surface of the spacecraft. Mechanical beam balances can reject common mode forces very effectively, hence are very sensitive to differential effects. In this respect the GG design of the test bodies differs from both the STEP and µSCOPE designs in which each test cylinder is suspended independently. In addition, the GG capacitance bridge is a differential sensor, similarly to the STEP differential SQUID. However, no feed back is required because of the restoring force provided by the mechanical suspensions. For the same reason, common mode motions need not be controlled either. A scheme of the mechanical system formed by the GG test cylinders is given in Fig. 9.

The effects of air drag –and of any other non gravitational forces– are partially rejected by the coupled system of the test bodies and partially compensated by means of FEEP thrusters. They require only a few tens of grams of Cs propellant, allowing long mission duration and data taking. Vibration noise due to the thrusters firing at the spin frequency is attenuated by the mechanical suspensions of the cage enclosing the test cylinders.

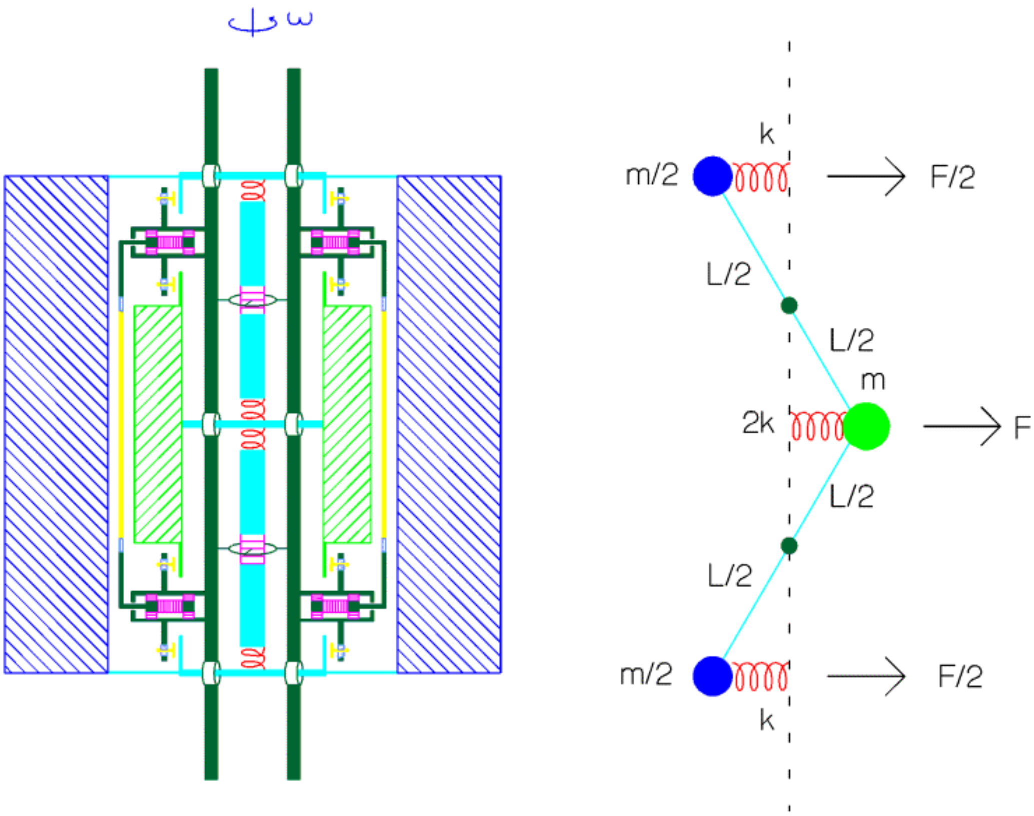

Fig. 9. – (Figure to scale) Section through the spin axis of the GG test cylinders (10 *kg* each) and the capacitance plates of the read-out in between. The lower density cylinder (21 *cm* in height) encloses the higher density one. Inside the inner cylinder is a narrow tube rigidly connected to a laboratory not shown here (also of cylindrical shape, and in its turn suspended inside the spacecraft) enclosing the test bodies and the read-out capacitance plates shown here. Two arms inside the tube, but not in contact with it, are used to couple the test bodies; the only connection between the coupling arms and the laboratory is via two flat gimbals at the midpoints of each arm. The inner test cylinder is suspended from the coupling arms at its center by means of two helical springs; the outer one is also suspended from the arms with helical springs, one at the top and one at the bottom of its symmetry axis. Being pivoted on torsion wires the gimbals allow conical movements of the coupling arms around their midpoints, e.g. in response to a differential force between the test bodies. The PZT actuators shown next to the gimbals are for adjusting the length of the two halves of each coupling arm. The capacitance plates of the read–out are shown in between the test cylinders; they are connected to the laboratory tube and have inch–worms for adjusting their distance from the surfaces of the test cylinders.

The GG bodies all spin at a frequency much higher than their natural frequencies of oscillation (which are very low because of the very weak suspensions that can be used in the absence of weight). This state of rotation is very close to that of ideal, unconstrained, rotors and allows the test cylinders to self-center very precisely (the center of mass of an ideal free rotor would be perfectly centered on the spin axis). Self–centering is possible if the suspended bodies are free to move in a plane; it is not possible if they are constrained to a 1-dimensional motion, as in the rotating experiment proposed by [24] (see [25]). However, suspensions are not perfect, which means that, as they undergo deformations at the frequency of spin, they also dissipate energy. The higher the mechanical quality of the suspensions, the smaller the energy losses. Energy dissipation causes the spin rate to decrease, hence also the spin angular momentum will decrease; and since the total angular momentum must be conserved, the suspended bodies will develop slow whirl motions one around the other. Although very slow, whirl motions must be damped. In GG they are damped actively with small capacitance sensors/actuators and appropriate control laws which have been developed, implemented and tested in a numerical simulation of the full GG satellite dynamical system using the software package DCAP of Alenia Spazio (also checked by simulating the GG dynamical system in Matlab). Simulations include drag free control as well. They demonstrate that the system can be fully controlled and that the control does not affect the expected sensitivity of the GG experiment (10^{-17} in the Eötvös parameter η). In fact, with the measured value of the quality factor of the suspensions ($\cong$ 20000), whirl motions of the test cylinders are so slow that they can be damped at time intervals long enough to allow data taking in between, when active damping is switched off and will therefore produce no disturbance at all on the Equivalence Principle test. Laboratory tests of the GG prototype (sect. 8) performed with the damping devices switched off, have confirmed that the growth rates of whirl motions are very slow.

As a novel subject, damping of whirl motions in the GG experiment has been the subject of extensive analysis. Doubts have been expressed and a paper has been published [44] arguing that the GG proposed test of the Equivalence Principle would be limited, because of whirl motions instabilities, to a sensitivity of 1 part in 10^{14}, which is 3 orders of magnitude worse than the sensitivity expected by the GG Team. The issue has now been settled [35, 36 Ch. 6].

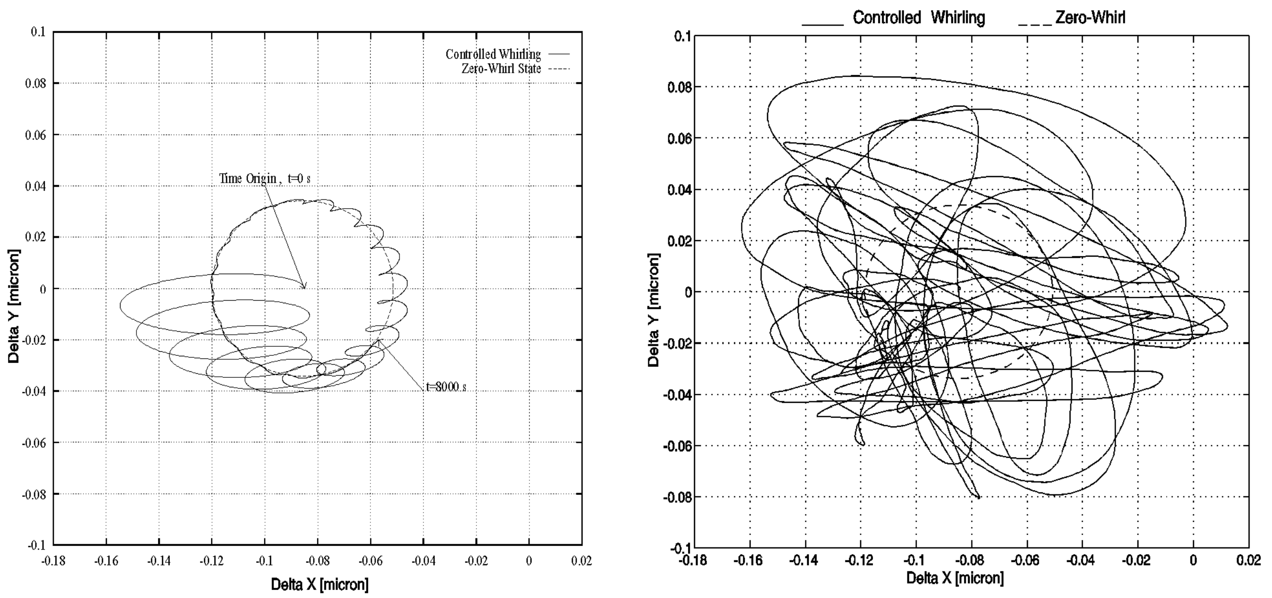

Fig. 10. – (Taken from [35]) Trajectory of the relative motion of the centers of mass of the GG outer spacecraft and the laboratory which encloses the test cylinders in the plane perpendicular to the spin axis in a 2-body model (coupling constant 0.02 *N/m*, Q=90). The Y axis is pointed to the center of the Earth, hence the largest effect of the residual atmospheric drag, assumed to be of $5\cdot 10^{-9}$ *N*, is a constant displacement along the X axis (of $\cong$ 0,08 μm); its second harmonic (assumed to be 40% of it) appears in this system as a variation at the orbital period (5700 *s*). This is the dashed circle, showing –in both plots– the stationary state that the system would reach if the whirl motion were perfectly damped. The plot on the left is obtained with the control laws of the GG team assuming the following errors: initial bias of 10 μm linear and 1° angular; fractional error in spin rate measurements $\Delta\omega_s/\omega_s=10^{-4}$; offset (by construction and mounting) of 10 μm; errors in the capacitors of 0.1 μm r.m.s. Whirl oscillations with the natural period of 314 *s* (around the points of the dashed circle) and of decreasing amplitude are apparent as the system is brought to its stationary state in 8,000 *s* only. Note that at this point the relative distance of the two centers of mass is below 5 *Å*. The plot on the right shows, for the same system, but under much more ideal assumptions (perfect knowledge of spin

rate; perfect centering of the rotor; an initial linear bias of 1μm and no angular bias; an error in the sensors/actuators 10 times smaller, i.e. of 10^{-2} μm) the results obtained by applying the control laws proposed by [44]. It is apparent that even in a much more favorable situation the same system has been unwittingly transformed into one dominated by very large active forces for which there is in fact no need, as the plot on the left demonstrates. Note that the dissipation has been assumed to be the same in both cases (Q=90), hence failure to stabilize the whirl motion (right-hand plot) has to be ascribed only to the control laws implemented in that case. Regarding the plot on the left, note that the assumptions for the various error sources are conservative. For instance, small capacitors like those designed for GG can be shown in the laboratory to be sensitive to relative displacements of 10^{-2} μm.

The plots of Fig. 10 are worth showing; although they refer to a simplified 2–*body* model (in this case the GG outer spacecraft and the cylindrical laboratory suspended inside it), they show a very clear comparison between the two approaches. Results from simulations of the complete system are reported in [36 Ch. 6]. The basic physical principles which govern the behavior of weakly coupled fast spinning rotors in space may also be of interest to the reader due to the novelty of the subject [45].

The GG experiment allows signal modulation at high frequency (much higher than in other experiments of its kind); moreover –similarly to the torsion balance and unlike a general purpose accelerometer– it has been designed as a *differential* instrument specifically to detect a violation from the Universality of Free Fall. It is operated at room temperature. Does the radiometer effect limit the GG sensitivity as severely as in the case of µSCOPE? In GG the radiometer effect must be computed in the plane perpendicular to the symmetry axis of the test cylinders (Fig. 7). Any temperature gradient in this plane in the direction of the Earth will result in a radiometer effect indistinguishable from the signal. However, azimuthal temperature asymmetries on the surface of the spacecraft itself are reduced by its 1-*axis* rotation according to the formula:

$$\Delta T_{sc} = \frac{\alpha \cdot \Phi \cdot h \cdot r \cdot P}{c \cdot m / 2} \tag{24}$$

yielding a temperature difference ΔT_{sc} of a few *mK* for a spinning spacecraft exposed to the infrared radiation flux of the Earth ($\Phi \cong 2.4 \cdot 10^5$ $erg\ cm^{-2}\ s^{-1}$) and resembling the outermost shell of GG (radius r=0.5 *m,* height h=1.3 *m,* mass m=33 *kg,* specific heat c=$0.9 \cdot 10^7$ $erg\ g^{-1}\ K^{-1}$ (0.2 $cal\ g^{-1}\ K^{-1}$), absorption coefficient α =0.73*,* spin period P=0.5 *s*). A thin (0.2 *cm*) insulating layer (Mylar or Kapton) inside the spacecraft shell, whose timescale of thermal inertia is τ = 40 *s*, will further reduce the temperature difference to ΔT_{mylar} of the order of 10 μK:

$$\Delta T_{mylar} \cong \frac{\Delta T_{sc} P}{2\tau} \tag{25}$$

Finally, vacuum between this layer and the cage enclosing the test cylinders (made in Cu and coated with Mylar) does ensure radiative transfer of heat and consequent very effective reduction of temperature differences in the direction of the Earth, to ΔT_{cage} of the order of 10^{-10} K (comparable to quantum fluctuations over half the spin period) according to:

$$\Delta T_{cage} = \frac{\sigma \cdot S_{cage} \cdot T^3 \varepsilon_{mylar} \cdot P}{c_{cage} M_{cage}} \Delta T_{mylar} \tag{26}$$

where σ is the Stefan-Boltzmann constant, S_{cage}=1 m^2, M_{cage}=40 kg, c_{cage}=3.9·10^6 $erg\ g^{-1}\ K^{-1}$ are the mass, surface and specific heat of the cage, ε_{mylar}=0.05 is the emissivity of Mylar.

It is apparent that temperature differences as small as these make the radiometer effect totally negligible in the GG mission. The result holds at room temperature and shows no need for a cryogenic experiment. The radiometer effect is not a limiting factor in Equivalence Principle testing for this mission. Thermal noise is higher at higher temperature, but since it is proportional to $\sqrt{(T/M)}$ (with M the mass of a test body), more massive test cylinders (10 *kg* in GG, about 100 *g* in STEP) compensate for the higher temperature.

Fast spin of the whole GG system has other advantages. Any local disturbing source rotates with the sensors, and therefore gives a DC effect. This helps considerably in dealing with perturbations such as those caused by local mass anomalies, parasitic capacitances, or the so called "patch effects". They can be separated from the expected signal (modulated at the spin frequency) without posing severe requirements on the experiment design. The differential acceleration caused by the Earth tidal perturbation, due to the centers of mass of the test cylinders not being exactly coincident in the plane perpendicular to the spin/symmetry axis, appears at twice the frequency of spin.

In the present baseline the GG satellite is designed to fly on an equatorial orbit with the spin axis almost perpendicular to the orbit plane. This configuration maximizes the signal for the entire duration of the mission without any active control of the satellite. However, the GG satellite will be in the shadow of the Earth for about 2000 *s* each orbit, each orbit going from sunlight to darkness and viceversa. Fast spin helps reduce thermal effects and it is found that requirements on thermal stability can be met by means of passive isolation only. However, it appears that launchers capable to inject small satellites into low equatorial orbits are few and expensive, while the situation is more favorable for sun-synchronous, high inclination orbits such as those of STEP and µSCOPE. For this reason a new GG baseline, based on a sun-synchronous orbit, is being investigated within an advanced study funded by the Italian space agency (ASI). An additional accelerometer is also incorporated in the new design, whose test cylinders are made of the same material, for zero check. A unique property of the new accelerometer is that of being concentric to the original one, so that they are both close to the center of mass of the spacecraft and do not undergo different tidal effects from Earth, which would make the zero check more problematic.

Finally, a peculiarity of the GG design –based on mechanical suspensions and sensitive in the plane perpendicular to the symmetry axis of the test cylinders rather than along it, as in the case of STEP and µSCOPE– is that the system proposed for flight can be tested on the ground looking for a signal of violation in the horizontal plane of the laboratory while using the vertical direction to suspend the rotating cylinders against local gravity.

8 The GGG ("GG on the Ground") experiment: laboratory test of a proposed space apparatus