

## "GALILEO GALILEI" (GG)

A SMALL SATELLITE TO TEST THE EQUIVALENCE PRINCIPLE  
of  
GALILEO, NEWTON AND EINSTEIN

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## EXECUTIVE SUMMARY

The scientific goal of GG is to improve the current best ground tests of the Equivalence Principle (EP) by 5 orders of magnitude, searching for a new composition dependent effect to 1 part in  $10^{17}$ . Such an experiment would probe –flying a small satellite in low Earth orbit– a totally unexplored field of physics which is inaccessible to ground laboratories and where new findings are expected no matter whether the Equivalence Principle is confirmed or violated. GG has been studied to Phase A level by the Italian Space Agency (ASI) in 1998; the result of the study was consistent with the target proposed here. Proposals for space missions to test the Equivalence Principle go back almost to the very beginning of the space age; all major space agencies around the world have seriously considered –and still consider– EP missions for flight. The Stanford proposed STEP project has been studied twice by ESA at Phase A level; both times the studies reported a target in EP testing of 1 part in  $10^{17}$ .

As a small, 1-axis spin stabilized spacecraft in low Earth orbit, GG poses no problems and its subsystems can be taken from available busses. The only novelty is drag-free control with FEED mini-thrusters (an ESA technology largely developed in Italy), which is of considerable interest for the LISA mission. While pursuing a major scientific goal GG would also fully test the FEED for accurate drag-free control at low frequency and at room temperature. ESA itself has officially stated that the STEP drag-free control was to be seen as a preliminary test for LISA. If this is the case for STEP, which needs a different technology (He thrusters and not ion thrusters), and in cryogenic conditions, it must be the more so for GG, since it would test the technology of interest and not just the software. FEED could also be tested with the proposed ELITE technology mission. Yet, why only a technology mission if a major scientific result can be achieved in combination with a technology test? It is a trade off game. However, unless a technology is of immediate interest to the ordinary people (which is not the case here), it is always the science achieved by a space mission to capture the imagination of the media, the public and –ultimately– of the taxpayers which provide the resources for all space activities.

It is not unusual that challenging scientific experiments need, at some point, to be rethought completely anew. This is the case with GG, which is based on new concepts. These concepts have been debated in the open literature and within space institutions for a few years by now, and proved to be sound. More importantly, the GG prototype experiment in the laboratory demonstrates that these concepts are sound. The challenge in this field is to exploit the stronger signal in space and the absence of weight to fly an experiment able to improve, by many orders of magnitude, the current sensitivity. Very accurate EP tests require (on Earth and in space) that spurious relative motions of the test bodies be greatly reduced, leaving them essentially motionless. Achieving that in space, with more than one pair of test bodies, is an unnecessary complication if the issue is to prove high sensitivity. For this reason GG is proposed with a single pair of test masses, whose composition can be carefully selected.

ESA has identified an EP mission as a high priority since 1996, and has allocated the sum of 21.7 Meuro as a contribution to a NASA-led STEP mission, should NASA decide to fly it. ESA is therefore totally dependent on NASA with respect to the implementation of this priority. As the future of STEP is uncertain (Nature [402](#), 7, 1999), we argue that GG is a viable back up for a mission which has been identified as being of prime importance to ESA. The argument is twofold: (i) the scientific and technological goals of GG; (ii) the cost of GG to ESA, which can be limited to the cost of the spacecraft (19 Meuro estimated by ALENIA; see Letter I), thus placing GG in the category of particularly cheap missions (Sec. 2.8 of Call). Reference is to the annexed Letters IV and VI, by the president of ASI, in which he seeks collaboration between ASI and the Indian space authority for the launch of GG, expresses the willingness of ASI to provide the GG payload, offers the use of the Malindi tracking station for ground operations, envisages the possibility for GG to be injected in its orbit with the qualification launch of Vega, should Vega evolve positively. Reference is also to Letter VII, by the Principal of Pisa University, to confirm that GG science operations and archiving would be carried out entirely at the University of Pisa, at no cost to ESA.

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ANNEXED LETTERS: (online at: [http://tycho.dm.unipi.it/ESA\\_F2&F3/annexed\\_letters.html](http://tycho.dm.unipi.it/ESA_F2&F3/annexed_letters.html))

- I. Letter by ALENIA AEROSPAZIO (Dr Carlo Fea) to A.M. Nobili. Date: January 20, 2000. Subject: GG Cost Estimate for Phases B + C/D. 2-page letter plus Work Breakdown Structure (page 3) and Hardware Matrix (page 4)
- II. Letter by LABEN (Ing. Marco Pascucci) to A.M. Nobili. Date: January 21, 2000. Subject: GG Payload Cost Estimate for Phases B + C/D. 2-page letter.
- III. Letter by ASI (Professor G.F. Bignami) to A.M. Nobili. Date: January 11, 2000. Subject: Endorsement of GG Proposal to ESA. 1-page letter.
- IV. Letter by the President of ASI (Professor S. De Julio) to Dr. K. Kasturirangan, Chairman of Indian Space Commission and Secretary, Department of Space. Date: January 14, 2000. Subject: Collaboration on GG Small Mission Project. 2-page letter.
- V. Letter by Professor R. Cowsik, Director of Indian Astrophysics Institute, to Professor S. De Julio, President of ASI, expressing interest in GG (also on behalf of Dr. K. Kasturirangan). Date: December 8, 1998. 1-page letter.
- VI. Letter by the President of ASI (Professor S. De Julio) to A.M. Nobili. Date: January 28, 2000. Subject: Launch of GG Small Satellite. 1-page letter.
- VII. Letter by the Principal of the University of Pisa, Professor Luciano Modica, addressed "to whom it may concern in ESA and ASI". Date: January 25, 2000. Subject: GG Science Operations.

## 1. BACKGROUND, SCIENTIFIC AND TECHNOLOGICAL GOALS

### 1.1 THE BACKGROUND AND THE SCIENTIFIC GOAL

“GALILEO GALILEI” (GG) is a small satellite project devoted to testing the EQUIVALENCE PRINCIPLE (EP) to 1 part in  $10^{17}$  (long range), an improvement by 5 orders of magnitude over the best results obtained so far on Earth. It is the same target of the STEP mission proposal as evaluated twice by ESA at Phase A level within the competitions for the medium size missions M2<sup>1</sup> and M3<sup>2</sup>.

Do bodies of different composition fall with the same acceleration in a gravitational field? If not, the so called Equivalence Principle (EP) is violated. The Equivalence Principle, expressed by Galileo and later reformulated by Newton, was assumed by Einstein as the founding Principle of General Relativity, so far the most widely accepted theory of gravitation. In fact, it is not a Principle but a starting hypothesis unique to Gravity: no Equivalence Principle holds for the other fundamental forces of Nature (the electromagnetic, weak and strong interactions) and almost all theories trying to unify gravity with these forces require an EP violation, thus indicating that General Relativity may not be the final truth on gravitation, just as Newton’s theory of gravitation was proved by Einstein not to be the final truth at the beginning of 1900. All tests of General Relativity, except those on the Equivalence Principle, are concerned with specific predictions of the theory; instead, EP tests probe its basic assumption, and this is why they are a much more powerful instrument of investigation. A high accuracy, unquestionable, experimental result on the Equivalence Principle –no matter whether it is confirmed or violated – will be a crucial asset for a long time to come. And this is how it has to be, because physics is an experimental science in which any theory, in spite of its internal consistency and beauty, has to confront experiments, and ultimately will stand or fall depending solely on experimental results.

Galileo questioned Aristotle’s statement that heavier bodies should fall faster than lighter ones, arguing instead that all bodies fall at equal speeds regardless of their mass (which he proved by reasoning) and composition (which he proved by experiments). Galileo’s formulation of the universality of free fall, which lately became known as the Equivalence Principle, was first published in 1638: “...veduto, dico questo, cascai in opinione che se si levasse totalmente la resistenza del mezzo, tutte le materie descenderebbero con eguali velocità “ (“... having observed this I came to the conclusion that, if one could totally remove the resistance of the medium, all substances would fall at equal speeds ”). It appeared in his Discorsi e dimostrazioni matematiche intorno a due nuove scienze attinenti alla meccanica e ai movimenti locali, which was published outside Italy (in Leiden) few years after completion due to Galileo’s prosecution by the Church of Rome<sup>3</sup>. Aged 74, Galileo was blind and under house arrest; but the Discorsi are based on much earlier work, mostly on experiments with the inclined plane and the pendulum going back almost 40 years to the time when he was a young lecturer at the University of Pisa, or had just moved to Padova. Galileo was well aware that his experiments with inclined planes and pendula were much more accurate than just dropping masses from a tower; but ideal mass dropping experiments allowed him to express the universality of free fall in a very straightforward manner, not requiring any deep understanding of mechanics. Indeed, no image of science has captured the imagination of ordinary people more than that of Galileo dropping masses from the leaning tower of Pisa, a symbol of the birth of the modern scientific method.

About 80 years after Galileo's first experiments Newton went further, actually recognizing the proportionality of mass and weight. Newton regarded this proportionality as so important that he devoted to it the opening paragraph of the Principia<sup>4</sup>, where he stated: "This quantity that I mean hereafter under the name of ... mass ... is known by the weight ... for it is proportional to the weight as I have found by experiments on pendulums, very accurately made..." . At

the beginning of the 20<sup>th</sup> century, almost 300 years since Galileo's work, Einstein realized that because of the proportionality between the gravitational (passive) mass  $m_g$  and the inertial mass  $m_i$ , the effect of gravitation is locally equivalent to the effect of an accelerated frame, and can be locally cancelled. This is known as the Weak Equivalence Principle which Einstein introduced in 1907<sup>5</sup> as the "hypothesis of complete physical equivalence" between a gravitational field and an accelerated reference frame: in a freely falling system all masses fall equally fast, hence gravitational acceleration has no local dynamical effects. Therefore, according to Einstein, the effects of gravity are equivalent to the effects of living in a curved space-time. In this sense the Equivalence Principle expresses the very essence of General Relativity and as such it deserves to be tested as accurately as possible. In the last 30 years since the advent of the space age General Relativity has been subjected to extensive experimental testing as never before in its first 50 years of existence, and so far it has come out having no real competitors; the crucial area where experimental gravitation is likely to play an important role is in the verification of the universality of free fall as a test of the weak equivalence principle itself, since it is tantamount to testing whether gravitation can be ascribed to a metric structure of space-time.

The total mass-energy of a body can be expressed as the sum of many terms corresponding to the energy of all the conceivable interactions and components:  $m = \sum_k m_k$ . The adimensional Eötvös parameter  $\eta = 2[(m_g/m_i)_A - (m_g/m_i)_B]/[(m_g/m_i)_A + (m_g/m_i)_B]$  which quantifies the violation of equivalence for two bodies of composition A and B, inertial mass  $m_i$  and gravitational mass  $m_g$ , can be generalized into

$$\eta_k = \frac{2[(m_g/m_i)_{A_k} - (m_g/m_i)_{B_k}]}{[(m_g/m_i)_{A_k} + (m_g/m_i)_{B_k}]} \quad (1.1)$$

such that a non-zero value of  $\eta_k$  would define the violation of equivalence between the inertial and gravitational mass-energy of the k-th type. For instance, the rest mass would contribute (as a fraction of the total) for  $\cong 1$ ; the nuclear binding energy for  $8 \cdot 10^{-3}$ , the mass difference between neutron and proton for  $8 \cdot 10^{-4}$  (A-Z) (A being the number of protons plus neutrons and Z the number of protons in the nucleus), the electrostatic energy of repulsion in the nuclei for  $6 \cdot 10^{-4} Z^2 A^{-4/3}$ , the mass of electrons for  $5 \cdot 10^{-4} Z$ , the antiparticles for  $\cong 10^{-7}$ , the weak interactions responsible of  $\beta$  decay for  $\cong 10^{-11}$ . From the point of view of conventional field theory, the verification of all these separate "Equivalence Principles" corresponds to a very peculiar coupling of each field to gravity; whether and why it should be so in all cases is a mystery. Let us consider the case of antiparticles. A peculiarity of gravity, strictly related to the Equivalence Principle, is that there is so far no evidence for antigravity, namely for the possibility that matter is gravitationally repelled by antimatter. A negative ratio of inertial to gravitational mass would obviously violate the Equivalence Principle and forbid any metric theory of gravity. Yet, there are theoretical formulations which would naturally lead to antigravity. Unfortunately, while experiments concerning the inertial mass of antiparticles have been highly successful, and these are very accurately known, gravitational experiments (i.e. involving the gravitational mass of antiparticles) are extremely difficult because of the far larger electric effects, such as those due to stray electric fields in the walls of the container. In absence of such direct tests, an improvement by several orders of magnitude of current tests of the weak Equivalence Principle with ordinary matter would also be an important constraint as far as the relation between gravity and antimatter is concerned.

Nearly all attempts to extend the present framework of physics predict the existence of new interactions which are composition dependent and therefore violate the Equivalence Principle. EP tests are by far the most sensitive low energy probes of such new physics

beyond the present framework. This is because any deviation from the universality of free fall –expressed as a fractional differential acceleration  $\Delta a/a$  between falling bodies of different composition– is proportional to the post-Newtonian deviations from General Relativity measured, for instance, by the adimensional parameter  $\gamma^* \equiv \gamma - 1$  ( $\gamma$  the Eddington parameter) with a proportionality factor  $\ll 1$  (from  $10^{-5}$  to  $10^{-3}$ , depending on scalar or vector models). While  $\gamma^*$  is constrained by post-Newtonian or pulsar tests below  $10^{-3}$ , the current ground results on the Equivalence Principle, giving  $\Delta a/a \leq 10^{-12}$ , already constrain  $\gamma^*$  below  $10^{-7}$  or  $10^{-9}$ , which clearly shows the superior probing power of EP tests.

No precise target accuracy, at which a violation should occur, has been predicted by these theories; an EP violation is expected, but only below the  $10^{-12}$  level reached so far, probably well below it. Whether this is really so, only high accuracy experiments can tell.

The first experimental apparatus to provide very accurate EP tests (to  $10^{-8}$ - $10^{-9}$ ) was the torsion balance used by Eötvös<sup>6</sup>, at the turn of the 20<sup>th</sup> century, and later on by his students<sup>7</sup>. The reason is simple: an EP test requires to detect tiny differences in the accelerations of two test bodies falling in the gravitational field of a source mass. It is therefore a differential experiment, naturally yielding the best sensitivity if performed with a differential apparatus like the torsion balance: no violation, no signal. Although in reality no apparatus is perfectly differential, the advantages are enormous. The next leap in sensitivity (to  $10^{-11}$ - $10^{-12}$ ) came in the 60s<sup>8</sup> and early 70s<sup>9</sup> with the recognition that by taking the Sun as the source mass rather than the Earth, any differential effect on the test bodies of the torsion balance would be modulated by the 24<sup>hr</sup> rotation of the Earth on which the experiment sits. Everyone who has attempted to detect a weak signal knows how important modulation is. Indeed, the modulation frequency should be as high as possible, in order to reduce "1/f" noise (electronic and mechanical). Which explains why the best and most reliable results in EP testing (to about 1 part in  $10^{12}$ ) have been achieved in recent years by the "Eöt-Wash" group at the University of Seattle<sup>10</sup> with a torsion balance placed on a turntable which modulates the signal at 1–2hr period. An alternative to attempting faster rotation is pursued in India<sup>11,12</sup> by R. Cowsik and his group, based on a much heavier torsion balance (1.5kg) in a very low noise environment (25m under the ground) with very good thermal stability (obtained by means of two, very large, concentric vacuum chambers).

In GG the signal modulation (Figure 2.1) is provided by the 2Hz rotation rate of the entire satellite which encloses the test bodies, about 4 orders of magnitude higher than the modulation frequency of the best ground based experiments. In addition, it is well known since the beginning of the space age that if the test bodies of an EP experiment orbit the Earth the driving signal of a possible EP violation increases by about 3 orders of magnitude, correspondingly increasing the achievable sensitivity in EP testing. Last but not the least, in absence of weight test bodies do not need to be suspended against the 1-g local acceleration of gravity; the largest force acting on the GG test bodies in space is about  $10^8$  times smaller than 1-g, which obviously simplifies the experiment. If the risks of working in remote, with no direct access to the apparatus, are minimized by manufacturing and testing a ground based payload prototype (in addition to performing the usual simulation and tests of all space instruments), the advantages of working in space can be fully exploited to improve the current best ground results by 5 orders of magnitude. Even with further progress in ground experiments (e.g. to an accuracy of 1 part in  $10^{13}$ , possibly  $10^{14}$ ) the GG small mission would undoubtedly mean a great leap forward, allowing space scientists to probe a totally unknown, highly promising field of physics like no other ground experiment can even dream of.

To a less ambitious level of target accuracy, interesting results can be obtained by dropping an ISA<sup>13</sup>–type differential accelerometer inside a capsule in sub-orbital flight with a free falling time of  $\approx 30$ sec<sup>14,15</sup>. Similarly to GG, ISA is based on very weak mechanical

suspensions and a capacitance read out; also, the instrument is spun up to  $\cong 1\text{Hz}$  when dropped inside the capsule in order to modulate the expected signal at high frequency, similarly as in GG. According to the analysis published<sup>14,15</sup>, the Equivalence Principle can be tested to about  $10^{-14}$  at room temperature and to about  $10^{-15}$  in cryogenic conditions. Note that this target accuracy is the same as that expected for the MICROSCOPE<sup>16</sup> small satellite mission proposed in France, but with no need to place a satellite in orbit around the Earth, hence to a much lower cost and with the additional advantage of repeatability.

Surprisingly enough, completely different tests of the Equivalence Principle (for the Earth and the Moon falling towards the Sun) have achieved an accuracy close to that of torsion balance experiments<sup>17,18,19</sup>. The Earth–Moon distance is measured by lunar laser ranging (LLR) to the corner cube laser reflectors left by the astronauts on the surface of the Moon, accurate to better than 1cm. Were the Earth and the Moon to be attracted differently by the Sun because of their different composition (1/3 iron core and 2/3 silicate mantle the Earth; entirely silicate mantle the Moon), a physical model based on conventional Newtonian gravity with general relativistic corrections would not be able to make predictions reconcilable with the observed LLR data. This is an EP for different composition, but also for gravitational self–energy effects in the Earth (testing gravity's pull on gravitational energy), effects which are obviously absent in test bodies of laboratory size. According to Einstein, all forms of matter and energy, including the gravitational binding energy, accelerate at the same rate in a uniform gravitational field, and the gravitational binding energy of the Earth amounts to  $5 \cdot 10^{-10}$  of its mass and is therefore not negligible to the current achieved accuracy.

## 1.2 THE TECHNOLOGICAL GOAL

From the viewpoint of space technology GG is no challenge at all (it is a small satellite –263 kg including system margins<sup>Table 4.1</sup>– of cylindrical symmetry, stabilized by passive one axis rotation, moving in a low Earth orbit at 520 km altitude) except for one single item: that of being actively controlled for accurate drag compensation by means of the FEEP (Field Emission Electric Propulsion) minithrusters, a technology developed within ESA over many years. FEEP thrusters use Caesium propellant, have very high specific impulse and are electrically tuned far more precisely than mechanical thrusters. The driving signal is provided to the FEEP actuators by the capacitance sensors which monitor the relative position of the weakly suspended GG payload (the PGB, Pico Gravity Box laboratory) with respect to the spacecraft (see Figure 2.4). GG would be the most accurately drag free controlled satellite ever flown and an extremely valuable experiment in preparation for more complex and demanding missions in Fundamental Physics, namely the LISA project for the detection of gravity waves by laser interferometers. The control laws need to be adjusted from those required in GG (absence of rotation in LISA makes control laws easier) but the actuators, the required thrust and the frequency range are the same.

## 2. MAIN FEATURES AND NOVELTIES OF THE GG SPACE EXPERIMENT

In this chapter we briefly describe the main features of the GG space experiment and mission, outline the main differences with respect to STEP<sup>20,21,22,1,2</sup>, and describe the major advantages we see in the GG design. Details on GG are available in the literature<sup>23,24,25</sup>; the most complete analysis so far is given in the ASI Report on GG Phase A Study<sup>26</sup>.

### 2.1 HIGH FREQUENCY MODULATION OF THE EXPECTED SIGNAL

The advantage of a space experiment for EP testing (with a much stronger signal) was recognized soon after the beginning of the space age. While designing a space experiment

scientists also tried to provide high frequency modulation. The first proposed fast rotating experiment<sup>27</sup>, in 1970, envisaged a fast rotating platform so as to modulate the signal at its rotating speed. Unfortunately, in this apparatus the test bodies were constrained along one diameter of the rotating platform, and it is well known that any such unidimensional rotating system is always strongly unstable above the critical speed<sup>28, Ch. 6.1</sup>. The experiment concept was therefore incorrect, as long as high frequency modulation was the issue. Freedom to move in a plane (as it is the case for the GG test bodies) would solve this problem.

Figure 2.1 shows, in the plane perpendicular to the spin/symmetry axis, how the GG coaxial test cylinders (of different composition) would move one with respect to the other were they attracted differently by the Earth because of an EP violation. The Figure shows the test cylinders one inside the other and two pairs (for doubling the output data) of capacitance plates in between them to measure any relative displacement. If one of the bodies is attracted by the Earth more than the other, the two centers of mass move away from one another always towards the center of the Earth. In GG the test cylinders are coupled by very weak mechanical suspensions so that even a tiny differential force (in the plane perpendicular to the spin/symmetry axis) causes a mechanical displacement which is detectable once transformed into an electric potential signal by the capacitance read-out. 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 EP violation.

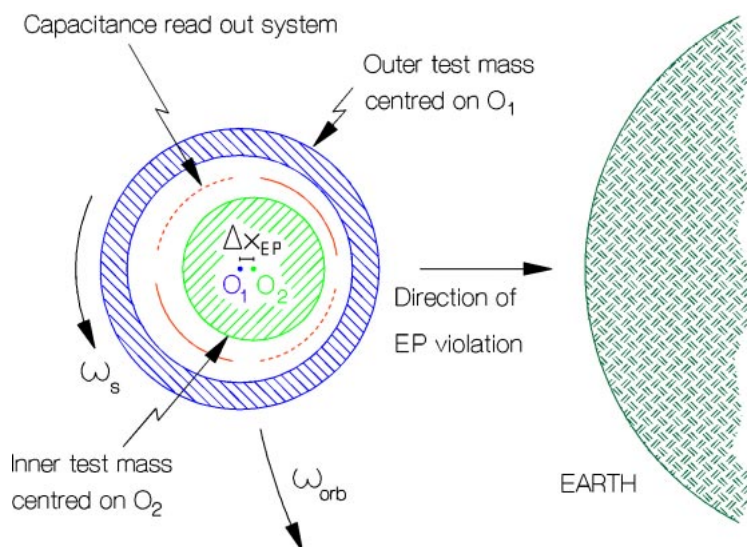


Figure 2.1. Section of the GG coaxial test cylinders and capacitance sensors in the plane perpendicular to the spin axis (not to scale). The capacitance plates of the read-out are shown in between the test bodies, in the case in which the centers of mass of the test bodies are displaced from one another 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 (see plot of simulation in<sup>26</sup>, Fig. 6.4). 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.

In the current settings and full simulation of GG at Phase A level<sup>26</sup> the natural period for differential oscillations of the test bodies is about 545sec: an EP violation by only 1 part in  $10^{17}$  would cause, in this system, a displacement of the test cylinders by about  $6 \cdot 10^{-11}$ cm, which can be detected as a voltage signal of about 1nV with a capacitance read-out which



has already been manufactured and tested in the laboratory<sup>Sec. 5</sup>. It is apparent from Figure 2.1 that spinning capacitance plates modulate the amplitude of the  $\Delta\vec{x}_{EP}$  displacement caused by an EP violation at their spinning frequency with respect to the Earth (2Hz in the current baseline), with a well defined phase (the vector does always point towards the center of the Earth). In absence of spin the signal has constant intensity (except for the effect of the orbital eccentricity of the satellite, which is close to zero:  $e \lesssim 0.01$ ) and a direction changing at the orbital frequency of the satellite around the Earth ( $\cong 1.75 \cdot 10^{-4}$  Hz); so in GG the signal is modulated at a frequency about  $10^4$  times higher than the frequency of the signal, the advantage being the reduction of low frequency electronic and mechanical noise. The spinning state of the GG spacecraft is a stable 1-axis rotation and needs no active control.

In STEP<sup>20,21,22,1,2</sup> (Figure 2.2) the concentric test cylinders must be kept fixed with respect to inertial space by active control of the spacecraft, their symmetry axis is the sensitive axis and lies in the orbital plane (the system is very stiff in the plane perpendicular to the symmetry axis). If the cylinders are attracted differently by the Earth because of an EP violation there is a relative movement of the two one inside the other; the effect is maximum when the symmetry axis is directed towards the center of the Earth (changing sign as the satellite moves by  $180^\circ$  around the Earth) and it is zero when the symmetry axis is perpendicular to the satellite-to-Earth direction. Hence, the signal has an intensity varying at the orbital frequency of the satellite. Any higher frequency signature, higher than the orbital frequency, that one would wish to impress on the signal requires the spacecraft to be spun around its actively controlled space-fixed attitude. Due to the STEP design these can only be slow rotations (hence yielding only low frequency modulation) which in addition require a careful and accurate active control.

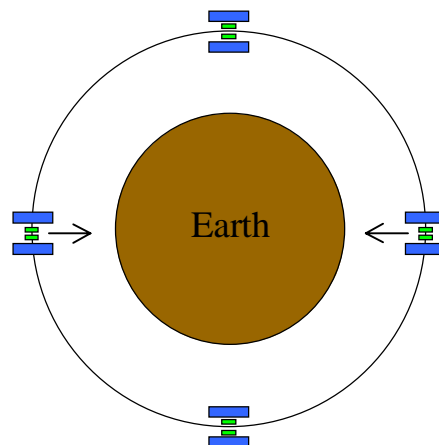


Figure 2.2 Schematic view of the STEP test cylinders as they orbit around the Earth. The sensitive axis is the symmetry axis of the cylinders which, together with the spacecraft (not shown), are kept fixed with respect to inertial space by active control. A differential attraction from the Earth due to a violation of the Equivalence Principle would give a signal with the same period as the orbital period of the satellite ( $\cong 6000$  sec).

## 2.2 ROOM TEMPERATURE VS CRYOGENICS: ADVANTAGES OF THE GG DESIGN AT ROOM TEMPERATURE AND FOR A MORE ACCURATE CRYOGENIC MISSION IN THE FUTURE

A very important consequence of the fact that in GG the expected signal lies in the plane normal to the spin/symmetry axis of the test cylinders is that a major perturbation due to the so called radiometer effect is zero also at room temperature<sup>29</sup>. It is known that, in low pressure conditions where the mean free path of the gas particles is much larger than the dimensions of the vessel, a cylinder whose faces are not at the same temperature is subject to an acceleration along its symmetry axis whose value is exceedingly large unless the

residual gas pressure is extremely low, down to values which can only be obtained at extremely low temperature close to absolute zero.

In STEP the radiometer effect along the symmetry/sensitive axis of the test cylinders competes directly with the signal, and is reduced thanks to the extremely low level of residual pressure (and to a millikelvin requirement on temperature gradients), which can be obtained by operating at superfluid He temperature. Instead, a hollow cylinder whose inner and outer surfaces were not exactly at the same temperature, would have zero radiometer effect in the plane perpendicular to its axis, for pure symmetry reasons. In reality, azimuthal asymmetries as well as the radiometer effect along the symmetry axis of the cylinders must be taken into account in GG, since it is a non cryogenic experiment; however, the requirements they impose on the amount of acceptable temperature gradients are compatible with a pure passive thermal control of the GG experimental apparatus<sup>29</sup>. This eliminates one of the main reasons why a high accuracy EP experiment in space should be operated in cryogenic conditions.

Low temperature is certainly helpful in reducing thermal noise. However, it is worth recalling that thermal noise acceleration depends not only on the experiment temperature  $T$ , but also on the mass  $M$  of the test bodies according to:  $\propto(T/M)^{1/2}$ . Therefore, in GG we use more massive test bodies than in STEP in order to compensate for the higher temperature: test masses of 10kg each at 300K, as we have, result in the same thermal noise acceleration as with test masses of 0.1kg at a temperature of 3K, as in STEP.

Nevertheless, in order to reduce thermal noise even further by also decreasing the temperature, a future, lower temperature version of the GG experiment can be envisaged for which the rapid spin gives a very important advantage: the very high centrifugal force at the periphery of the spacecraft would dominate the motion of the refrigerating (movable) material and largely reduce, by symmetry, its perturbations on the experiment core; evaporation can take place along the spin axis for symmetry reasons too. Non-spinning or slowly spinning satellite experiments for EP testing do not have this property, and in fact perturbations from the nearby refrigerant mass (a few hundred liters of He in the case of STEP) are known to be a serious source of perturbation which has to be taken care of<sup>1,2</sup>.

As for the read-out, capacitance sensors at room temperature are proved to be adequate to the task (the expected bridge unbalance electric signal is of about 1nV; see<sup>Sec. 5</sup>) thus indicating no need for a low temperature measurement device.

### 2.3 WEAK MECHANICAL COUPLING OF THE TEST BODIES AND PASSIVE ELECTRIC DISCHARGING

Inside the GG spacecraft (Figures 2.3 and 2.4) there are no free-floating masses: the test bodies are mechanically suspended from an intermediate laboratory (the so called PGB, Pico Gravity Box), in its turn weakly suspended from the spacecraft (for vibration isolation), in a nested configuration of cylindrical symmetry. In this way the suspensions can provide electric grounding of the test bodies and no active discharging device is needed (which would also require to measure the exact amount of the acquired charge by somehow acting on the test bodies themselves). Passive electric discharging is a major advantage because the electric forces caused by even a very limited amount of charge (in the Van Allen belts and South Atlantic Anomaly) are enormous compared to the extremely small gravitational force to be detected.

A comparison with STEP makes it apparent how serious charging problems can be. In STEP as studied by ESA at Phase A level<sup>2</sup> for the M3 competition (with a target in EP testing of 1 part in  $10^{17}$  like GG), a 2-cm thick tungsten shield (weighing  $\cong 130$ kg) was considered as baseline in order to have a time span of a few days available before discharging was needed

again<sup>2</sup>, Mission Summary and Sec. 3.6.1. In the previous Phase A Study of STEP carried out by ESA for the M2 competition in collaboration with NASA (same target in EP testing) the problem had already been recognized as a serious one, although the baseline solution was different: it was decided to add a radiation sensor on board so as to be able to discard the contaminated data<sup>1</sup>, Sec. 3.4.4. In addition, it must be noted that in STEP charged particles affect the EP experiment also by asymmetrical momentum transfer along the sensitive axis of the test bodies, especially because their masses are small (a few hundred grams)<sup>1</sup>, Sec. 3.4.3. It is therefore a very good feature of GG to be essentially unaffected by Van Allen belt effects and electrostatic charging.

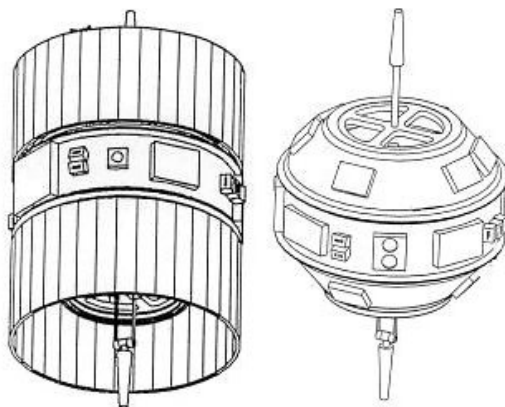


Figure 2.3. The GG spacecraft with solar panels (left) and without (right), showing its compact “spinning top”-like shape. The outermost cylinder is 1m wide and 1.3m high. On the central girdle are located some electronic boxes, the Earth/Sun Sensors and the FEEP thrusters. One of the two antennas can be folded to reduce the required fairing space at launch. The total mass is of 232 kg (263 kg including system margins). As a small, 1-axis spin stabilized spacecraft (at 2Hz) in low Earth orbit the GG spacecraft poses no problems. Its only novelty is the drag-free control with FEEP ion thrusters (simulated in<sup>26</sup>, Ch. 6), which is a new technological capability worth testing in its own right, primarily for use in space science, but also for spacecraft operation.

In point of fact, if we look at the history of small force gravitational experiments for EP testing, as well as for measuring the universal constant of gravity  $G$  (an experiment even more difficult than EP testing!), there is no question that ever since the work of Henry Cavendish at the end of the 18<sup>th</sup> century till the sophisticated experiments of more recent years, the best results have been obtained with an apparatus (the torsion balance, in different variants) where the suspension is mechanical and the test bodies are not acted upon by any active device. In STEP and in similar proposed experiments the test bodies are not suspended mechanically, but this does not mean that they are free floating: they are coupled with a low stiffness (but non zero!) elastic constant which however does not provide electric discharging as a very thin mechanical suspension (possible in space thanks to weightlessness) would do.

The weak mechanical coupling of the GG test bodies, obtained by means of helical springs (Figure 2.5) and flat gimbals (Figure 2.6) pivoted on thin torsion wires, is the key feature which allows GG to cope with a major dangerous effect: that of air drag along the satellite orbit. Air resistance acting on the spacecraft surface is experienced by the test bodies suspended inside it as a translation inertial acceleration equal and opposite to the one caused by air drag on the center of mass of the whole satellite (spin axes are stable due to the extremely high energy of spin). This acceleration is about 8 orders of magnitude weaker than 1-g on Earth, but about as many orders of magnitude larger than the expected signal; it should be the same on both test cylinders, but only in the ideal case that their masses and suspensions were exactly the same.

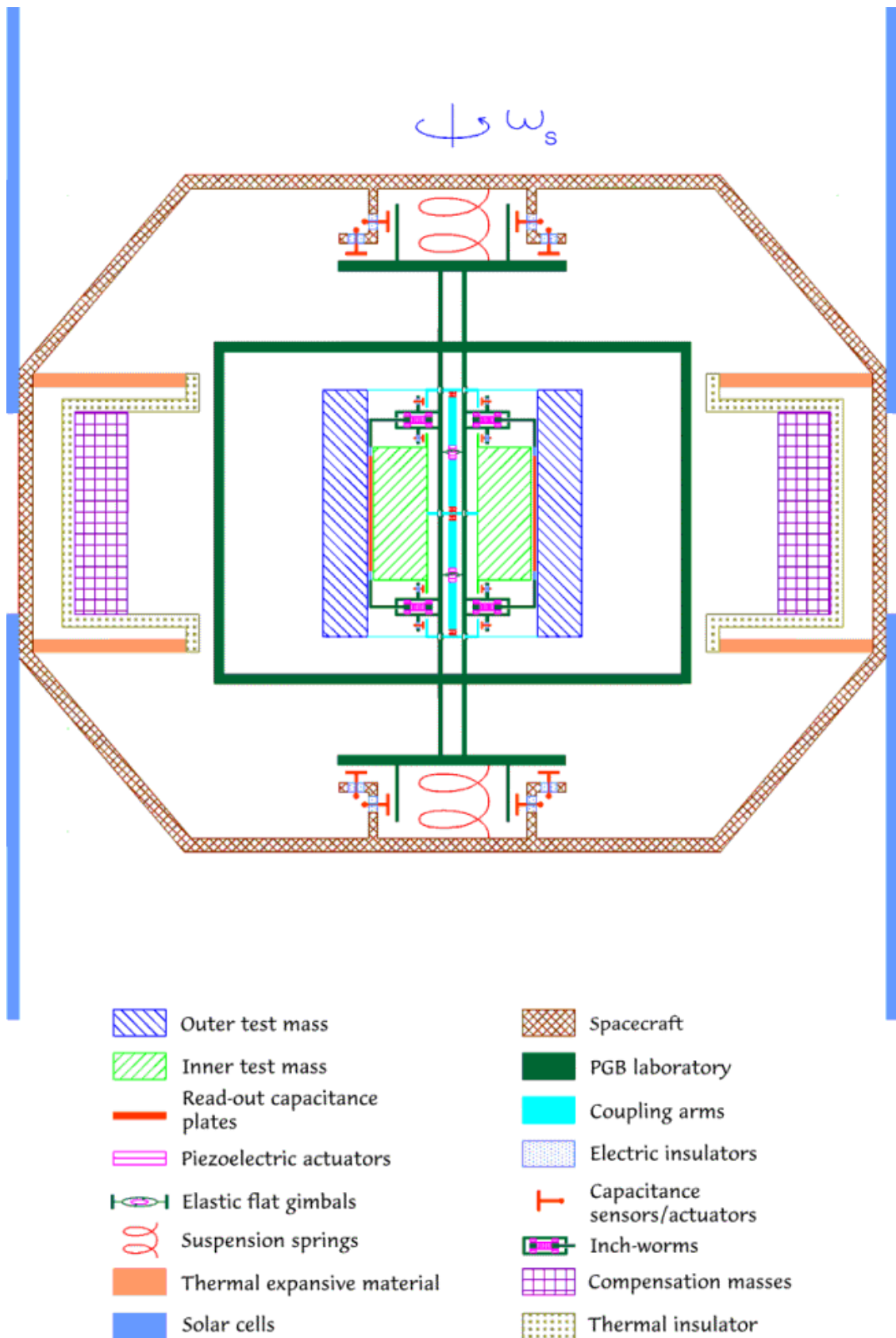


Figure 2.4. Section through the spin axis of the GG satellite. The solar panels are shown, in two cylindrical halves at the two ends of a girdle. Inside the spacecraft is shown the PGB laboratory with its helical suspension springs.

Drag-free control (with FEEP ion thrusters) of the GG spacecraft reduces the corresponding inertial acceleration on the payload. In order to further reduce its differential effect on the test cylinders due to small differences in their suspensions, the test cylinders are coupled similarly to the two weights of an ordinary balance (with a vertical instead of horizontal beam in this case) whose arms can be adjusted (by means of piezoceramic actuators) so as to eliminate differential effects. Note that small forces are much easier to balance than large ones. This balancing procedure, which has been tested on the ground prototype<sup>Sec. 5</sup> (in a more difficult 1-g environment) to the level currently required for the space experiment, is performed before taking data; electric voltages can be switched off after balancing if inch-worms are used rather than ordinary piezo.

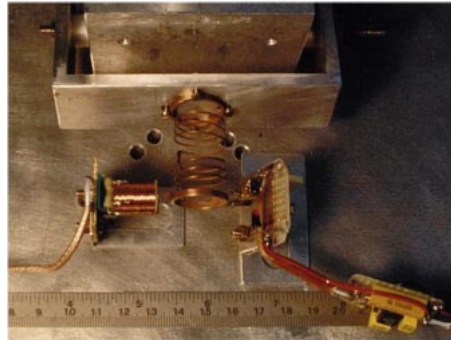


Figure 2.5. One helical spring, to be used for suspending the GG test bodies, clamped and ready for measuring its quality factor at a frequency of a few Hz (in vacuum). A small mass is attached to the free end of the spring in order to obtain the desired oscillation frequency. Note that the measurement is done for horizontal oscillations for the result not to be affected by local gravity. The spring has been manufactured by electroerosion in 3D from a single piece of CuBe with special equipment; Brush-Wellman heat treatment and ultrasound cleaning have been applied. The elastic properties are close to the desired ones. The best measured value for its quality factor (at 5 Hz) was 19,000. Two springs are needed for each test body (Figure 3.2). Each spring is clamped by the thick rings at its ends. Note that half turns of the springs are clockwise and the other half counter-clockwise, for de-coupling torsional from longitudinal (axial) oscillations. No electric signal is required to go through these helical springs.

The property of being balanced is a property of the system, not of the particular force acting on it; hence, all other common mode perturbations beside drag (e.g. solar radiation pressure) are also balanced once the main drag effect is balanced. Balancing the drag does not eliminate an EP violation signal because it is a differential effect; moreover, drag is variable in time and about 90° out of phase with respect to the signal; the drag free control laws developed during the GG Phase A Study<sup>26, Ch. 6</sup> show that memory of the phase difference between the drag and the signal remains after drag compensation. Vibration noise from the FEEP thrusters close to the spin frequency is attenuated by the suspensions of the PGB laboratory enclosing the test bodies.



Figure 2.6. One of the 2 flat gimbals to be used for coupling the GG test bodies (see Figure 3.2). The outer ring of the gimbal is clamped to the PGB tube and the inner one to the coupling arm (in Figure 3.2 the PGB tube

is shown in dark green and the coupling arm in light blue). There are 6 wire sectors in between the clamping rings; 3 of them (in alternation) carry electric signals and are insulated at the clamping (on the outer and inner clamping rings). No electric insulation is applied on the thin wires themselves where deformations occur, as it would worsen the mechanical quality.

## 2.4 DISSIPATION, WHIRL MOTIONS AND THEIR STABILIZATION

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 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). 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. Indeed, with the measured value of the quality factor of the suspensions (see Figure 2.5), whirl motions of the test cylinders are so slow that they can be damped at time intervals long enough<sup>26, Ch. 2.1.5</sup> to allow data taking in between, when active damping is switched off and will therefore produce no disturbance at all on the EP experiment.

Damping of whirl motions in the GG experiment has been the subject of extensive analysis, by the GG Science Team as well as within ESA. Doubts have been expressed and a paper has been published<sup>30</sup> arguing that the GG proposed test of the Equivalence Principle would be limited to a sensitivity of 1 part in  $10^{14}$ , which is 3 orders of magnitude worse than the sensitivity expected by the GG Team<sup>26</sup>. The issue has now been settled<sup>31, 26 Ch. 6</sup>. The plots of Figure 2.7 are worth showing; although they refer to a simplified 2-body model, they show a very clear comparison between the two approaches. Results from simulations of the complete system can be found in<sup>26, Ch.6</sup>. Classical literature is available<sup>32,33,34</sup>, as well as a brief summary on the specific issue<sup>35</sup>. The basic physical principles which govern the behavior of weakly coupled fast spinning rotors in space may also be of interest due to the novelty of the subject<sup>36</sup>. In addition to demonstrating that whirl motions can be accurately damped under realistic flight conditions and therefore the experiment concept is sound, 3 issues claimed in<sup>30</sup> as serious difficulties for the GG experiment concept could also be settled, namely: (i) that the pen-shaped small rods which are used to couple the test cylinders are stable; (ii) that memory of the drag phase remains after drag-free control (hence a large angular separation from the signal remains, which is helpful in signal recovery; see Figure 2.8); (iii) that losses in the electrostatic dampers themselves are negligible<sup>37</sup>.

Once whirl motions are damped the relative distance of the test cylinders remains within about  $1\text{\AA}$  (Figure 2.8), undergoing oscillations at their natural differential period (545 sec). The expected signal is about 2 orders of magnitude smaller. Nevertheless, it can be recovered from the data because of its fixed direction (in a non spinning frame it points towards the center of the Earth). Moreover, the numerical simulations reported in Figure 2.8 show that an EP violation signal 100 times smaller than the amplitude of whirl can be

recovered even in the presence of a residual drag effect (at a large phase difference from it) about a factor 10 larger than the signal.

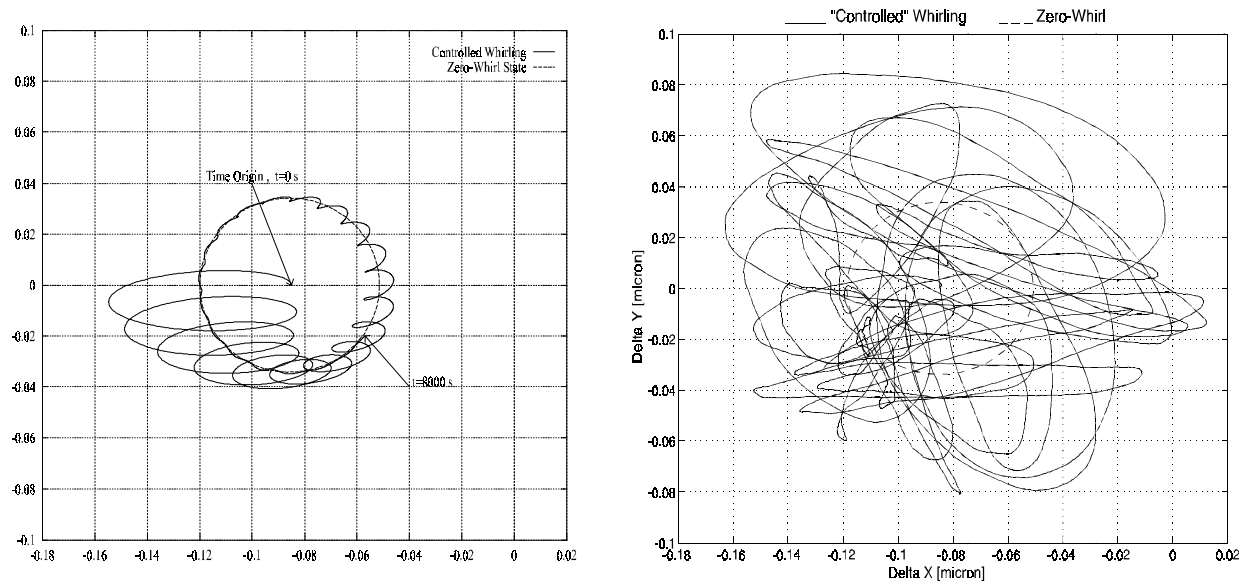


Figure 2.7 (Taken from<sup>31</sup>.) Trajectory of the relative motion of the centers of mass of the GG outer spacecraft and the PGB in the plane perpendicular to the spin axis in a 2-body model (coupling constant  $0.02\text{N/m}$ ,  $Q=90$ ). The Y axis is pointed to the center of the Earth, hence the largest effect of the residual atmospheric drag, assumed of  $5 \cdot 10^{-9}\text{N}$ , is a constant displacement along the X axis (of  $\cong 0,08 \mu\text{m}$ ); its second harmonic (assumed 40% of it) appears in this system as a variation at the orbital period (5,700 sec). 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  $10\mu\text{m}$  linear and  $1^\circ$  angular; fractional error in spin rate measurements  $\Delta\omega_s/\omega_s=10^{-4}$ ; offset (by construction and mounting) of  $10\mu\text{m}$ ; errors in the capacitors of  $0.1\mu\text{m}$  r.m.s. Whirl oscillations with the natural period of 314 sec (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 sec only. Note that at this point the relative distance of the two centers of mass is below  $5\text{\AA}$ . These results have been obtained independently using DCAP software package (of Alenia Spazio) and Matlab. 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  $1\mu\text{m}$  and no angular bias; an error in the sensors/actuators 10 times smaller, i.e. of  $10^{-2}\mu\text{m}$ ) the results obtained by applying the control laws proposed by<sup>30</sup>. 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  $10^{-2}\mu\text{m}$ .

It is clear by now that fast rotation and weak mechanical suspensions are the main features of the GG experiment design, distinguishing it from the STEP design. Other advantages of fast rotation beside the modulation of the signal are that a large number of perturbing effects (e.g. due to inhomogeneities of the test bodies, spacecraft mass anomalies, non-uniform thermal expansion, parasitic capacitances, etc.) appear as DC because the entire system is spinning. In addition, as shown in<sup>26, Ch. 2.2.2</sup>, Earth tidal effects act on the test bodies at twice the spin/signal frequency.

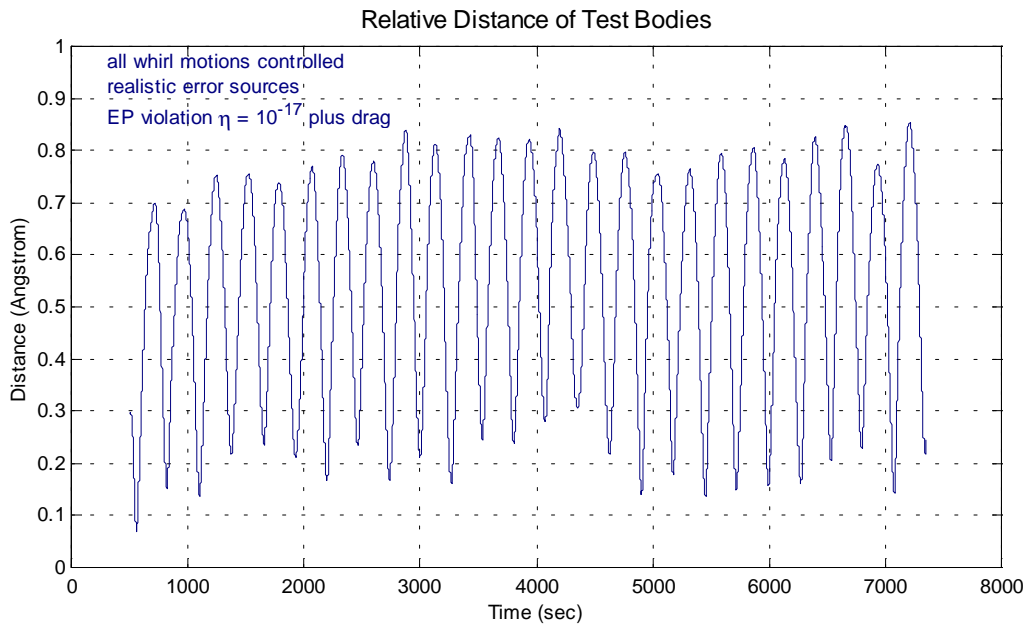


Figure 2.8 Relative distance of the GG test masses with their whirl motions actively controlled in a reference frame where the Y axis points to the center of the Earth and the X axis is in the along track direction. The simulation concerns a full scale GG system with realistic error sources according to the GG requirements<sup>Sec 2.5</sup>. In this case, an EP violation signal was introduced in the system (corresponding to  $\eta=10^{-17}$ , hence yielding about  $1/100 \text{ \AA}$  relative displacement pointing to the center of the Earth) and a larger drag effect along track. Both of them could be recovered from this set of data in spite of the much larger whirl oscillations. A large phase difference between the signal and the residual drag is realistic because numerical simulations of drag free control show that memory of the original phase difference is not lost during drag free control (for the contribution by solar radiation pressure see<sup>26, Fig. 2.21</sup>). Note that this is a worst case exercise of signal recovery because the mechanical quality of the suspensions of the test bodies assumed in the simulation must be much worse than the measured value (by about 40 times) in order to speed up the onset of the whirl instability during the timespan of the numerical integration (typically requiring 8 hr of CPU time).

## 2.5 REQUIREMENTS AND ERROR BUDGET

The error budget for the GG experiment is given in<sup>26, Ch. 2.2</sup>. In the worst case assumption of flying the mission close to solar maximum (when air drag perturbation is maximum), assuming the maximum drag value along the satellite orbit and using values already measured in the laboratory for key quantities such as the quality factor and the common mode rejection, the experiment target of testing the Equivalence Principle to 1 part in  $10^{17}$  can be achieved (see Table 2.1). The situation improves when flying close to solar minimum and with improved values of the quality factor and common mode rejection<sup>26, Table 2.2</sup>.

The requirements which lead to the error budget reported in Table 2.1 are the following (see<sup>26, Ch.2.2</sup> for details):

- compensation of drag (in fact of all non gravitational perturbations acting on the outer surface of the s/c) to 1 part in 50,000 in the plane perpendicular to the spin axis and to 1 part in 150 along the spin axis
- rejection level of common mode forces by balancing of the test cylinders (vertical beam balance) to 1 part in 100,000 (tested in the more difficult 1-g environment with the GGG test cylinders to 1 part in 200,000 in  $\Delta m/m$ )



- mechanical quality factor of the test bodies suspensions at the frequency of spin  $Q=20,000$  ( $Q=19,000$  measured for the helical spring manufactured by electroerosion in 3D when set in horizontal oscillation, so as not to be affected by local gravity, at 5Hz; see Figure 2.5)
- mechanical balancing of the read-out capacitance plates half way in between the test cylinders to  $3.7 \cdot 10^{-4}$
- temperature stability, in time, inside the PGB at the level of the test bodies not to exceed 0.2 K/day
- temperature gradients along the coupling arms of the test bodies not to exceed 1K (having chosen the arms material with a thermal expansion coefficient of  $10^{-5}/K$ )
- relative changes with temperature in the stiffness of the suspensions of the test bodies not to exceed 1/4,000 per degree of temperature
- angular distance between the spin axis and the orbit normal not to exceed  $1^\circ$
- accuracy of electrostatic sensors  $10^{-6}$  cm r.m.s
- relative accuracy in the measurement of the spin rate of the s/c by Earth Elevations Sensors not worse than  $10^{-4}$  r.m.s
- magnetic impurities in the Be test cylinder smaller than  $\cong 10^{-7}$  Am<sup>2</sup> (no magnetic shield needed; see details in<sup>26, Ch. 2.2.4</sup>, also in comparison to Eot-Wash ground experiment<sup>10</sup>)

If temperature requirements are fulfilled, 20 days of continuous data taking are allowed before rebalancing the test bodies, and at least 15 days (more if some care is taken in the manufacture of the sensor plates arms) before rebalancing the read-out capacitance bridge. With a mechanical quality factor like the measured one, thermal noise requires an integration time of about 7 days (Table 2.1); for this interval of time the same quality factor allows data taking without active control of whirl instabilities (once damped, there is not enough time for them to grow to values of importance).

### 3. THE PAYLOAD

The GG payload is constituted by: the PGB laboratory (Pico Gravity Box) enclosing, in a nested configuration, two cylindrical test bodies with the read-out capacitance plates for very accurate sensing of their relative displacements, the small capacitance sensors/actuators for sensing relative displacements and damping the whirl motions, the suspension springs and the coupling flat gimbals, the FEED thrusters for drag compensation (physically located on the spacecraft outer surface), the inchworms and piezo-ceramics for fine mechanical balancing and calibration. All suspended bodies are provided with a locking mechanism to withstand launch accelerations and to be unlocked once the nominal attitude (perpendicular to the orbit plane) and spin rate (2Hz) have been achieved at the nominal orbit (circular, equatorial, 520 km altitude). In addition, all bodies have a locking mechanism made of inchworms for finer control of their unlocking at the beginning of the mission<sup>26, Ch. 2.1.6</sup>. The payload apparatus includes the electronics (for calibration, signal measurements, FEED control and whirl damping), although a large part of it is located at the s/c level outside the PGB. The PGB also carries a small mirror, in correspondence of a photo-detector mounted on the inner surface of the spacecraft, for the measurement of small residual phase lags between the spacecraft and the PGB which might remain despite the passive mass compensation mechanism<sup>26, Ch. 2.1.2 and Fig. 5.7</sup>; residual phase lags will be reduced to acceptable levels using the FEED. No such phase lags will arise between the test bodies due to the thermal stability achieved inside the PGB<sup>26, Ch. 4.4</sup>.

The total mass of the payload is 79.6 kg (with system margins), including electronics, capacitors, inch worms, rods etc... The breakdown is given in<sup>26, Ch. 4.1</sup>, with mention to the materials used. See also Table 4.1. A 3D view of the payload internal to the PGB is shown in Figure 3.1 where the locking/unlocking mechanisms (LUM) of the test bodies are well visible.

Table 2.1. GG error budget for a target of 1 part in  $10^{17}$  in EP testing (SI units). Worst case assumptions: launch close to solar maximum; maximum drag value along the orbit assumed. Q as measured in the lab; Common Mode Rejection as tested (taken from the "GG Phase A Study Report"<sup>26</sup>, Ch. 2.2 Table 2.1)

Acceleration (transverse plane) DUE TO:	Formula	Frequency (inertial frame) (Hz)	Frequency (detected by spinning sensors) (Hz)	Phase	Differential acceleration ( $m/sec^2$ )	Differential displacement (m)
EP SIGNAL	$\frac{GM_{\oplus}}{a^2} \eta$	$V_{orb} \cong 1.75 \cdot 10^{-4}$	$V_{spin}$ w.r.t. Earth	test body to center of Earth	$8.38 \cdot 10^{-17}$ $\eta = 10^{-17}$ $h=520 \text{ Km}$	$6.3 \cdot 10^{-13}$ $\omega_{dm} \cong 1.15 \cdot 10^{-2}$ 545 sec diff. period
AIR DRAG	$\frac{1}{2} C_D V_{sc}^2 \frac{A}{M} \rho_{atm}$	$V_{orb}$	$V_{spin}$	~ along track	$5.21 \cdot 10^{-17}$ AFTER : $\chi_{FEEP} = \frac{1}{50000}$ $\chi_{CMR} = \frac{1}{100000}$	$3.9 \cdot 10^{-13}$
SOLAR RADIATION PRESSURE	$\frac{A}{M} \frac{\Phi_{\oplus}}{c}$	$V_{orb} - V_{\oplus}$ $\cong V_{orb}$	$V_{spin}$	test body to center of Earth compo nent	$9.57 \cdot 10^{-19}$ same $\chi_{FEEP}, \chi_{CMR}$	$7.2 \cdot 10^{-15}$
INFRARED RADIATION FROM EARTH	$\alpha_{\oplus} \frac{A}{M} \frac{\Phi_{\oplus}}{c}$	$V_{orb}$	$V_{spin}$	test body to center of Earth	$1.44 \cdot 10^{-18}$ same $\chi_{FEEP}, \chi_{CMR}$	$1.08 \cdot 10^{-15}$
EARTH COUPLING TO TEST BODIES QUADRUPOLE MOMENTS	$\frac{3 GM_{\oplus} \Delta J}{8 a^2 J_x} \cdot \left( \frac{r_1^2 + r_2^2 + l^2 / 3}{a^2} \right)$	$V_{orb}$	$V_{spin}$	test body to center of Earth	$2.4 \cdot 10^{-19}$	$1.8 \cdot 10^{-15}$
MECHANICAL THERMAL NOISE	$\sqrt{\frac{4 K_B T \omega_{dm}}{m Q}} \frac{1}{\sqrt{T_{int}}}$	$V_{d.m.}$	$V_{spin} \pm$ $V_{d.m.}$	random	$3.99 \cdot 10^{-17}$ $T_{int} \cong 7 \text{ days}$ $Q = 20000$	$3 \cdot 10^{-13}$
					TOTAL ERROR BUDGET	$3.59 \cdot 10^{-13}$

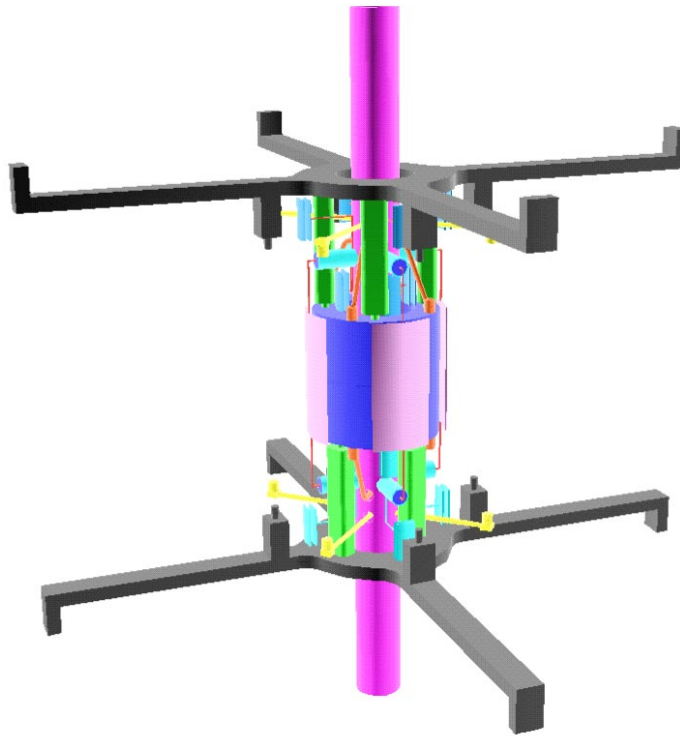


Figure 3.1 Overall, 3D view of the GG experimental apparatus internal to the PGB laboratory (of 55 cm height; only the central tube of the PGB is shown, in dark pink). Of the actual apparatus to be located inside the PGB everything is shown here except the outer test cylinder, which would hide all the components inside it. The locking/unlocking mechanisms are shown in gray; the cylindrical bullets and their actuators, also in gray, are well visible only for the outer test cylinder; the inner test cylinder is locked. It is shown in blue, partially covered by the capacitance plates of the read-out (in light pink). The inch-worms for the mechanical balancing of the read out capacitance plates are schematized as small cylinders (in light blue). Note that these plates are rigidly connected (through the inch worms) to the PGB tube. There is one inch-worm per radial shaft, each plate has 2 shafts, 1 at the top and 1 at the bottom, amounting to 8 shafts and 8 inch-worms for the total read-out system. The small plates of the active dampers are shown in light blue. Each damper consists of 2 halves: 1 is connected to the inch-worm case, hence to the PGB, and the other to the test body. In this way it is possible to sense the relative position of each test body with respect to the PGB, and to actuate in order to damp their whirl motions (details in<sup>26</sup>, Ch. 6).

Each LUM (there is one at the top and one at the bottom) has: 4 mechanical arms connecting it rigidly to the PGB laboratory, 8 fixing cylindrical bullets, 4 for holding the inner test cylinder and 4 for holding the outer test cylinder, which are inserted into the test bodies during the GG assembling (note that the inner test cylinder has smaller height than the outer one and therefore the bullets for holding it need to be mounted on higher supports); 8 actuators, 4 per test body, to pull out the cylindrical bullets whereby unlocking the test bodies; a transmission mechanism. At the time of unlocking the actuators, by means of the transmission mechanism, pull out the cylindrical bullets from the test bodies whereby freeing them. The actuators taken into consideration for this purpose are either electric motors or paraffin actuators (as used already in BeppoSAX). The electric motors would be located on the mechanical arms far away from the test bodies; in any case, they need to be used only once, at the beginning of the operation phase. After unlocking, the motors would be switched off and, in case of paraffin actuators, the required heat would be dissipated and the heat source turned off. Note that, once freed, the test bodies are constrained by mechanical stops which allow them to perform only little movements (about 0.5 cm room). This is well visible also in Figure 3.1, showing the shafts sticking out of the PGB tube (8 per test body, 4 at the top and 4 at the bottom, each arm at 90° from the next). Inside the PGB tube they are

movements of the coupling arms around their midpoints, e.g. in response to a differential force between the test bodies. The piezoelectric 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 PGB tube and have inch-worms for adjusting their distance halfway between the surfaces of the test cylinders (mechanical balancing of the capacitance bridge) so as to improve sensitivity to differential displacements. On the PGB tube are shown the mechanical stops which constrain the test bodies to only slight movements. The small capacitance sensors/actuators (with plates of about 2 cm<sup>2</sup>) are for sensing and damping the slow whirl motions of the test bodies with respect to the PGB<sup>26, Ch. 6</sup>.

#### 4. THE SATELLITE, THE ORBIT AND THE LAUNCHER

The test bodies, their mechanical coupling and the capacitance read-out are the core of the GG mission. Once the experimental design has been conceived, the features of the required spacecraft, its attitude and orbit are also identified. In the first place, the cylindrical symmetry of test bodies and PGB and the request to spin (in order to provide high frequency signal modulation), suggest a spacecraft of cylindrical symmetry too, stabilized by one-axis rotation along the symmetry axis. The nature of the signal (Figure 2.1 and<sup>26, Eq. 2.1</sup>) requires the spin axis to be as close as possible to the orbit normal; the need to reduce non gravitational perturbations on the spacecraft surface (Sec. 2.3) suggest that it should be small and compact (which in addition helps reducing its cost); the need to reduce perturbations on the test bodies from nearby moving masses suggests to use electric minithrusters of high specific impulse (FEEP) in order to reduce the amount of propellant required for drag compensation during the mission; indeed, the need is reduced to only a few grams of Caesium for the entire 6 months duration of the GG mission (6 FEEP thrusters are needed; see<sup>26, Fig. 5.14</sup>) as opposed to a few hundred liters of He for the mechanical He-thrusters of STEP). The drag-free control analysis and simulations are given in<sup>26, Ch. 6.1.15</sup>.

A section of the GG satellite through its spin/symmetry axis showing how the PGB and the experimental apparatus is accommodated, in a nested arrangement inside it, is shown in Figure 2.4; a 3D view is given in Figure 2.3 (details in<sup>26, Ch. 5</sup>). The spacecraft is 1m wide and 1.3m high. The area of the external (cylindrical) surfaces covered by solar cells is dictated by the power needs of the mission (112W, of which 66W for the payload; see<sup>26, Table 5.18</sup>); the compactness of the spacecraft (similar to a spinning top in shape) is for maximizing the moment of inertia with respect to the symmetry axis whereby providing passive spin stabilization around it. The current nominal spin rate is 2Hz (120rpm), yielding a peripheral acceleration of about 8-g, which is well doable. A careful analysis of the perturbing torques which could tilt the spin axis of the GG spacecraft shows that no active control of the direction of the spin axis in space is needed, the simple physical reason behind this fact being that the kinetic spin energy once at the nominal rate of 2Hz is so high compared to all torques that they would need a very long time to even slightly displace the spin axis<sup>26, Ch. 2.1.2</sup>. As for phase differences due to a different rotation rate between the s/c outer shell and the PGB, they are mostly compensated passively, residuals are sensed and corrected with FEEP thrusters (details in<sup>26, Ch.2.1.2</sup>).

The total mass amounts to 231.7Kg (262.7kg with system margins), as shown in Table 4.1.

The case for a low, almost circular orbit is apparent; the preference for it to be almost equatorial is explained in<sup>26, Ch. 2.1.2</sup> as a trade off between stronger signal and passive attitude control vs larger thermal perturbations (as long as they are compatible with pure passive thermal control, which is the case). None of the requirements on orbit and attitude is strict. Three candidates launch vehicles have been identified as suitable<sup>26, Ch. 5.1</sup>: the Orbital Sciences Corporation Pegasus launcher; the Indian Space Research Organization PSLV launcher; the future European small launcher VEGA.

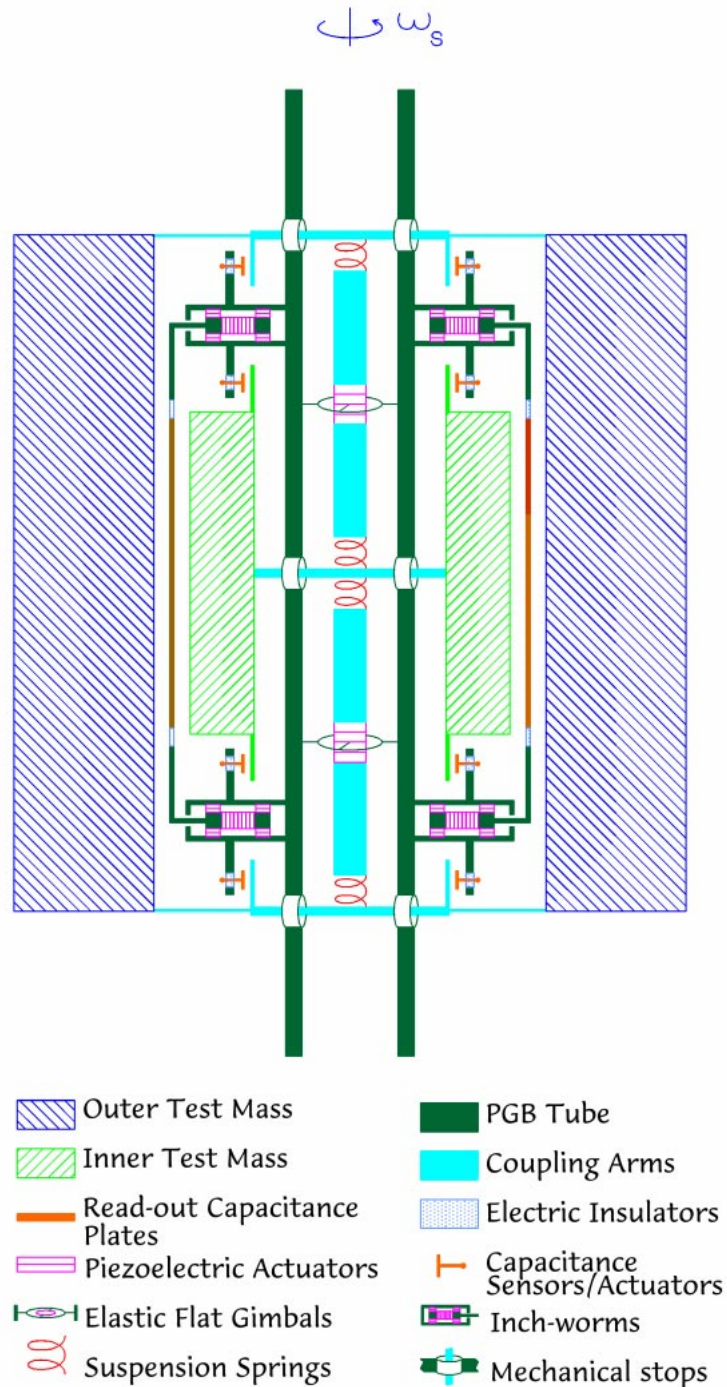


Figure 3.2 (to scale). Section through the spin axis of the GG test cylinders (10 kg each; Be and Pt/Ir in this drawing; the height of the outer Be cylinder is 21 cm) and the capacitance plates of the read-out in between. The lower density cylinder (21 cm in height) encloses the higher density one. Inside the inner cylinder is a narrow tube rigidly connected to a laboratory (also of cylindrical shape) called PGB (Pico Gravity Box) enclosing the test bodies and the read-out capacitance plates for sensing the relative position of the test cylinders. The PGB in its turn is mechanically suspended inside the spacecraft (not shown; see Figure 2.4 for an overall view). For coupling the test bodies there are two “coupling” arms (shown in light blue) located inside the PGB tube but not in contact with it; 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. The only connection between the coupling arms and the PGB laboratory is via two flat gimbals (Figure 2.6) at the midpoints of each arm. 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 piezoelectric 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 PGB tube and have inch-worms for adjusting their distance halfway between the surfaces of the test cylinders (mechanical balancing of the capacitance bridge) so as to improve sensitivity to differential displacements. On the PGB tube are shown the mechanical stops which constrain the test bodies to only slight movements. The small capacitance sensors/actuators (with plates of about 2 cm<sup>2</sup>) are for sensing and damping the slow whirl motions of the test bodies with respect to the PGB<sup>26, Ch. 6</sup>.

#### 4. THE SATELLITE, THE ORBIT AND THE LAUNCHER

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Table 4.1. Mass budget of the GG satellite

Equipment	Q.ty	Dimensions [mm] L x W x H	Mass [kg]	Margin [kg]	Total Mass [kg]
Inner Test Mass	1	dia. 98 x 98	10.	0.	10.
Outer Test Mass	1	dia. 220 x 212	10.	0.	10.
PGB	1	dia. 560 x 550	43.65	2.	45.6
Capacitors, Inch Worms, Rods, etc.			3.5	1.5	5.
PGB Electronics	1	250 x 170 x 70	7.	2.	9.
<b>Total P/L</b>					<b>79.6</b>
Integrated Control System	1	280 x 260 x 210	10.	2.	12.
<b>Total OBDH</b>					<b>12.</b>
Transponder & Antennas	2	230 x 220 x 155	4.8	1.	11.6
<b>Total RF</b>					<b>11.6</b>
Solar Array	2	dia. 1040 x 465	5.2	1.	12.4
PPDU	1	225 x 175 x 160	7.3	1.1	8.4
Battery	1	260 x 150 x 80	4.3	0.7	5.
<b>Total EPS</b>					<b>25.8</b>
CSS	1	86 x 86 x 53	0.25	0.05	0.3
Earth & Sun Sensor	1	166 x 150 x 127	1.4	0.3	1.7
<b>Total Attitude Control</b>					<b>2.</b>
FEEP Thrusters	6	70 x 50 x 50	0.3	0.06	2.2
FEEP Electronics	2	250 x 140 x 200	5.5	1.1	13.2
<b>Total FEEP</b>					<b>15.4</b>
Nitrogen Thrusters	4	50 x 10 x 10	0.1	0.01	0.4
Nitrogen Propellant			1.5	0.7	2.2
Nitrogen Tank	1	dia. 200	1.5	0.3	1.8
Lines, Valves etc.			1.8	0.4	2.2
<b>Total Auxiliary Propulsion</b>					<b>6.6</b>
<b>Total Harness</b>			<b>5.</b>	<b>1.</b>	<b>6.</b>
<b>Total Thermal Control</b>			<b>7.5</b>	<b>1.5</b>	<b>9.</b>
Satellite Structure	1		47.9	9.6	57.5
Mass Compensation System	1		5.	1.	6.
<b>Total Structure</b>					<b>63.5</b>
<b>Total SVM</b>					<b>151.9</b>
<b>Total Satellite</b>					<b>231.6</b>
<b>System margin on P/L (20 %)</b>					<b>15.9</b>
<b>System margin on SVM (10 %)</b>					<b>15.2</b>
<b>GRAND TOTAL</b>					<b>262.7</b>

The characteristics of Pegasus (fairing envelope, limit loads, payload mass) are by far the most constraining of the three. Therefore, our design exercise has been focused on Pegasus. As for orbit injection performance, no capability for correction of injection errors is

to be provided on board of GG. Instead, the satellite is designed to have an autonomous system for spin-up to the final nominal spin rate of 120rpm as well as for correction of angular momentum depointing and damping of angular rates. See<sup>26, Ch. 5</sup> for details (to Phase A level) of the GG satellite and specific analysis, in particular, on: structural design, materials selection, finite element model, structural analysis and thermal control.

## 5. STATUS OF THE GGG (GG on the Ground) PROTOTYPE EXPERIMENT

The GG test of the Equivalence Principle is designed for space for two reasons: a driving signal stronger than on Earth (by about 3 orders of magnitude) and the absence of weight (the largest perturbation is  $\cong 10^8$  times smaller than 1-g). Yet, a 1-g version of GG can be conceived. This is possible because in the GG design the expected signal lies in the plane perpendicular to the spin/symmetry axis of the test cylinders (Figure 2.1): if on the ground the apparatus is suspended against local gravity along this axis, an EP violation signal has a component in the horizontal plane that the system is sensitive to. If the mechanical suspensions are stiff along the vertical (enough to withstand weight) and soft in the horizontal plane (in order to provide a very weak mechanical coupling of the test cylinders<sup>26, Ch. 3</sup>), the rotor is safe and at the same time it is very sensitive to differential forces in the horizontal plane, such as the force due to a possible violation of Equivalence.

The GGG apparatus, located at the LABEN laboratories in Florence, is shown in Figure 5.1. It is mounted on a metal frame fixed inside a vacuum chamber of 1m diameter. The test cylinders, of which only the outer one is visible in the picture, weigh 10kg each (as in GG) and so far are both made of Al. The capacitance plates of the read out, which measure the relative displacements of the test cylinders in the horizontal plane, are located in between the test cylinders. The suspension tube, held by a shaft turning inside ball bearings is shown. Inside this tube is the most delicate mechanical part of the apparatus: the coupling arm, and 3 laminar cardanic suspensions<sup>26, Ch. 3</sup>, one for carrying the total weight (at the center of the arm), one for suspending the outer test cylinder (at the top of the arm), and one for suspending the inner test cylinder (at the bottom of the arm). Such a mechanical system is very similar to an ordinary beam balance (with a vertical beam), so that masses and lengths can be adjusted to make it most sensitive to differential effects (balancing to  $\Delta m/m=1/200,000$  achieved). The electronic core of the experiment is shown in Figure 5.2; the annular shape of the support is for placing the circuits around the suspension tube and for reasons of cylindrical symmetry. The digitized signal produced by these circuits (giving the relative displacements of the test cylinders as an electric signal) is optically transmitted to the non rotating system, and eventually outside the vacuum chamber to the computer. The required electronics (located at the top of the metal frame shown in Figure 5.1), is shown in Figure 5.3. Sliding contacts are used for power transmission inside the rotor. Details of the GGG design and its parts –particularly the laminar cardanic suspensions which are an essential component of the system– are given in<sup>26, Ch. 3</sup>.

An EP violation with the Earth as the source mass would cause a constant displacement of the GGG test rotors in the North-South direction. However, due to the diurnal rotation of the Earth, a gyroscopic effect arises between the test rotors (proportional to the spin rate of the apparatus) which is also in the North-South direction and much larger: in the current design it amounts to about  $3\mu\text{m}$ <sup>38</sup>. A non zero tilt angle between the spin axis and the direction of local gravity would also give rise to a constant relative displacement (in the direction of the residual tilt). The GGG apparatus must therefore look for a possible EP violation signal with the Sun as the source mass, like in the experiments by<sup>8,9</sup>. This means a driving signal 1400 times weaker than it is in space for GG. Note that none of these difficulties (verticality of the rotation axis and gyroscopic effect) would affect the GG space experiment, in which there is no local gravity preferential direction and no gyroscopic effect (the rotation axis is almost perfectly fixed in space, and moreover –unlike in GGG– the test cylinders are suspended by their centers of mass<sup>26, Ch. 2.1.2 and Ch. 3</sup>).





Figure 5.1 The GGG apparatus mounted in a metal frame fixed inside a vacuum chamber (not shown) of 1m diameter.

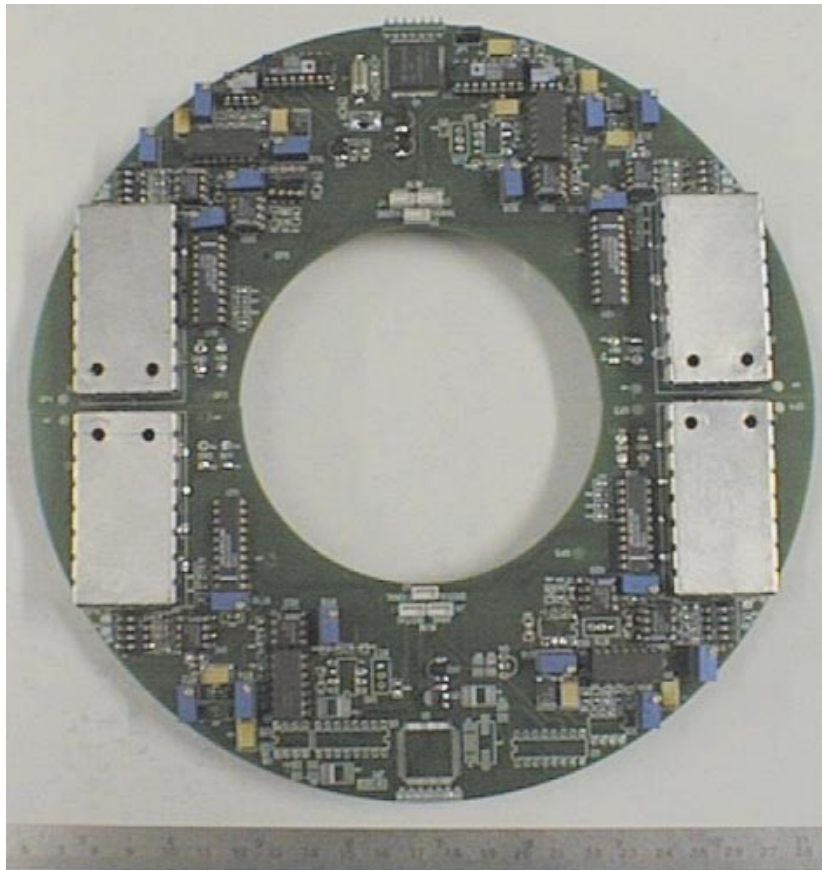


Figure 5.2 The GGG read-out electronics. Half annulus contains all the necessary circuits; the two halves are for symmetry and for redundancy. On each half annulus are visible two small boxes: each of them contains the circuits of one capacitance bridge (one for each coordinate in the horizontal plane). The rest of the circuits is for

demodulation of the signal, digitization and optical transfer (see Figure 5.3). Another set of circuits in all similar to this one contains the electronics of two less sensitive capacitance bridges used as sensors for active damping of whirl motions in combination with 4 high tension cards used to command the capacitance actuators.

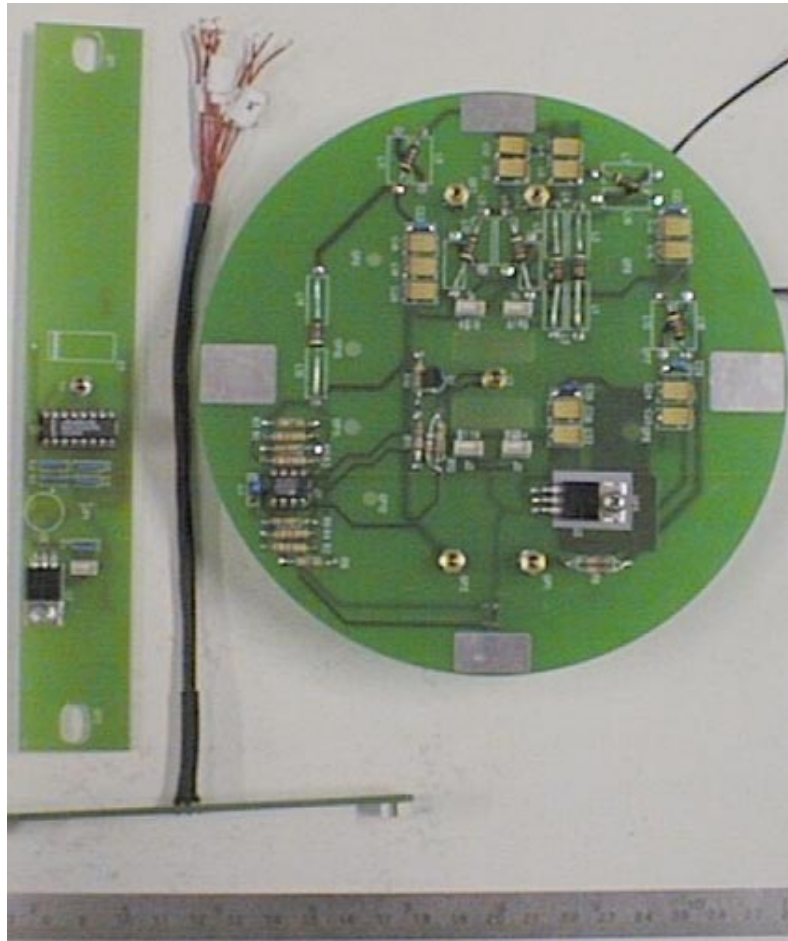


Figure 5.3 The electronics used for optical transfer of the digitized signal.

The sensitivity of the GGG capacitance read-out has been tested on bench in 1998, finding that it can measure 5 picometer displacements in 1 sec integration time. This is fully adequate for the GG space experiment, which must be sensitive to slightly less than 1 picometer displacements in order to fulfill its goal of an EP test to  $10^{-17}$ ; less than 100 sec integration time is enough for the GGG read out to complete the task. This result is to be expected for a carefully designed capacitance bridge. However, things are more difficult when the read out is mounted on the real apparatus for a real measurement. The best result obtained with the GGG apparatus operational on the 4<sup>th</sup> floor of the LABEN building is shown in Figure 5.4. The rotor has been running at 6Hz for more than 1hr, and the two data sets reported are separated in time by 1/2 hour. It appears that, on the average over all spin periods, the test cylinders are displaced in an almost fixed direction of the horizontal plane by about  $6.5\mu\text{m}$ . This is due to a residual tilt of the rotation axis with respect to the direction of local gravity which adds up to the expected gyroscopic effect at this spin rate ( $\approx 3.6\mu\text{m}$ ). More important, this displacement is almost constant, within  $0.2\mu\text{m}$ . This is the best sensitivity that could be achieved while GGG was located on the 4<sup>th</sup> floor of the LABEN building, in spite of the fact that the capacitance read out in itself was much more sensitive. The physical limitation was seismic noise at low frequencies. For this reason, on January 2000, the entire apparatus (GGG, the vacuum chamber and all instruments) was moved to a less noisy location, in the basement of the LABEN building, almost fully underground, where years ago was installed and operational a particle accelerator.

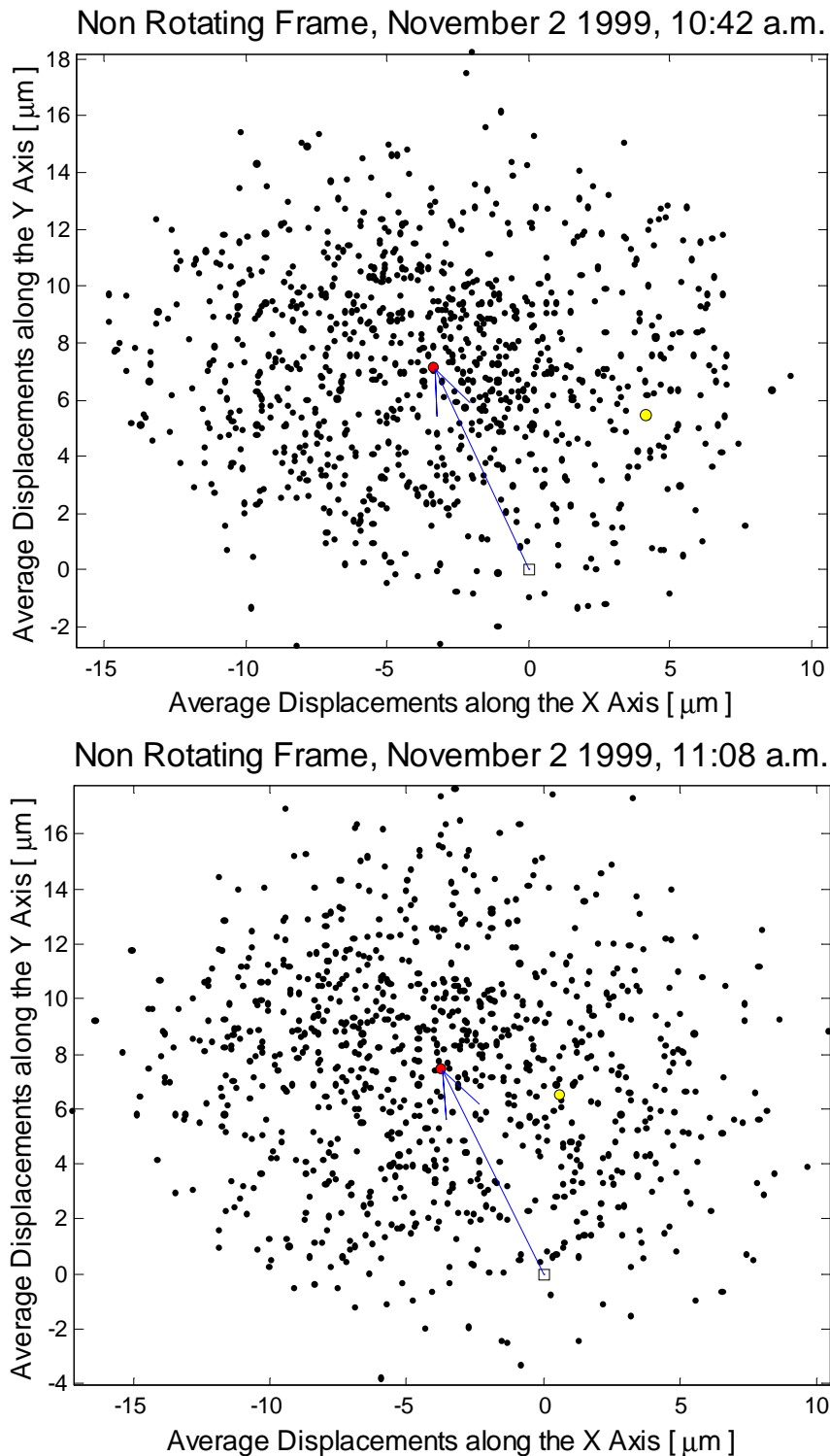


Figure 5.4 Relative displacements of the GGG test cylinders in the horizontal plane as recorded at about 1/2 hr distance without stopping the rotor or acting on the system in any way. The spin rate is 6 Hz, the oil damper is on (whirl motions are well damped; the natural period of differential oscillations is 12 sec), each dot is the relative position of the test cylinders averaged over one spin period (as recorded by the reference signal). The yellow dot is the average position for the first spin period of the data set. The red dot is the average of all black dots; the vector drawn gives the average relative position vector of the test cylinders over the entire data set. It is apparent that the two vectors are very close to one another; indeed, the data show that in half an hour the GGG test rotors maintain a constant relative displacement (in a given direction of the horizontal plane) of about  $6.5\mu\text{m}$  to within  $0.2\mu\text{m}$ . Therefore, this test proves a sensitivity of the GGG apparatus to relative displacements of the test bodies of  $0.2\mu\text{m}$ .

In order to measure low frequency seismic noise independently, an ISA (Italian Spring Accelerometer) instrument was installed next to GGG on January 14, 2000 thanks to V. Iafolla and colleagues. Figure 5.5 shows a 1-day measurement data by ISA. ISA does not distinguish horizontal forces in one direction from torques around the other direction in the plane, i.e. horizontal effects from tilts. In GGG horizontal oscillations of the terrain (hence of the vacuum chamber) are rejected extremely well (by a factor  $10^8$ ; see<sup>26, Ch. 3</sup>) leaving negligible differential perturbations. Instead, tilts of the terrain are, in the current set-up, only slightly rejected (by a factor 5 only). To be conservative we assume that all effects measured by ISA are due to tilts; from these data we compute the resulting relative displacement of the GGG test cylinders, and this gives an upper limit for what has to be expected from seismic noise at low frequencies. These data give, for the current GGG set up, a diurnal oscillation (upper limit) of  $\cong 0.5\mu\text{m}$ ; over 1/2 hr the effect is about 2 orders of magnitude smaller than the one measured on the 4<sup>th</sup> floor, amounting to a few  $10^{-3}\mu\text{m}$ .

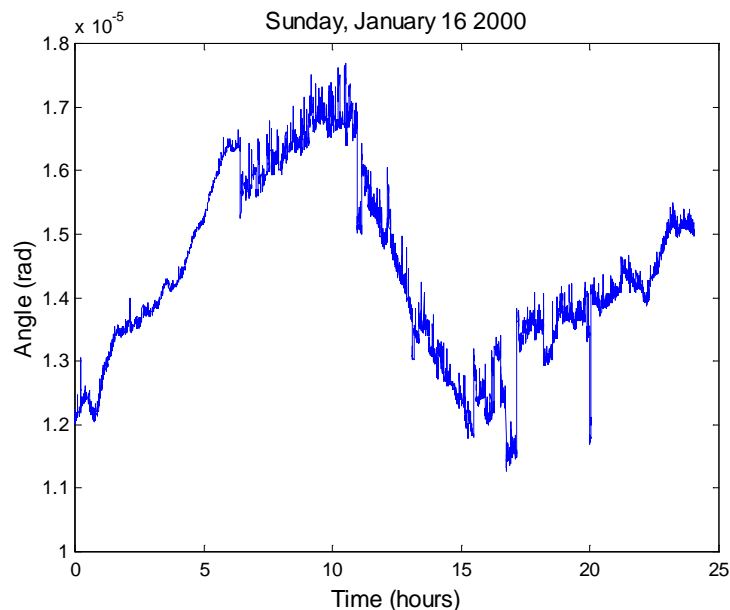


Figure 5.5 A 24-hr data set taken by the ISA accelerometer next to the GGG apparatus in the basement of the LABEN building (Florence). ISA data are plotted as tilt angles, in the assumption that all the effect measured by the instrument is due to tilts and that there are no horizontal oscillations. Since GGG is almost insensitive to horizontal oscillations of the terrain, these data allow us to compute an upper limit for the relative displacements to be expected between the GGG test cylinders due to seismic noise at low frequencies.

In summary, while the read out in itself is fully adequate for the GG mission to meet its goal, the GGG prototype data as of November 1999 were 5 orders of magnitude away from the sensitivity to relative displacements of the test cylinders required in the GG space experiment. In the current underground location, a reduced level of seismic noise allows this gap to be reduced by about 2 orders of magnitude. Further reduction requires low frequency seismic tilts to be attenuated on GGG; a laminar, cardanic suspension similar in its geometry to the three in use for the test cylinders<sup>26, Ch. 3</sup> has been designed for suspending the whole GGG apparatus from the vacuum chamber. Calculation of the transfer function shows that a reduction factor by 1/200,000 can be achieved, and that no spurious mode is introduced close to those of the GGG dynamical system. Then, differential displacements due to lunisolar tides will become relevant ( $\cong 10^{-3}\mu\text{m}$ ), all with well known frequencies and phases. Only the 24-hr tesseral harmonic due to the Sun competes with the GGG expected signal. However, it has a distinct signature in response to the declination of the Sun (zero at the equinoxes; maximum at the solstices) to be filtered out from a 3-month measurement series (data taking does not need to be continuous). For an EP test of its own GGG has, w.r.t GG,

a weaker signal and a stiffer coupling of the test bodies (inevitable at 1-g). Yet, we are confident that it can compete with the best torsion balance ground tests.

The importance of a full scale ground test is apparent. All crucial items of the space experiment (except drag free control) are tested in the lab, where local gravity is obviously a disadvantage; should any major difficulty arise –which might have been overlooked in the theoretical analysis and the numerical simulations of the space experiment– it can be fixed; were the problem to be a fundamental obstacle, the funding Agencies would have the choice to stop the project before construction begins.

## 6. MISSION OPERATION, GROUND CONTROL, MANAGEMENT OF SCIENTIFIC DATA, IMPACT ON THE MEDIA AND THE GENERAL PUBLIC

The GG mission is devoted to a single experiment that, once initialized, runs uninterrupted to the end of the scientific data collection (6 months after the end of the set-up and first calibration). There are no maneuvers, either orbital changes or attitude slews, during the scientific mission. The processing of scientific data is done in bulk, therefore no scientific quick-look is required. All scientific operations are autonomous, executed on the basis of time-tagged operation sequences that are loaded at least one day in advance. Given the high level of autonomy, the tasks of the ground control are essentially limited to generation and transmission of command sequences and parameters, and analysis of satellite data to establish that the satellite is operating correctly. The mission requires an equatorial orbit and therefore an equatorial station (e.g., Malindi) is ideally suited. Because of the low-inclination orbit, a regular pattern of ground passes with almost constant duration can be assumed. Support by other stations in the early orbit phase is assumed as a standard service. After the nominal attitude has been achieved no other attitude maneuvers are needed throughout the life of the mission.

As it is customary, the ground segment will include, besides the ground station, an Operational Control Center (OCC), responsible for the execution of the mission operations, and an Operational Scientific Center (OSC), responsible for the generation of the scientific operation sequences. There is no special requirement for real-time interaction between the on-board payload and the OSC, or, in general, between the satellite and the OCC.

The main operational modes of the satellite (after commissioning at the beginning of life) are:

- a) Experiment Set-up and Calibration Mode
- b) Normal mode (scientific operation of the experiment)
- c) High-rate Data Collection Mode
- d) Safe (Hold) Mode.

The experiment set-up includes the balancing of the test masses and the mechanical balancing of the capacitance read-out sensors. Both operations need to be repeated at regular intervals, estimated as 20 days for the balancing of the test masses and 15 days for the mechanical balancing of the capacitance bridge. Automatic procedures for such operations will be elaborated, possibly with some interaction with the ground control.

In the science measurements phase, the operation will be essentially autonomous. The Normal Mode is characterized by the drag-free control, executed by the FEED electric min-thrusters. However, the survival of the mission does not depend on the drag-free control, since the stability of the operational attitude is guaranteed by the gyroscopic stability. In case of malfunctions, the scientific operations will be put on hold and housekeeping data will be collected and transmitted to ground on the next station passes; resumption of the operations will be commanded by the ground. Generally, the command and parameter sequences of the Normal mode will need to be updated on a time basis of several weeks, except in the set-up phase when the frequency will be higher (some hours).

The scientific data are sent to ground after demodulation, and the telemetry rate is generally small. Exceptionally, it may be necessary to transmit to Earth the raw (non demodulated) data, for special checkout, parameter identification, and troubleshooting. Because of the nature of the experiment, the duration of such high rate data collection periods will not exceed about 10 minutes. Therefore, the telemetry capacity of the telecommunication links is not exceeded. The scientific data comprise the position of the test masses relative to each other and the "laboratory" (PGB), the time, the spin reference signal and ancillary data such as the temperature, the attitude of the spin axis and the phase difference between the PGB and the spacecraft's outer vessel. The scientific signals are demodulated on board at the spin frequency and only demodulated data (i.e., the data that contain the putative Equivalence Principle violation signal at the orbit frequency) are sent to ground. The only exception is the spin reference signal, used for the demodulation, that is sampled 15 times per spin period of 0.5 sec, that is at 30 Hz, and is sent to the ground without further elaboration. The scientific data collection rate is small, about 1.5 kbit/s, and the total telemetry rate is well below the limit data rate (1 Mbps) of the ESA S-band ground stations, including Malindi, even in the worst case of 24-hour autonomy from the ground. In normal circumstances, we assume the data are downloaded to ground at each orbital pass. Tracking with a normal accuracy of several km along-track is sufficient for the purposes of the scientific mission.

The minimum integration time of the experiment is determined by the thermal noise and is about 7 days. Hence, examination of the scientific data at shorter intervals is, strictly speaking, not significant. Therefore, quick look procedures are not needed and the scientific data can be routed to the Scientific Data Center within a couple of days of reception. On the other hand, for the purposes of checking the health of the scientific payload and the correct execution of the measurement procedures, shorter reaction times may be desirable. Tests based on consistency checks, threshold parameter values etc. will be elaborated and implemented in automatic self-check procedures that can be run periodically by the payload computer, and can be used to alert the ground control of any non-nominal state of the scientific payload. Data affected by anomalies of any sort will be rejected on post-processing and will have no effect but a shortening of the data collection period (which could be made up for by a corresponding extension of the mission lifetime).

The tasks of the Operational Control Centre will comprise, besides the normal spacecraft operations (mission planning, monitoring and control; orbit and attitude determination), also the execution of the operations required by the scientific measurements. The OCC will be responsible for routing of the payload telemetry to the OSC, and processing of the telecommand requests from the OSC. Co-location of experimenter staff at the OCC, particularly during the early set-up phase, when interaction with the payload on board is more frequent, may be considered.

The data set resulting from the mission will be archived on CDROM and put at the disposal of the scientific community. The complete data set will include raw data, calibrated data and support data (housekeeping, tracking and attitude). The complete data set is expected to comprise about 26 Gbit.

A small satellite based on fine technology and simple mechanical principles, and capable to test to an unprecedented level of accuracy a physical principle that three fathers of modern science have regarded as fundamental, would have an enormous impact on the general public. The mission will be presented primarily through a Web Site with different levels of sophistication aimed at Universities, School and the general public, which will provide material on the history and development of the theory of gravitation from Galileo and Newton, to Einstein and beyond, including a description of general relativity (at levels appropriate for the different audiences). This will place the Equivalence Principle in its historic context, describing past experiments as well as the GG mission in space. Additionally we will seek to present information on the experiment and the scientific results through popular articles and broadcasts. Galileo, Newton and Einstein are well known to the

public and attract the attention and interest of the media, both press and television. Even though the project is not yet approved for flight we have already had the opportunity to bring the subject to the attention of national TV programmes and newspapers. Images of the GGG payload prototype were broadcast by a major Italian TV channel conveying to a very large audience the simple message that small satellites can be designed by ordinary scientists, they contribute to the advance of human knowledge and help develop new technology. It was never a difficulty to explain what GG is aiming to, why its goal is so important, why only space technology can provide a crucial scientific result to be reported in textbooks for a long time to come.

## 7. GG PROGRAMME DEVELOPMENT APPROACH

The scientific and technical characteristics of GG are such that the spacecraft functions are completely standard, whereas the payload manufacturing, integration and test and the associated controls are new and complex. Accordingly, the spacecraft development programme can be matched to that of a standard bus (here, PRIMA is assumed), developed with a protoflight approach, whereas the payload is given a dedicated development model. The Work Breakdown Structure (reported on page 3 of annexed letter by ALENIA) reflects this approach, with separate project offices at the system/SVM level and at the payload level.

The GG Satellite development and verification will be based on a simplified Protflight approach in which only one complete satellite model is manufactured and assembled at flight standard. Furthermore, the subsystem verification is performed at system level in the frame of the integration and system tests. On the other hand, at payload level (PGB with test masses and active damping and drag-free control electronics) both a Structural-Thermal Model (STM) and Development Model (DM) are planned. The purpose of such models is to verify the mission specific functionalities separately, thus avoiding adverse impacts on the system level programme.

The STM will be subjected to a test and validation campaign whose main purpose is to validate and refine the mechanical and thermal mathematical models. As a result, simulations of the P/L performance will provide more accurate predictions. Moreover it will be possible to perform experiments on critical mechanisms, such as the lock/unlock devices. The Development Model will be a breadboard, functionally representative of the entire payload module, and will be subjected to a validation campaign consisting of functional and electrical tests. The main purpose of this model is to debug well in advance the design of critical items and verify the integration of the relevant software (active damping and drag-free control running in the main computer). The basic building blocks of the DM are already being assembled as part of the GGG laboratory prototype<sup>Sec. 5</sup>. In this way the programme C/D phase can start with the most critical aspects of P/L design already verified.

The schedule is based on a Phase B of 9 months and Phase C/D of 27 months (see<sup>26</sup> Ch. 8, Fig. 8.2). An essential prerequisite to a 3-year programme is the advanced development of the payload critical items, already ongoing as part of the GGG laboratory experiment.

The proposed design presented herein does not rely on any completely new technologies. Although many requirements of the GG payload are very stringent, they can be met by technologies and processes already existing in the commercial market, which will have to be adapted for use in a space application. Field Emission Electric Propulsion (FEED) is undergoing complete qualification under ESA contract, including an orbital test on the Space Shuttle. GG is likely to be the first satellite using FEED for fine drag free control, a development that will be of great interest for future fundamental physics missions, such as LISA. A number of critical aspects of the payload design can be verified in the laboratory while testing the GGG prototype. Advanced breadboarding is planned on the lock/unlock mechanism, the elastic suspensions (prototype already manufactured and tested for losses)

and other delicate mechanisms. A qualification campaign is required for the inch-worms. A first breadboard of the capacitance read-out circuit has been manufactured and is under testing with GGG, as is the active damper control electronics. These laboratory activities will continue and be concluded (for what concerns the space-qualification aspects) in the satellite DM programme. The complete drag free control system cannot be tested on ground. Verification will be performed by software simulation, incorporating results from laboratory tests of the key elements (capacitance sensors, active dampers, FEEP thrusters), so as to optimize the control laws with respect to real-world sensor and actuator characteristics.

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