COSPAR, Nagoya July 1998
To appear in: Advances in Space Research

THE "GALILEO GALILEI" (GG) PROJECT: TESTING THE EQUIVALENCE PRINCIPLE IN SPACE AND ON EARTH

A.M. Nobili[1], D. Bramanti[1], E. Polacco[1], G. Catastini[2], A. Anselmi[2], S. Portigliotti[2], A Lenti[3] and A. Severi[3]

[1]*Università di Pisa, Via Buonarroti 2 Pisa, Italia*
[2]*Alenia Spazio, Corso Marche 41, Torino, Italia*
[3]*Laben Milano e Firenze,Viale Machiavelli 31 Firenze, Italia*

ABSTRACT

"**G**ALILEO **G**ALILEI" (**GG**) is a proposal for a small, low orbit satellite devoted to testing the Equivalence Principle (**EP**) of Galileo, Newton and Einstein to 1 part in 10^{17}. At the end of 1997 **GG** has been selected and funded by ASI (Agenzia Spaziale Italiana) for a 1-year Phase A study. The main novelty of **GG** is that the concentric hollow test cylinders whose relative motion (in the plane perpendicular to the spin axis) would be affected by an EP violation, spin together with the read-out capacitance sensors placed in between them. The nominal spin rate is 2 Hz, and this is the frequency at which the putative EP violation signal is modulated by the sensors. As compared to other experiments the modulation frequency is increased by more than a factor 10^4, thus reducing *1/f* (low frequency) electronic and mechanical noise. **GG** will have FEEP ion thrusters for drag compensation. The required amount of propellant is of a few grams only. The experiment works at room temperature. To demonstrate the feasibility of the space experiment a payload prototype for EP testing on the ground (**GGG** - **GG** on the **G**round) is under development in the laboratories of Laben. The challenge in this field is to fly an experiment able to improve by many orders of magnitude the current best ground sensitivity ($\cong 10^{-12}$). This requires spurious relative motions of the test bodies to be greatly reduced, leaving them essentially motionless. Doing that with more than one pair of bodies appears to be an unnecessary complication. This is why GG is now proposed with a single pair of test masses. Information, research papers and photographs of the ground apparatus are available on the Web (**http://tycho.dm.unipi.it/nobili/ggproject.html**).

INTRODUCTION

Do bodies of different composition fall with the same acceleration in a gravitational field? If not, the so called Equivalence Principle -the founding pillar of General Relativity- is violated. The driving signal of an EP violation in the gravitational field of the Earth is about 3 orders of magnitude stronger than on Earth if the test bodies move in low Earth orbit. Since the expected signal is a differential force, the best results so far have been obtained with the test bodies arranged on a torsion balance, because it is sensitive to torques produced by differential forces. A torsion balance is not well suitable for space, where all scientists agree to use coaxial test cylinders, with a read out system to detect relative displacements between them. In the STEP project (Worden and Everitt, 1973; Worden 1976; Worden 1987; Blaser *et al.* 1993; Blaser *et al.* 1996) the s/c (with the test cylinders inside) is kept fixed with respect to inertial space by a very accurate active attitude control; the test cylinders lie in the orbit plane and are sensitive to differential forces along their symmetry axis, hence an EP violation in the field of the Earth gives a signal at the orbital period of the satellite (≅ 6000 sec). In GG the s/c (with test cylinders and sensors) spins very rapidly (0.5 sec period) with the spin axis perpendicular to the orbit plane (this attitude is stable and needs no control). The test cylinders are sensitive to differential forces in the plane normal to the spin axis and an EP violation is modulated at the (high) frequency of spin. Indeed, the history of EP testing, from the pioneering experiments by Eötvös to the recent, careful work of the "Eöt-Wash" group, shows a continuing effort to increase the modulation frequency: from a DC signal in the Eötvös experiments, when the test masses had to be switched manually on the torsion balance, to a 1-day modulation when the Sun was considered as a source rather than the Earth and the diurnal rotation of the laboratory provided the modulation (in the experiments by Dicke, Braginsky and coworkers), to 1 or 2-hour modulation obtained by carefully rotating the torsion balance (Su *et al.* 1994). The novelty of GG is that the coaxial test cylinders are weakly coupled by very soft mechanical suspensions and fast spinning (much faster than their natural frequency of differential oscillations). The weak coupling makes the system sensitive to differential forces in the plane perpendicular to the spin/symmetry axis. In addition to electric grounding, this design provides extremely good centering once unstable whirl motions caused by losses in the suspensions are damped. These motions are very slow if the mechanical quality of the suspensions is good and can be controlled actively on board the satellite; their growing time is so slow that data taking can be carried out with the whirl control switched off. The error budget for GG is compatible with a target sensitivity in EP testing of 1 part in 10^{17}; details can be found in Nobili *et al*. (1995), Nobili *et al*. (1998), the GG Phase A Report (1998) and on the GG Web page (http://tycho.dm.unipi.it/nobili/ggproject.html).

THE GG SPACE MISSION AND ITS NOVELTIES

Fig. 1 shows 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 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 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 due to an EP violation. In the current settings and full simulation of GG at Phase A level the natural period for differential oscillation of the test bodies is about 500 sec: an EP violation by only 1 part in 10^{17} would cause a displacement of the test cylinders by $\cong 6\cdot10^{-11}$ cm, to be transformed into a voltage signal of ≅ 1nV and detected with a capacitance read-out which has already been tested in the laboratory. The 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 (2 Hz 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, which is close to zero; variations from the electrostatic contribution to the coupling can be made negligible) and a direction changing at the s/c orbital frequency around the Earth ($\cong 1.75\cdot10^{-4}$ Hz); so in GG the signal is modulated at a frequency about 10^4 times larger than the frequency of the signal, the advantage being the reduction of low frequency noise, both electronic and mechanical The spinning state of the GG s/c is a stable 1-axis rotation and needs no active control.

In STEP the concentric test cylinders are kept fixed with respect to inertial space by active control of the s/c, their symmetry axis is the sensitive axis and lies in the orbital plane. If one cylinder is attracted by the Earth more than the other 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 s/c moves by 180° 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. Any higher frequency signature, higher than the orbital frequency, that one would wish to impress on the signal requires the s/c to be spun around its actively controlled space-fixed attitude. Due to the STEP design these can only be slow rotations and require a careful active control.

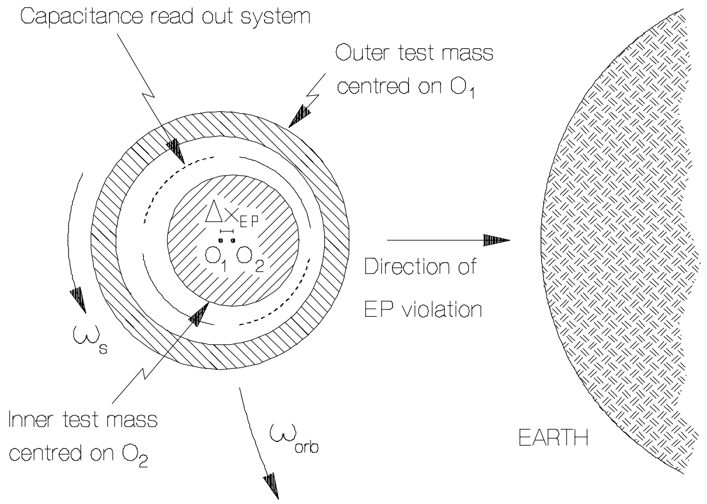

Fig. 1. Section of the GG coaxial test cylinders and capacitance sensors in the plane perpendicular to the spin axis. The capacitance plates of the read-out are shown in between the test bodies, in the case in which the centers of mass of the test bodies are displaced from one another by a vector $\Delta\vec{x}_{EP}$ due to an Equivalence Principle violation in the gravitational field of the Earth (e.g., the inner test body is attracted by the Earth more than the outer one because of its different composition). Under the (differential) effect of this new force the test masses, which are weakly coupled by mechanical suspensions, reach equilibrium at a displaced position where the new force is balanced by the weak restoring force of the suspension, while the bodies rotate independently around O_1 and O_2 respectively. The vector of this relative displacement has constant amplitude (for our needs) 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.

An 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. 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 which is too large unless the residual gas pressure is very low. In STEP this 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, which can be obtained by operation close to absolute zero 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. Azimuthal asymmetries and the radiometer effect along the symmetry axis of the cylinders must be also be taken into account in GG, but the requirements they impose on the acceptable temperature gradients are compatible with a pure passive thermal control of the GG experiment. This eliminates one of the main reasons why a high accuracy EP experiment in space should be operated in cryogenic conditions. Low temperature is helpful in reducing thermal noise. Since the dependence of thermal noise acceleration on the experiment temperature and the mass of the test bodies is $\propto(T/M)^{1/2}$, in GG we use more massive test bodies: test bodies of 10 kg each at 300 K, as we have in GG, result in the same thermal noise as with test masses of 0.1 kg and at a temperature of 3 K. A lower temperature version of the GG experiment can be envisaged for which the rapid spin gives an important advantage: the high centrifugal force at the periphery of the s/c would dominate the motion of the refrigerant (movable) material and largely reduce, by symmetry, its perturbations on the bulk of the experiment; evaporation can take place along the spin axis for symmetry reasons too. In non-spinning or slowly spinning satellite experiments perturbations from the nearby refrigerant mass (a few hundred liters of He in STEP) is known to be a source of perturbation.

The weak mechanical coupling of the GG test bodies is the key feature which allows us to cope with the effect of residual air drag along the satellite orbit. Air resistance acting on the s/c surface is experienced by the test bodies suspended inside it as a translational 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. Drag-free control (with FEEP ion thrusters) of the GG s/c reduces the corresponding inertial acceleration on the payload. In order to further reduce its differential effect on the test cylinders they are coupled similarly to the two weighs of an ordinary balance whose arms length can be adjusted (by means of piezo actuators) so as to balance the system. This balancing procedure, which has been tested on the ground prototype (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. To be 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 drag is variable in time and many degrees away from the signal; the drag free control laws developed during the GG Phase A Study show that memory of this phase difference is not lost after drag compensation, and that the signal can be recovered even in the presence of a larger residual drag. Vibration noise from the FEEP thrusters close to the spin frequency is attenuated by the suspensions of the PGB (Pico Gravity Box) laboratory enclosing the test bodies.

The GG bodies all spin at a frequency much higher than their natural frequencies of oscillation. 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. In GG whirl motions 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 GG system using the software package DCAP of Alenia Spazio. Simulations of the full 6-body GG system (outer s/c, PGB, 2 test bodies and two balancing arms), with realistic errors and including both whirl and drag control, are published in the GG Phase A Report (1998, Ch. 6). They demonstrate that the system can be fully controlled and that the control does not affect the expected sensitivity. Instead, the control used by Jafry and Weinberger (1998) fails to reconstruct the small whirl velocity to be damped, thus applying exceedingly large active forces; it is a wrong control for GG, hence it cannot be used to assess the sensitivity of the GG experiment in EP testing (Nobili *et al.*, 1999). The physical principles of the GG control were outlined in the GG Pre-Phase A Report (1996) and in Nobili *et al.* (1996). In fact, with the measured value of the quality factor of the suspensions, whirl motions of the test cylinders are so slow that they can be damped at time intervals long enough to allow data taking in between, when active damping is switched off.

Fast rotation and weak mechanical suspensions and coupling 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, s/c mass anomalies, non-uniform thermal expansion, parasitic capacitances, etc.) appear as DC because the entire system is spinning. Due to mechanical suspensions there are no floating bodies; they are all connected by mechanical conductive suspensions which once coated with the same conductive material provide a “Faraday cage” and consequent electrical discharging of the experimental apparatus. This is a major advantage because electric forces caused by even a minute amount of charge are enormous compared to the tiny gravitational force to be detected. To avoid the disturbances of a discharger the STEP teams envisaged either to discard “contaminated” data (Blaser *et al.*, 1993) or to carry a 130 kg tungsten shield (Blaser *et al.*, 1996).

THE "**G**ALILEO **G**ALILEI ON THE **G**ROUND" (**GGG**) EXPERIMENT

GGG is an apparatus for EP testing on the ground made of 2 weakly coupled, fast spinning concentric rotors (10 kg each) and a capacitance read-out in between, similarly to the GG proposed experiment in space. For test bodies suspended on the surface of the Earth the driving signal of an EP violation, from either the Earth or the Sun, is much weaker than it is for test bodies in low orbit around the Earth (by about 3 orders of magnitude). Moreover, the mechanical coupling of the GGG bodies in the horizontal plane cannot be as low as in space, due to the need to withstand local gravity. Once these facts are taken into account, it can be shown that a GGG test of the Equivalence Principle to the level of $\cong 10^{-12}$ (i.e. competitive with the best torsion balance results) requires to detect differential displacements of $\cong 10^{-10}$ cm, namely what is required by a GG test in space to about 1 part in 10^{17}. So far the GGG system appears to be a promising instrument for the measurement of small differential effects such as the signal of an EP violation. The currently measured displacements between the GGG test cylinders of 10 kg each, spinning at about 3 Hz in a weakly coupled suspension, are within a few μm (whirl motions are damped by a tiny 0.1 gr passive damper). This indicates that the physics behind the GGG and the GG design is correct. We are now at the level of measuring the tilting of the terrain caused by horizontal tidal forces (later to be eliminated by gimballed suspensions, now useful to test the instrument). The sensitivity of the capacitance read out (in all similar to the read out to be flown in space) tested on bench is of 5 picometers in 1 sec integration time, which is what we need both for GGG and for GG.

REFERENCES

Blaser, J.P. *et al.* (including A.M. Nobili), Satellite Test of the Equivalence Principle, *Report on the Phase A Study*, ESA/NASA SCI(1993)4 (1993)

Blaser, J.P. *et al.*, STEP: Satellite Test of the Equivalence Principle, *Rep. on the Phase A Study*, ESA SCI (1996) 5

Jafry Y and M. Weinberger, Evaluation of a Proposed Test of the Weak Equivalence Principle Using Earth-Orbiting Bodies in High-Speed Co-Rotation, *Class. Quantum Grav.* **15** 481-500 (1998)

Nobili, A.M. *et al.*, "GALILEO GALILEI". Flight Experiment on the Equivalence Principle with Field Emission Electric Propulsion, *J. Astronaut. Sc.*, **43**, 219-242 (1995)

Nobili, A.M. *et al.*, GG-Test of the Equivalence Principle with a Small Spinning Spacecraft: The Stabilization of its Weakly Coupled Masses, in *Scientific Satellites Achievements and Prospects in Europe*, Proceedings, AAAF-ESA, 3-74/89 (1996)

Nobili, A.M. *et al.*, Proposed Non Cryogenic, Non Drag Free Test of the Equivalence Principle in Space, *New Astronomy*, **3**, No. 3, 175-218 (1998)

Nobili, A.M. *et al.*, Evaluation of a Proposed Test of the Weak Equivalence Principle Using Earth-Orbiting Bodies in High-Speed Co-Rotation: Re-Establishing the Physical Bases, *Class. Quantum Gra.* **16** 1463-1470, (1999)

Su, Y. *et al.*, New tests of the universality of free fall, *Phys. Rev. D*, **50**, 3614-3636 (1994)

Worden, P.W. Jr. and C.W.F. Everitt, Test of the Equivalence of Gravitational and Inertial Mass Based on Cryogenic Techniques, in *Proc. Int. School of Physics E. Fermi, Course LVI*, Academic Press, NY, 381 (1973)

Worden, P.W. Jr., A Cryogenic Test of the Equivalence Principle, *PhD thesis*, Stanford Univ. (1976)

Worden, P.W. Jr., *Acta Astronautica*, **5**, 27 (1987)

“GALILEO GALILEI” (GG) Pre-Phase A Report, ASI (Agenzia Spaziale Italiana) (1996), http://tycho.dm.unipi.it/nobili/ggweb/gg/ggcover.html

“GALILEO GALILEI” (GG) Phase A Report, ASI (Agenzia Spaziale Italiana) (1998), htttp://tycho.dm.unipi.it/nobili/ggweb/phaseA