The GALILEO GALILEI small-satellite mission with FEEP thrusters (GG) (*)

A. M. Nobili, D. Bramanti and G. Catastini
Gruppo di Meccanica Spaziale, Dipartimento di Matematica, Università di Pisa - Pisa, Italy

(ricevuto il 5 Dicembre 1996; approvato il 18 Marzo 1997)

Summary. — The Equivalence Principle, formulated by Einstein generalizing Galileo's and Newton's work, is a fundamental *principle* of modern physics. As such it should be tested as accurately as possible. Its most direct consequence, namely the *Universality of Free Fall*, can be tested in space, in a low Earth orbit, the crucial advantage being that the driving signal is about three orders of magnitude stronger than on Earth. GALILEO GALILEI (GG) is a small space mission designed for such a high-accuracy test. At the time of print, GG has been selected by ASI (Agenzia Spaziale Italiana) as a candidate for the next small Italian mission. Ground tests of the proposed apparatus now indicate that an accuracy of 1 part in 10^{17} is within the reach of this small mission.

PACS 04.80 – Experimental studies of gravity.
PACS 01.30.Cc – Conference proceedings.

An experiment to test the equivalence of inertial to gravitational (passive) mass in space offers two main advantages: a signal about a factor of a thousand bigger than on Earth and the possibility of exploiting the absence of weight. GALILEO GALILEI (GG) is a small-satellite mission currently under study in Italy by eight research institutions with approval and funding by ASI (Agenzia Spaziale Italiana). The mission concerns a small, low Earth satellite (150 kg total mass, 520 km altitude) with two objectives. One is scientific, in the field of fundamental physics, and the other technological in the frame of spacecraft propulsion and drag compensation. The scientific goal is to test the equivalence principle to 1 part in 10^{16}, four orders of magnitude better than the best ground results. The technological goal is a full, comprehensive test of FEEP (Field Emission Electric Propulsion) thrusters for accurate drag compensation. FEEPs have been invented, designed and developed by ESA (European Space Agency) and will most probably become an essential component of all space experiments which require measurement of small forces. The GG

(*) Paper presented at the VII Cosmic Physics National Conference, Rimini, October 26-28, 1994.

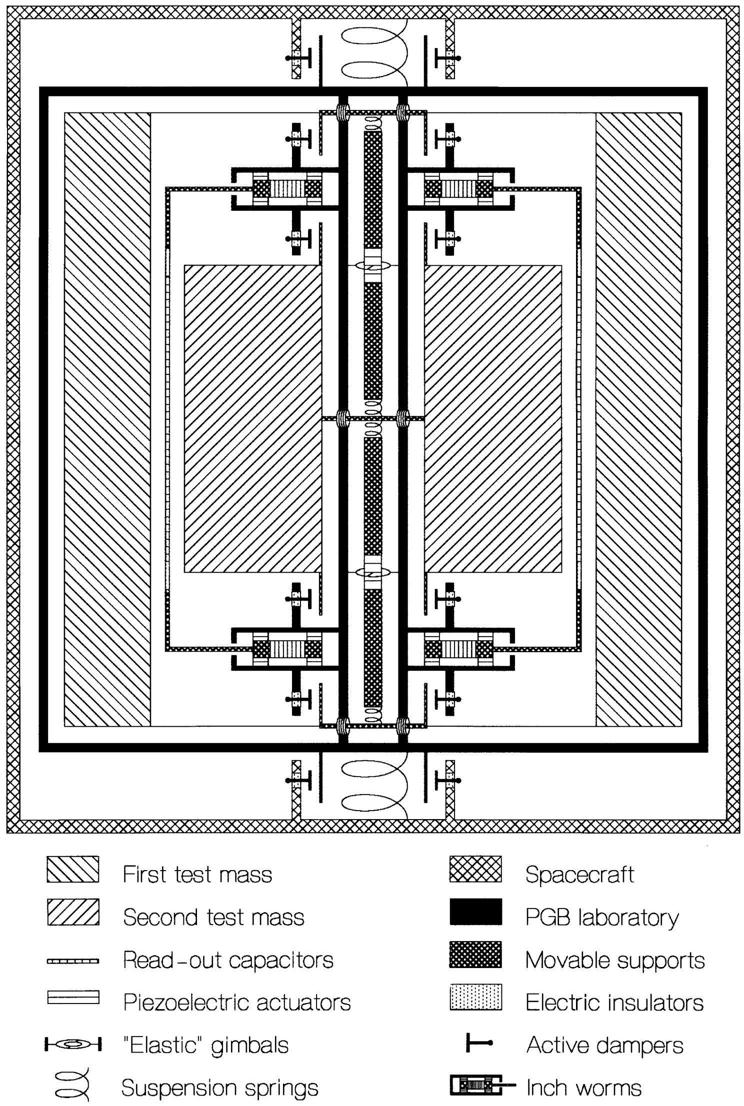

Fig. 1. – Section through the spin axis of the spacecraft showing the spacecraft, the PGB (Pico Gravity Box) laboratory and the test masses (not to scale). The PGB laboratory and the test masses are suspended with springs. The suspensions of the test masses also employ «elastic» gimbals (*i.e.* gimbals pivoted with torsion wires) on two movable rods for the balancing of inertial forces. The capacitive plates of the read-out system, between the test masses, are attached to inch worms for adjusting their distance from the surfaces of the test masses.

experiment is carried by a small, cylindrical spacecraft of about 100 cm base diameter and 70 cm height stabilized by single-axis rotation at 5 Hz (fig. 1). The symmetry axis of the cylinder is, by construction, the axis of maximum moment of inertia so as to stabilize the rotation around it. The orbit is almost circular, almost equatorial at about 520 km altitude, which allows the satellite to avoid the perturbing effects of radiation from the

TABLE I. – *Main characteristics of the* GG *satellite.*

Total mass (payload included)	150 kg
Shape and size	cylinder
diameter	100 cm
height	70 cm
antenna	dipole-array (like METEOSAT)
solar cells	around external surface of cylinder (no panels)
Stabilization	passive, one-axis rotation (5 Hz) almost perpendicular to orbit plane
Orbit	520 km altitude, almost equatorial, almost circular
Pointing accuracy	1–3 degrees
Lifetime	$\simeq$ 6 months
Drag compensation	to 10^{-3} by FEEP thrusters with liquid Cs propellant
Total mass of propellant	$\simeq$ 5 g of liquid Cs
Total power	$\simeq$ 85 W
Data rate	$\simeq$ 1 kbit/s for a few minutes each orbit

Van Allen belts in the so-called South Atlantic Anomaly. The spin axis of the satellite is almost perpendicular to the orbit plane. This maximizes the signal and makes it unnecessary to perform any attitude manoeuvres after initial set-up and for the total $\simeq 6$ month duration of the mission. There are no severe requirements as far as orbit injection and spacecraft attitude are concerned. The satellite is very similar (but for the smaller mass and size) to the spin-axis–stabilized METEOSAT satellites used by ESA for meteorological prediction. Similarly to them it has solar cells around the external surface, which can easily generate the required power of $\simeq 85$ W, and a METEOSAT-like dipole array antenna for communication with Earth. This antenna does respect the cylindrical symmetry of the satellite and needs no moving parts, which would perturb the experiment. Since the orbit is low and equatorial the satellite will be in view of the ground station only for a fraction of its orbital period. However, since there is no special need for continuous tracking, the experimental data can be stored on board and downloaded once per orbit. The required bit rate is low ($\simeq 1$ kilobit/s for a few minutes every orbit). The spacecraft is equipped with FEEP thrusters, arranged in cylindrical symmetry, in order to partially compensate for the effect of air drag which amounts to $\simeq 1$ dyn. FEEPs require only $\simeq 5$ g of cesium for 6 months nominal duration of the mission. They are operated in pulsed mode, driven by four capacitance sensors symmetrically placed around the suspended PGB (Pico Gravity Box) laboratory inside the spacecraft (see fig. 1), which acts as test body for drag-free operation. Table I gives a summary of the satellite main characteristics. The satellite carries two mechanically suspended, concentric, cylindrical test bodies (10 kg each) made of different material whose relative displacements are measured by capacitive sensors to detect a possible violation of the equivalence principle. Rotation in supercritical conditions and absence of weight are exploited for ensuring self-centring and to reduce vibrational perturbations. Stabilization in supercritical rotation is achieved with active electrostatic dampers because the required force is very small; their contribution to thermal noise is shown to be negligible. The experiment is performed at room temperature. The differential acceleration to be detected is $\simeq 8.4\cdot 10^{14}$ cm/s^2, giving rise to a relative displacement at the satellite spinning frequency

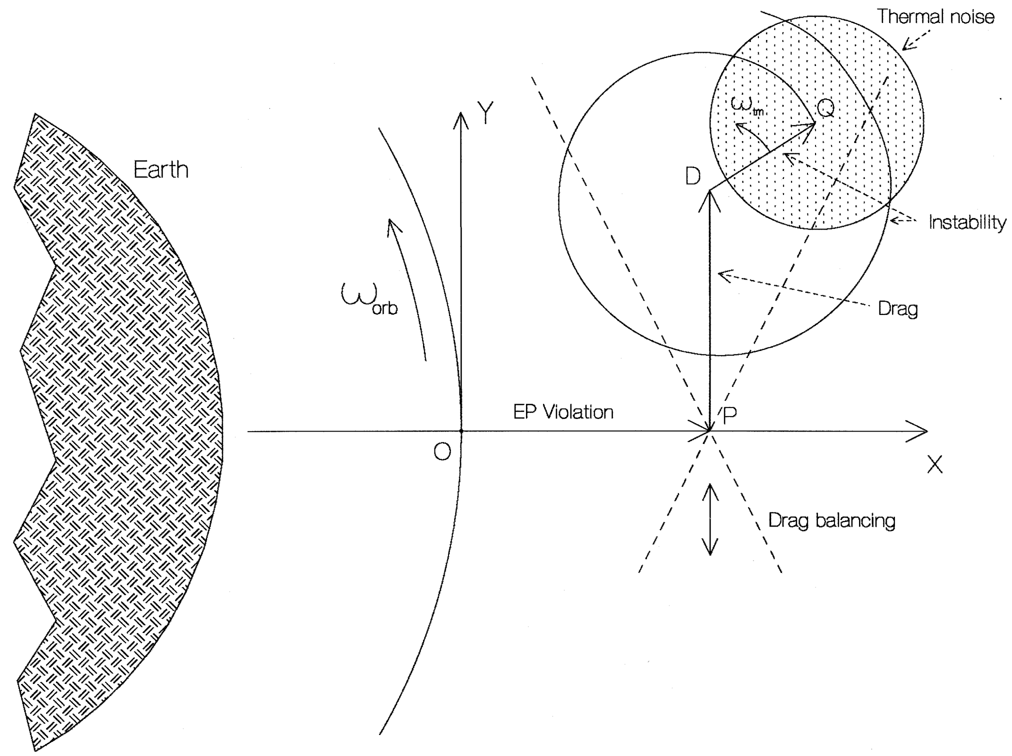

Fig. 2. – Qualitative representation, in the orbital plane and for one pair of test masses, of the differential displacements obtained from the synchronous demodulation of the 2-phase 5 Hz signal. The X-axis is in the Earth-to-satellite direction and the vector OP is the differential displacement, directed along the X-axis and constant in amplitude, of the two masses due to an EP violation. The perturbation PD due to the initially unbalanced atmospheric drag will be found in the area between the two dashed lines crossing in P: the angle between them is about 0.8 rad, and is due to the fact that the drag has a variable component in the radial direction because of the solar radiation pressure (of amplitude about 0.4 times the atmospheric drag and in the Sun-satellite direction). Smaller contributions to the PD vector come from the Earth albedo, the Earth infrared radiation and, by a smaller amount, from a possible small eccentricity of the orbit. By finely adjusting the lengths of the suspension arms the point D is displaced up or down inside this area, and this balancing of the drag should be continued until D is as close as possible to P. In doing so, also the radial component is automatically balanced. The resonant variations of the drag (not shown) will oscillate inside the same area. The vector DQ is the instability due to the internal dissipation of the springs, slowly rotating and increasing: it must be actively damped until Q is as close as possible to D (and P). The circle around point Q represents the error in the measurement due to the thermal noise of the mechanical oscillations in a few days of integration time. The actual values of all these quantities have been computed.

and with known signature of amplitude $\simeq 2.1 \cdot 10^{-10}$ cm. The read-out system is capacitive and the sensitivity needed for such measurements is well feasible. With a FEEP drag compensation by a factor 10^3 the capacitance bridge can detect the expected displacement provided it is balanced to within only a few 10^{-5}, amounting to an accuracy of a fraction of a micrometre in the positioning of the capacitance plates in between the test bodies, which is well feasible with piezoelectric actuators. Forces which, unlike the expected one, act in common mode must be rejected to a few 10^{-6} to allow detection of the expected differential signal. This is achieved by suspending the test bodies on the opposite ends of two arms pivoted at their centres like in balances and torsion balances. In the latter systems the level of balancing (*i.e.* rejection) needed here is well feasible even in the more difficult $1-g$ environment. Arms length adjustments will be performed with piezoelectric actuators whose properties and reliability are well known. Figure 2 shows the procedure for the recovery of the signal. Temperature gradients in space across the test bodies are negligible thanks to the fast spin as compared to orbital motion. Those along the spin axis are much larger, but the requirement is far less strict and can be easily fulfilled. Temperature in the PGB experimental chamber containing the test bodies must be constant for the entire integration time of a few days to 0.01 K. We have shown that this can be achieved by means of an insulation shell on the inner surface of the spacecraft, vacuum in between this surface and the PGB and multilayer insulation (less than 10 layers) of the PGB. Experience with metallic springs in gravimeters used for accurate measurements of Earth tides shows that springs with good properties of stability, both in time and with temperature, can be built. Appropriate machining, annealing and attaching procedures are available. Ground testing of the actual springs to be used in the space experiment is possible using torsion balances and the test procedure is being checked in the laboratory. No electrostatic problems arise due to the absence of free floating masses and the presence of conducting hair-like suspension springs instead. Magnetic effects have been computed and it has been demonstrated that no μ-metal shielding is required. Many perturbing effects which are usually a matter of concern in similar experiments are irrelevant here thanks to the common rotation of the entire system (*i.e.* inhomogeneities of the test bodies, coupling of the higher mass moments of the test bodies to spacecraft mass anomalies, non-uniform thermal expansion, parasitic capacitances, electrostatic patch effects...). A system of mechanical stops and static lockers has been designed to withstand launch phase accelerations and limit the suspended bodies to small movements only. Unlocking will take place once the spacecraft has reached its nominal supercritical rotation rate. A scientific requirement document is in preparation in which all the perturbing effects and noise sources that we are aware of at present are analyzed and the corresponding limit they set on relevant parameters is given. A less sensitive ground-based version of the experiment, which retains its main characteristics, is under development. The goal is to provide the most comprehensive demonstration of the space experiment by performing, at the same time, a valuable ground test of the equivalence principle. Wide reference to the available literature and more details can be found in [1-3].

REFERENCES

[1] NOBILI A. M., BRAMANTI D., POLACCO E., CATASTINI G., GENTA G., BRUSA E., MITROFANOV V. B., BERNARD A., TOUBOUL P., COOK A. J., HOUGH J., ROXBURGH I. W., POLNAREV A., FLURY W., BARLIER F. and MARCHAL C., *Proposed non cryogenic, non drag-free test of the Equivalence Principle in space*, to be published in *New Astronomy.*

[2] Nobili A. M., Bramanti D., Polacco E., Catastini G., Milani A., Anselmo L., Andrenucci M., Marcuccio S., Genovese A., Genta G., Delprete C., Brusa E., Bassani D., Vannaroni G., Dobrowolny M., Melchioni E., Arduini C., Ponzi U., Laneve G., Mortari D., Parisse M., Curti F., Cabiati F., Rossi E., Sosso A., Zago G., Monaco S., Gori Giorgi G., Battilotti S., D'Antonio L. and Amicucci G., *J. Astronaut. Sci.*, **43** (1995) 219.

[3] "*GALILEO GALILEI*" (*GG*) *Pre-Phase A Report*, ASI (Agenzia Spaziale Italiana), September 1996.