Galileo Galilei (GG): a mission to test the founding pillar of General Relativity to 10^{-17}

Letter of Intent submitted in response to "Call for a medium-size mission opportunity in ESA's Science Programme for a launch in 2025 (M4)"

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Scientific goal of GG

General Relativity (GR) is founded on the experimental fact that in a gravitational field all bodies fall with the same acceleration regardless of their mass and composition. This is the Weak Equivalence Principle (WEP) or Universality of Free Fall (UFF). Experimental evidence of a violation would require either that GR is to be amended or that a new force of nature is at play. Either way, it would be a scientific revolution, while a confirmation would strongly constrain physical theories. There is no firm target as to the level at which violation should occur but the higher the precision of the test, the higher the chances to find new physics.

GG will test the Universality of Free Fall and the Weak Equivalence Principle on which General Relativity relies to 1 part in 10^{17}. It will do it by measuring to this level the fractional differential acceleration of two different composition test masses in the gravitational field of the Earth while orbiting around it at low altitude. GG will improve the best torsion balances results, currently at 10^{-13}[1], by 4 orders of magnitude, deeply probing a totally unexplored physical domain.

No other experimental tests of General Relativity are both so crucial for the theory and so precise.

Mass dropping tests of WEP/UFF have been superseded by torsion balances by many orders of magnitude, in spite of a driving signal almost 3 orders of magnitude stronger (on Earth). The best result obtained by dropping macroscopic bodies is $7.2 \cdot 10^{-10}$[2], while drop tests with cold atoms are at 10^{-7} [3], [4].

Aside from laboratory controlled experiments, laser ranging to the Moon has shown that the Earth and the Moon – whose composition is different – fall with the same acceleration in the field of the Sun to 10^{-13} [5], [6].

In less than two years time the mission μSCOPE, by the French space agency with contribution from ESA, will fly to test WEP/UFF to 10^{-15}[7], a target 100 times less ambitious than GG. Whatever the result of μSCOPE, it will need confirmation by a more sensitive experiment of different design and with different systematics. The signature of the expected signal is known, and the test is not an absolute measurement; as long as the sensitivity is better than the 10^{-13} level demonstrated so far, once an effect is measured whose classical origin is not identified it could be interpreted as a violation. Should μSCOPE data be compatible with a violation, no matter how cautiously this fact will be announced, it will make it to the first page of major newspapers and the pressure for checking it will be enormous.

The science case

General Relativity is the best theory of gravity to-date. It governs physics at the macroscopic and cosmic scales and it has been highly successful in the confrontation with experiments. However, all attempts at merging gravity with the other forces of nature have failed and most of the mass of the universe is unexplained.

Cosmology has advanced at an impressive pace. Yet, despite great experimental results and powerful theoretical tools, our understanding of the Universe is largely unsatisfactory. Direct measurements by means of very ambitious missions are one way of tackling the open issues. On the other hand, it is legitimate to question the underlying theory of gravity: *Is General Relativity the last word in our understanding of gravity? Do new fundamental forces exist? Who is wrong: Einstein or the Standard Model?*

With the advent of space age, the incredible accumulation of precise binary pulsar data and the progress of radio astronomy, GR has been tested in weak as well as in strong field conditions and it has always been confirmed, including the prediction – in the linear approximation – of gravitational waves [8], [9].

Since experiments in space are expensive and flight opportunities are limited one must ask the question as to which are the most powerful tests of the theory, namely those which are most likely to provide experimental evidence of a deviation leading to new physics beyond the current impasse[10]. There are two driving criteria. First, one should test the foundations of GR, rather than its numerous physical consequences. Secondly, the precision of the test should be as high as possible.

WEP/UFF tests satisfy both criteria.

In the 1916 paper[11] "*The foundation of the general theory of relativity*" Einstein showed how the physical equivalence between an accelerated frame and a uniform gravitational field – of which he became aware with his "happiest thought" is 1907 – leads to the general theory of relativity. In Sec. 2 he wrote that this is "*... made possible for us by the teaching of experience as to the existence of a field of force, namely the gravitational field, which possesses the remarkable property of imparting the same acceleration to all bodies.*" And since this fact of nature must be proved experimentally, Einstein brought as evidence the torsion balance experiments carried out in the same years by Eötvös, of which he was well aware. In a specific footnote to the previous sentence he wrote: "*Eötvös has proved experimentally that the gravitational field has this property in great accuracy*", thus making it clear that the general theory of relativity relies on the experimental evidence of the universality of free fall. It is unfortunate that, while this paper is very frequently quoted as a landmark for GR, it is not read as carefully, so much that it has become a commonplace in the literature that Einstein had no interest in experimental tests of the theory.

Tests of WEP/UFF are null experiments, which are known to be the most precise experiments in physics.

Is space really needed?

If a torsion balance type experiment is performed inside a spacecraft orbiting the Earth at low altitude the driving signal of a WEP/UFF violation is a factor 500 stronger than on ground, which gives by itself a factor 500 improvement in sensitivity. Secondly, in absence of weight test masses can be coupled very weakly, yielding much higher sensitivity than on ground (inside GG a 10 kg test cylinder requires the stiffness necessary on Earth to suspend 10^{-7} kg). Thirdly, being isolated in space the whole spacecraft spins with no need of motor and bearings (passive one axis stabilization), simply by angular momentum conservation.

In the case of mass dropping tests (either with macroscopic bodies or with cold atom clouds) there is no 500 factor gain in the strength of the signal, which it is in fact slightly weaker than the $9.8\,\mathrm{m/s^2}$ value on ground. Overall the advantage of space for a mass dropping test of UFF/WEP with cold atoms is limited and the need for such an experiment in space is hard to justify.

Torsion balances have proved to be the best sensors for a WEP/UFF test at 1-g, but in weightlessness conditions they lose their property of almost perfect common mode rejection, which is crucial to the success of a differential measurement such as this. Moreover, in a space experiment the test masses should be concentric in order to reduce gravity gradients (tides). The GG sensor is a new balance designed to replace the torsion balance for a WEP/UFF test in space.

Design of the GG sensor and sensitivity of its laboratory prototype

The theoretical bases of the GG sensor design have been firmly established in: "*Abatement of* *thermal noise due to internal damping in 2-D oscillators with rapidly rotating test masses*", published by Physical Review Letters in 2011[12]. Thanks to rotation and two degrees of freedom this sensor is affected, at room temperature, by a highly reduced level of thermal noise. The major consequence is the reduced integration time required to overcome thermal noise.

As demonstrated in: "*Integration time in space experiments to test the equivalence principle*", published by Physical Review D in 2014[13], the GG sensor can make a full WEP/UFF test at the target level of 10^{-17} in 1 day of integration time, leaving the 9 months nominal duration of the mission for rigorous checks of the physical nature of the "signal" against systematics, should anything emerge above thermal noise. For a 10 times better sensitivity the required integration time is 100 times longer, and still feasible. This means that some improvement beyond the stated 10^{-17} target might be possible and will be pursued.

The choice in GG is to address most of the critical issues by design rather than by brute force approaches, such as operating in cryogenics conditions.

Is the required rotation rate of 1 Hz feasible in a real sensor whose goal is to be sensitive to very tiny effects?

Results from the GGG laboratory prototype published in 2012[14] report – at the frequency of the GG signal in space ($1.7 \cdot 10^{-4}$ Hz), and with a rotation rate of 0.19 Hz – a sensitivity of $8.9 \cdot 10^{-12}$, a result which has been recently improved by 1 order of magnitude (paper in preparation). Given the lower sensitivity because of the inevitable stiffer coupling at 1-g, and given the presence of noise from motor/bearings and terrain tilts – all absent in the space experiment – the experimental results of GGG provide robust evidence that the GG sensor is feasible and that the theory behind it is correct.

GG mission configuration

GG is passively stabilized by 1-axis rotation at 1 Hz. Nutation damping is ensured by weak coupling to the intermediate stage called "PGB lab" suspended inside the outer shell of the bus. In its turn PGB encloses – in a nested configuration that preserves the cylindrical symmetry of the system – the GG payload. It is made of two coaxial concentric test cylinders of different composition (10 kg each) weakly coupled by U-shape CuBe suspensions constituting the GG differential acceleration sensor with 2 degrees of freedom in the plane perpendicular to the spin/symmetry axis.

The bus is capable of drag-free control at orbital frequency. It uses PGB as test mass, capacitance bridges as sensors and cold gas thrusters as actuators. Drag-free requirement for GG is 180 times less stringent than in μSCOPE and 6000 times less stringent than in LISA-PF, due to common mode rejection by the GG sensor (since it is a balance by design).

In addition to serving as test mass for drag-free control, the PGB lab carries all what is needed to "serve" the sensor and its test masses, so that they can be as passive as possible – as required in all experiments devoted to the measurement of extremely small forces. Self centering of the centers of mass on each other is ensured by physics; damping of a slow instability expected from theory (whirl damping) is required at many days intervals and it is always off during science measurements. Control laws are the same, at 10 times higher frequency, as for drag-free; sensors and actuators are small capacitors. In the ground prototype sensor the relative displacements of the test cylinders are read by capacitance plates in between them; in GG there will be a laser gauge. While capacitance sensor measurements are inversely proportional to the gap, the laser gauge is linear with it, thus allowing large gaps (e.g. 2 cm) which make the dangerous effects of electrical charged patches negligible in GG. Only light from the lasers is deposited on a few polished spots on the cylinders' surfaces – the spots being symmetrical around the axis – while the laser gauge itself is located on the PGB.

GG very short integration time has a major impact on the payload because it avoids the need for an additional sensor with test masses made of the same material for zero check purposes. This has been known to be an issue, because the s/c has only one center of mass and disturbances may be different. Having 9 months available and one WEP/UFF test to 10^{-17} per day, passive stability of the GG spin axis relative to inertial space under widely changing dynamical conditions (precession of the orbit plane) allows the most important known sources of systematics to be identified and discriminated from the signal on the basis of their different physical signature. This analysis can be done offline by different groups, independently and blindly. It is based on rigorous celestial mechanics and requires no sensor in addition to the one made of two concentric test cylinders of different composition at the center of mass of the spacecraft.

The orbit of GG is a standard, near circular, low altitude ($\simeq$ 600 km) sun synchronous orbit with no special launch requirements. The mission duration is 9 months. The total mass is 400 kg. GG can be easily injected in its orbit by the VEGA launcher using a fraction of its capability.

Heritage from the past, who will do what and where, cost estimate and supporters

ASI has funded industrial studies of GG since 1996. The GGG laboratory experiment has been funded by INFN and ASI.

The most relevant industrial study of GG at Phase A2 level has been conducted in 2009 at TAS-I in Torino, based on expertise accumulated with GOCE, in particular on drag-free control. In adapting the control to GG the spin rate was reduced from 5 Hz to 1 Hz, at which rate no critical issues were identified. This conclusion was confirmed in 2011 by a delta study using as actuators cold gas thrusters. A clever design for the launch locks of the suspended masses (to be used only at launch) was made by a spin off company from Ferrari. An ad hoc spin rate sensor was realized at INRIM.

A 2.5 month study of GG took place at JPL at the end of 2010. It focused on the implementation of a laser gauge developed by M. Shao under NASA funding. GG requirement for the read-out is 1 pm in 1 s, which is more or less routine with laser gauges. JPL laser gauge is based on spatial separation of the beams and well suited for GG. Collaboration with M. Shao is valuable and will continue.

The laser gauge for GG can be realized (as part of the GG bus) at INRIM. The payload (as described above) will be realized at INRIM under ASI funding.

Expertise on capacitance sensors is available at Univerity of Pisa (from GGG) and INAF-IAPS (from ISA accelerometer) Data analysis will be carried out at University of Pisa, MPIfR Bonn, Leibniz University Hannover, TU Wien, Imperial College London, Queen Mary University of London, University of Bologna. The scientific impact of the GG result will be investigated by G. Dvali at CERN.

The cost of GG was evaluated by TAS in 2009 within the Phase A2 Study. It has been updated in 2012 when GG was submitted for the S1 competition, amounting to 85 ME, with launch as piggy back of VEGA. As stated in the GG debriefing summary agreed with ESA this estimate was found to be correct (save for a small underestimate of mission operation costs).

A list of GG supporting scientists as of 2012 (S1 competition) is available: click here

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