12 GGonGround - Extended Synopsis

The science case. *General Relativity* (GR) is the best theory of gravity to-date. It governs physics at the macroscopic and cosmic scales and has been highly successful. However, all attempts at merging gravity with the other forces of nature have failed and most of the mass of the universe is unexplained.

General Relativity is based on the hypothesis that the gravitational force is composition independent: in a gravitational field all bodies fall with the same acceleration regardless of their mass and composition. This property is unique to gravity. It is referred to as the *Universality of Free Fall* (UFF) and it is a direct consequence of the *Equivalence Principle* (EP). It was first subject to experimental proof by Galileo in Pisa. Newton regarded testing it as so important that reported the results of his own experiments "*very accurately made*" in the opening paragraph of the *Principia* to justify the assumption that "*mass*" and "*weight*" are equivalent –i.e. the equivalence between inertial and gravitational mass. Einstein went much further and stated what he later referred to as the "*happiest thought of my life*": if all bodies fall equally fast, in a freely falling frame gravity has –locally– no dynamical effects. UFF is therefore equivalent to making the "*hypothesis of complete physical equivalence*" between a gravitational field and an accelerated frame([1], Ch. V *"Principle of relativity and gravitation"*, Sec. 17 *"Accelerated reference system and gravitation"*). Starting from this hypothesis –published in 1907– by extending it globally, 9 years later Einstein formulated the *General Theory of Relativity*, which is therefore founded on the UFF. Any violation of UFF (hence of EP) would violate General Relativity as well as all metric theories of gravity.

UFF experiments are unique tests of General Relativity in that –unlike all others– they address the assumed composition independence of gravity which sets it aside from all other forces of nature; this fact makes them the most deeply probing tests in the search for new physics beyond General Relativity and the current *impasse.*

It is widely recognized that experimental evidence of a violation of the UFF (hence of EP) would make for a scientific revolution, opening a totally new era in physics as it rarely happens. Even a null result (no violation) –if proven to very high precision– would constrain physical theories for decades to come. Either way, improving UFF tests by several orders of magnitude would be ground-breaking.

State of the art. Stringent limits to the validity of UFF have been set by small size experiments in which the test masses are mechanically coupled by means of a very sensitive torsion balance which is also slowly rotating. In terms of differential acceleration from the Earth they have measured $\Delta a_\oplus \simeq 1.69 \cdot 10^{-15}\,\mathrm{ms}^{-2}$, finding no violation to $\eta = 10^{-13}$ [2], ($\eta \equiv \Delta a_\oplus / a_\oplus$, $a_\oplus \simeq 1.69 \cdot 10^{-2}\,\mathrm{ms}^{-2}$ at their latitude). Despite the much larger free fall acceleration, Galileo-like mass dropping tests have been by far less sensitive than torsion balances. The reasons are twofold: a time of fall of just a few seconds and the test masses release errors. Careful physical modeling and analysis of laser ranging data to the corner cube reflectors left on the surface of the Moon by the Apollo missions have set a limit similar to that of torsion balances for the Moon and Earth falling in the gravitational field of the Sun [3]. However, although a violation is expected at some point, no firm prediction exists as to the precise level at which it should occur.

Slowly rotating torsion balances have hit the level of thermal noise ([4], Fig. 20); lunar laser ranging tests are close to their limit [5]. Even one order of magnitude improvement may be difficult with those techniques. Tests based on dropping cold atoms have achieved 10^{-7} [6] (6 orders of magnitude worse than torsion balances) and have yet to match the best result $\Delta g/g \simeq 3 \cdot 10^{-9}$ obtained in measuring the local gravitational acceleration by dropping a single species of atoms [7].

A radically new type of experiment is necessary to improve the current experimental limit in UFF and EP tests by several orders of magnitude thus deeply probing this physical domain so far unexplored.

The case for a test of UFF and EP in low Earth orbit. Back in the 1970s it was realized that a torsion balance kind of experiment in which two weakly coupled test masses orbit the Earth inside a low altitude spacecraft would be equivalent to dropping them from an "infinitely" tall tower, yielding both a stronger signal from Earth (by about 3 orders of magnitude) and a time of fall around it as long as the mission duration (and no mass release problems). A violation signal (pointing to the center of the Earth) would appear at the (low) orbital frequency of the satellite –of a few 10^{-4} Hz– to be upconverted to higher frequency by rotation of the spacecraft in order to reduce noise ([8], [9], [10]). Absence of weight and isolation of the laboratory (the spacecraft) are additional great advantages. Overall, in low Earth orbit an improvement by 4 orders of magnitude, down to $\eta = 10^{-17}$, is within reach and the idea has attracted the interest of NASA and later on of other space agencies.

At $h \simeq 600\,\mathrm{km}$ altitude where the attraction from the Earth is $g(h) \simeq 8\,\mathrm{ms}^{-2}$, the goal $\eta = 10^{-17}$ sets the differential acceleration between the proof masses which must be measured: $a = \eta\, g(h) \simeq 8 \cdot 10^{-17}\,\mathrm{ms}^{-2}$. This shows that a sensor in space only a factor 20 better than torsion balances would make 10^4 times better test. If the masses are coupled with a natural period of differential oscillation T_d, the relative displacement to be measured is $r = a\,(T_d^2/4\pi^2)$: the weaker the coupling, the longer the differential period, the more sensitive the instrument.

The case for "Galileo Galilei" (GG) to test UFF and EP to 10^{-17}. All investigators agree that in orbit the proof masses should be "concentric" cylinders –with the centers of mass as close as possible to each other to reduce classical differential effects due to non uniformity of the gravitational field– and should rotate, so as to upconvert the signal to higher frequency –the higher the better. The question is: should the concentric test cylinders be sensitive (i.e. weakly coupled) along the symmetry axis (1D accelerometer) and rotate around an axis perpendicular to it, or else should they rotate around the symmetry axis and be sensitive in the plane perpendicular to it (2D accelerometer)?

Although spinning around an axis which is not the symmetry axis is unnatural, the choice of coupling the test cylinders in 1D prevailed, despite the fact that it essentially rules out fast rotation because it is well known that forcing an oscillator above its natural frequency causes the forcing signal to be attenuated. This choice made it necessary to solve the main critical issues of a high sensitive space experiment by brute force, most notably by requiring that the experiment be carried out in cryogenic conditions, close to absolute zero temperature [11].

The signal to be measured asks for both weak coupling and fast spin, a situation which is known *Rotordynamics* as *rotation in supercritical regime*: it makes fast rotation possible through autocentering, but it is an established fact that it cannot work in 1D –it works only if coupling occurs in 2D ([12], [13]). The "Galileo Galilei" (GG) space experiment was proposed in the mid 1990s by A. M. Nobili and colleagues who realized that this choice makes most of the critical issues disappear by design: fast rotation does not attenuate the target low frequency signal; the centers of mass of the test cylinders center on each other by physics laws; many dangerous effects are DC; cryogenics is not required; fast rotation and cylindrical symmetry allow passive 1-axis stabilization of the spacecraft and significantly reduce its size and complexity; etc... ([14], [15]). Papers have been published showing the advantages of the novel idea of a differential accelerometer with the proof masses weakly coupled in 2D and rotating faster than their natural oscillation frequency ([16], [11], [17]). The GG space mission has been investigated with funding from ASI (Agenzia Spaziale Italiana) ([18]). More importantly, the new sensor design has allowed a full-size 1-g version of it –with the same number of degrees of freedom and the same dynamical features– to be built and tested on ground. GG on Ground (GGG) has been set up with funding ASI and INFN funding ([19], ÷ [22]); the latest experimental results (Fig.1) demonstrate that weak coupling of large proof masses and sensitivity to small forces are compatible with rapid rotation; indeed, it is rapid rotation that makes sensitivity to small forces possible.

The most relevant physical property of the GG/GGG novel sensor has been demonstrated very recently [23]: thermal noise due to internal damping and competing with the low frequency signal of interest is reduced as $1/\sqrt{\nu_{spin}}$ (with no signal attenuation) making rapid rotation more effective than cryogenics in reducing thermal noise. Taking into account also residual gas damping and eddy currents it turns out that GG can perform a full test to 10^{-17} in just 1 d [24]; in a 9-month mission all necessary checks against systematics can be performed so that the question as to whether the result is new physics or else it is due to a tiny known disturbance –hence it is a null result– can be established beyond doubt [25].

Recent collaboration with JPL (Jet Propulsion Laboratory, CalTech-NASA) has shown that an optical read-out based on the very low noise laser interferometry gauge developed and demonstrated at JPL will allow GG to fully exploit its very short integration time. The collaboration has led to an agreement between JPL and ASI to submit GG to the EXPLORER program as a NASA led mission

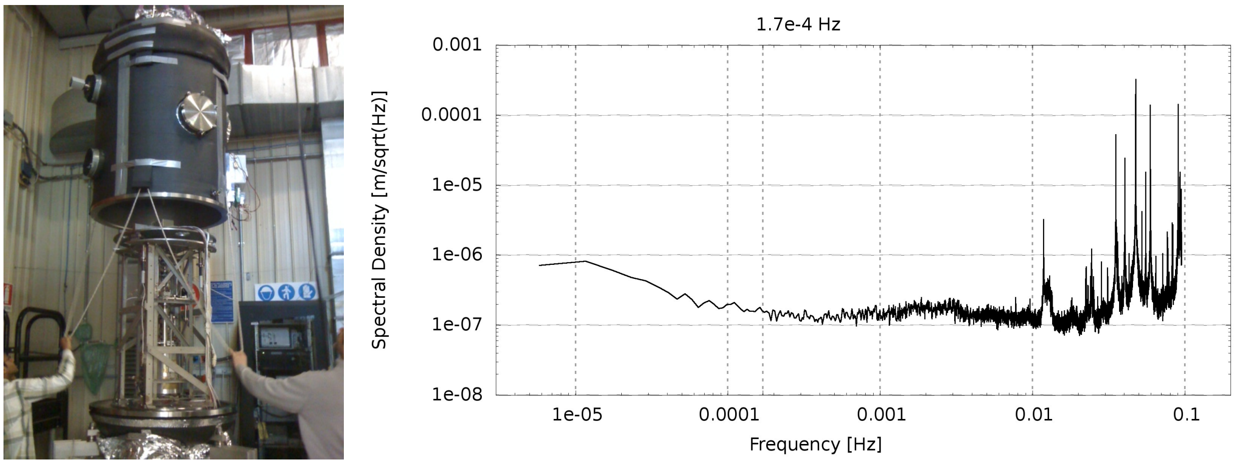

Figure 1: *Left:* the GGG apparatus (at INFN lab in San Piero-Pisa, built with ASI and INFN funding). The proof masses are concentric cylinders (10 kg each) with the symmetry axis in the vertical direction, weakly coupled in the horizontal plane by high quality $CuBe$ joints in 2D. Together they form a very peculiar beam balance in which the beam is vertical –hence the balance is sensitive to differential forces in the horizonal plane– and the masses are concentric. The relative displacements of the cylinders in the horizontal plane are read by 2 orthogonal capacitance bridges whose plates are located halfway in between them. The balance rotates around the vertical axis upconverting low frequency signals to the spin frequency. The rotating shaft is held by ceramic ball bearings. An additional 2D weak joint is located just below the bearings in order to reduce low frequency tilts and horizontal accelerations from terrain microseismic noise and bearings noise on the shaft. Note that both terrain and bearings noise are absent in space because the spacecraft is isolated (no terrain) and after initial spin up by the launcher no motor or bearings are needed (angular momentum conservation). *Right:* Linear spectral density of the relative displacements of the test cylinders in the horizontal plane of the lab in a 20 d run (still ongoing) after demodulation from the rotating frame ($\nu_{spin} = 0.19$ Hz). The frequency of interest is the orbital frequency $\nu_{GG} = 1.7 \cdot 10^{-4}$ Hz of the GG satellite at which a violation signal is expected in space. At ν_{GG} the measured displacement noise is $2 \cdot 10^{-7}$ m$/\sqrt{\text{Hz}}$; in 30 d and with the measured natural oscillation period of 10 s, the differential acceleration noise is $8.5 \cdot 10^{-11}$ ms^{-2}, limited mainly by ball bearings noise.

and the partnership of ASI, with M. Shao (JPL) as PI and A. M. Nobili as Co-PI. EXPLORER is a long time program of NASA dedicated to flying small size missions in a few years; the Nobel prize winner COBE was one of them. The 2010 Decadal Astronomy has ranked the EXPLORER program as its second highest priority and has advised NASA to further strengthen it. EXPLORER is the right framework for a small mission like GG –which is well below the size of ESA missions– and given that ASI cannot afford a full mission but would be willing contribute to a NASA led mission with a significant Italian rôle.

The case for GGonGround. GG is a high precision physics experiment which can reach its goal only in orbit, but that is just the final run of an experiment whose performance can and must be tested and demonstrated in the lab. The EXPLORER program is the only possible route to space for GG, but for GG to enter in the EXPLORER competition and eventually be selected for flight the GGG lab experiment must prove –by sufficiently isolating the sensor from ground noise sources and with an adequate read out– that the sensor in space can meet its target.

Synergy between the Corresponding PI Nobili, who has led GG and GGG so far, and the PI Zavattini, who will lead the efforts for implementing a low noise laser gauge can considerably improve GGG to meet the goal set in Table 3. Fig. 1 shows that GGG has reached a sensitivity of $8.5 \cdot 10^{-11}$ ms^{-2} in 30 d, while GG must reach $a_{GG} = 8 \cdot 10^{-17}$ ms^{-2} to meet its goal. We state with confidence that GGG can improve by 5 orders of magnitude its current performance to reach $a_{GGG} = 10 a_{GG} \simeq 8 \cdot 10^{-16}$ ms^{-2}

(slightly better than torsion balances) because –as the noise budget in the same table shows– there are no fundamental limitations. The main limitations are terrain and bearings low frequency tilt noise. Terrain tilt input noise at ν_{GG} has been measured ([26], [27]), its effect on the test cylinders is understood (it is expressed by a simple analytical formula with few parameters) and there is no doubt that the current suspensions can be improved (only a factor 4 is needed) and the apparatus properly modified to meet the goal. Air bearing is known to be several orders of magnitude less noisy than ball bearing (the vacuum chamber enclosing the torsion balance rotates on air bearing) and a solution is under study for GGG in which only the experiment rotates, not the chamber. This is feasible and can be realized by A. M. Nobili with the collaboration of Dr. R. Pegna who has significantly contributed to the current GGG performance and can effectively co-lead this activity. At full performance the capacitance bridges are no longer adequate and must be replaced by the laser gauge; this effort can be successfully led by the PI G. Zavattini based on his experience in Fabri-Perot interferometry, with collaboration and advise from Dr. M. Shao (JPL, CA, USA) who has already developed, built and demonstrated a very low nose laser gauge.

The roadmap Table 4 shows that this remarkable progress can be done in steps within the first 3 years of the project, to secure the success of GG through the various stages of the EXPLORER selection process (release of next Call is expected at the end of 2013). The remaining 3 years will be devoted –as outlined in Table 3– to bridge the remaining gap with laser gauge noise required in space and to manufacture and test the most crucial components of the space sensor. The final goal is to ensure to ensure the success of the experiment in space and to strengthen the European contribution to it.

Required funding and PIs time on the the project are given in the Budget Tables. Both PIs are strongly dedicated to this project, their time being limited only by teaching duties (AMN will leave teaching the second year). Funding is dominated by personnel cost due to the lack of funds in Italy to employ researchers and the very limited number of permanent ones; and also to the wide variety of disciplines which enter in this project and need to be mastered.

EGO is the best Institution to host a European project in experimental gravitation. GGonGround needs a specific but limited laboratory space (roughly $50\,\mathrm{m}^2$ with about $6\,m$ high roof) where the current apparatus and equipment (acquired with ASI and INFN funds) will be moved. All activity will be carried out by the two PIs and their collaborators.

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GGonGround goal vs GG goal in space				
	Differential acceleration between test masses a @ $1.7 \cdot 10^{-4}$ Hz	$a\,[\mathrm{ms}^{-2}]$	$r = a\frac{T_d^2}{4\pi^2}$ [m]	Integration time T_{int} [d]
GG goal in space	$a_{GG} = \eta g(h)$ (upconverted to 1 Hz)	$8 \cdot 10^{-17}$ ($\eta = 10^{-17}$, $h \simeq 600$ km)	$6 \cdot 10^{-13}$ ($T_d \simeq 540$ s)	1
GGonGround goal	$a_{GGG} = 10 a_{GG}$ (upconverted to $0.2 \div 3$ Hz)	$8 \cdot 10^{-16}$	$3.2 \cdot 10^{-14}$ ($T_d \simeq 40$ s)	30

GGonGround noise budget @ $1.7 \cdot 10^{-4}$ Hz					
Noise Source	Δa $[10^{-13} \frac{\mathrm{ms}^{-2}}{\sqrt{\mathrm{Hz}}}]$	Integrated Δa ($T_{int} = 30$ d) $[10^{-16}\mathrm{ms}^{-2}]$	Δr ($T_d \simeq 40$ s) $[10^{-11} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}]$	Integrated Δr ($T_{int} = 30$ d) $[10^{-14}\mathrm{m}]$	Conditions and physical data
Tilt noise sources: $a_{tilt} = \frac{k_c}{mgL} \frac{k_{shaft}}{M_{tot} g L_{shaft}} g\theta_{tilt}$					
terrain	8.2	5.1	3.3	2.1	$\theta_{terrain} \simeq 8 \cdot 10^{-6} \frac{\mathrm{rad}}{\sqrt{\mathrm{Hz}}}$
air bearing	4.1	2.5	1.7	1.0	$\theta_{ab} \simeq 4 \cdot 10^{-6} \frac{\mathrm{rad}}{\sqrt{\mathrm{Hz}}}$ $k_c \simeq k_{shaft} \simeq 0.04$ Nm/rad $m = 10$ kg $L = 0.5$ m $M_{tot} \simeq 80$ kg $L_{shaft} \simeq 4$ m
Thermal noise sources[23],[24]					
suspensions	1.3	0.8	0.5	0.3	Q=20000, $\nu_{spin} = 0.2$ Hz
eddy currents	1.3	0.8	0.5	0.3	no μmetal magnetic shield
residual gas	0.5	0.3	0.2	0.1	2 cm gap, P = 10^{-4} Pa
ReadOut noise: $a_{ROnoise} = (4\pi^2/T_d^2) r_{ROnoise}$					
laser gauge	7.4	4.6	3.0	1.8	$T_d \simeq 40$ s
Total noise	12	7.4	4.8	3.0	

Table 3: GGonGround goal and noise budget

GGonGround Roadmap		
Time (Months)		
		Performance achieved
	t_0	$a_0 = 8.5 \cdot 10^{-11}\,\mathrm{ms}^{-2}$ (INFN lab San Piero, Pisa; ASI and INFN funding; Fig. 1)
		First 18–month period targets
6	$t_0 + 6$	$a_1 = 2.8 \cdot 10^{-12}\,\mathrm{ms}^{-2}$ ($T_d = 14.8$ s $\mathrm{r_{capRO}} = 1.45 \cdot 10^{-8}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; can be done with capacitance read out and ball bearings, requires weaker joints by a factor 4)
12	$t_0 + 12$	$a_2 = 7.7 \cdot 10^{-14}\ ms^{-2}$ ($T_d = 40$ s $\mathrm{r_{capRO}} = 3 \cdot 10^{-9}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; can be done with capacitance readout and ball bearings, requires 10 times longer suspension shaft)
18	$t_0 + 18 = t_1$	$a_3 = 5.6 \cdot 10^{-15}\,\mathrm{ms}^{-2}$ ($T_d = 40$ s $\mathrm{r_{laserRO}} = 2.2 \cdot 10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; requires preliminary version of air bearings and laser metrology)
		Second 18–month period targets
24	$t_1 + 6$	reduce air bearings and rotation noise
30	$t_1 + 12$	reduce laser gauge read out noise
36	$t_1 + 18 = t_2$	$a_4 = 7.7 \cdot 10^{-16}\,\mathrm{ms}^{-2}$ ($T_d = 40$ s $\mathrm{r_{laserRO}} = 3.0 \cdot 10^{-11}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; requires air bearings to full performance and improved laser metrology)
		Third 18–month period targets
42	$t_2 + 6$	Install rotating whirl control (as required in GG)
48	$t_2 + 12$	Measure patch effects and demonstrate that they are not relevant; improve sensitivity to effect from Sun @ 24 h by Phase Sensitive Detection in preparation for analysis of space data
54	$t_2 + 18 = t_3$	Optimize test masses different composition, manufacture test masses, measure their quadrupole moments and confirm requirements
		Fourth 18–month period targets
60	$t_3 + 6$	Manufacture suspensions required for GG in space, measure their elastic constants and quality factors and confirm fulfilment GG requirements
66	$t_3 + 12$	Demonstrate on bench laser gauge read out noise to $r_{laserRO} \simeq 10^{-12}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ @ $1 \div 2$ Hz
72	$t_3 + 18 = t_4$	Test PZTs and inchworms to demonstrate feasibility of balancing in space

Table 4: GGonGround Roadmap