European Reasearch Council

ERC Synergy Grant 2012
Research Proposal (Part B1)

GG ("Galileo Galilei") and GG on Ground: a very high sensitive experiment to probe the foundations of General Relativity

GGonGround

Corresponding Principal Investigator: **Anna M. Nobili**
Principal Investigator: **Guido Zavattini**
Corresponding Host Institution: **EGO**
Proposal full title: **GG ("Galileo Galilei") and GG on Ground: a very high sensitive experiment to probe the foundations of General Relativity**
Proposal short name: **GGonGround**
Proposal duration in months: **72**

Proposal Summary

General Relativity (GR) is the best theory of gravity to-date but attempts at merging gravity with the other forces of nature have failed and most of the mass of the universe is unexplained. GR is based on the hypothesis that the gravitational force is composition independent: in a gravitational field all bodies should fall with the same acceleration regardless of their mass and composition (Universality of Free Fall, UFF). UFF is unique to gravity and it is a direct consequence of the Equivalence Principle (EP). Tests of UFF are unique tests of GR in that they address the assumed composition independence of gravity; this makes them the most deeply probing tests in the search for new physics beyond General Relativity and the current impasse. It is generally recognized that experimental evidence of a violation of UFF (hence of EP) would make for a scientific revolution. UFF has been tested to 10^{-13} but a radically new type of experiment is needed to improve this limit by several orders of magnitude. We propose an unconventional sensor which can be run in space with 10^4 improvement by making the main critical issues disappear by design. A small satellite GG ("Galileo Galilei") and the corresponding ground experiment GGG have been designed and a pre-prototype has been built by solving many problems in a variety of fields. An agreement exists between JPL -the Jet Propulsion Laboratory of CalTech and NASA- and ASI (Agenzia Spaziale Italiana) to submit GG to the EXPLORER program of small size missions as a NASA led mission and the partnership of ASI. GG is a high precision physics experiment which can reach its final sensitivity and meet its outstanding science 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 route to space for GG. GGonGround –by synergy between two highly dedicated groups with complementary skills– is the route for GG to be selected for flight within the EXPLORER competition.

1 GGonGRound project proposal: Part B1

2 B1–a: State of the art and objectives

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 tested experimentally by Galileo in Pisa. Newton regarded testing it as so important that he 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– and extending it globally, nine 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.

The physical quantity to be measured is the differential acceleration $\Delta a_{test-masses}$ between two test masses of different composition falling in the gravitational field of a source body with a common acceleration $a_{source-body}$. For UFF (and the EP) to hold, the dimensionless quantity

$$\eta = \frac{\Delta a_{test-masses}}{a_{source-body}} \tag{1}$$

(known as the Eötvös parameter) must be found to be zero. The closer to zero is its value, the more sensitive is the test, the more deeply GR is tested.

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 that is 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], ($\eta = \Delta a_\oplus / a_\oplus$, $a_\oplus \simeq 1.69 \cdot 10^{-2}\,\mathrm{ms}^{-2}$ 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: the time of fall of just a few seconds and release errors of the test masses. 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 these techniques. Tests based on dropping cold atoms have achieved $\eta = 10^{-7}$ [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 $h \simeq 600$ 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 a 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 in *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 ([13], [14]). 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, as we recently demonstrated experimentally (see Fig. 1; [12]); 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... ([15], [16]). 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 ([17], [11], [18]). The GG space mission has been investigated with funding from ASI (Agenzia Spaziale Italiana) ([19]).

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 from ASI and INFN ([20] $\div$ [23]) and it has achieved an interetsing sensitivity, as reported below (see: **The case for GGonGround**).

The most relevant physical property of the GG/GGG novel sensor has been demonstrated very recently [24]: at $\nu_s pin$ rotation frequency thermal noise due to internal damping which competes with

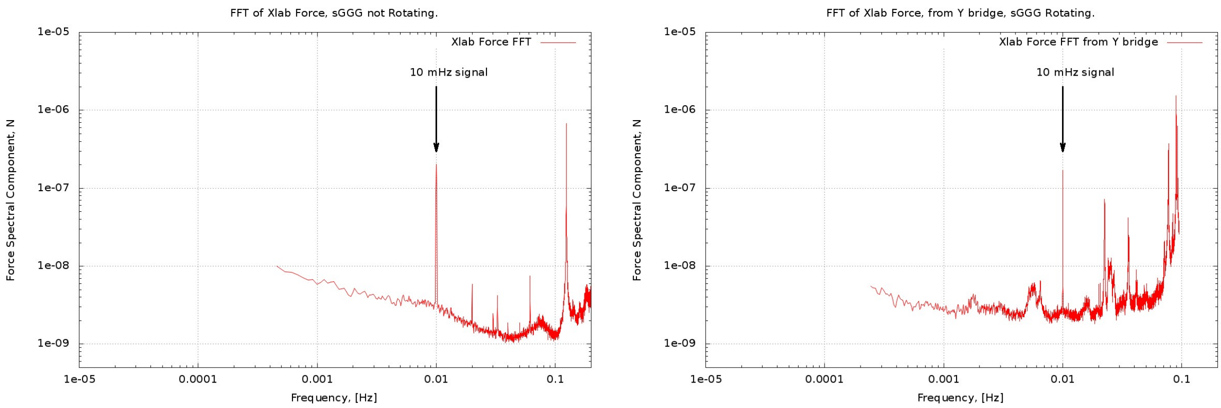

Figure 1: The plots show that in a 2D oscillator in supercritical rotation like GGG modulation of low frequency signals at a rotation frequency above resonance can be performed without signal attenuation. Left plot: GGG is not rotating and a differential force signal at 0.01 Hz is applied to the test cylinders along the X direction of the horizontal plane of the lab. In this direction the natural frequency of oscillation (resonance) of the test cylinders relative to each other is $\nu_x = 0.124\,\mathrm{Hz}$, thus the force is applied below the resonance. (We add that the natural oscillation frequency in the perpendicular direction is $\nu_y = 0.063\,\mathrm{Hz}$.) Right plot: GGG has been set in rotation at $\nu_{spin} = 0.19$ Hz, the natural oscillation frequency (resonance) during rotation is $\nu_w = \sqrt{(\nu_x^2 + \nu_y^2)/2} = 0.098\,\mathrm{Hz}$ and the same force signal is applied; it is up-converted close to the spin frequency, thus well above the GGG natural one. The experimental data –i.e. the relative displacements of the test cylinders as given by one of the rotating capacitance bridges which read their differential displacements– have been demodulated back to the non rotating horizontal plane of the lab for comparison with the non rotating case shown before along the X direction. If GGG were an oscillator in 1D, a similar rotation of the oscillator above its natural frequency would have attenuated the signal by a factor 2.56. We note in passing that in the non rotating case (left plot) the read out electronics noise increases at lower frequencies as expected, while in the rotating case the relevant read out electronics noise is that at the rotation (*modulation*) frequency.

the low frequency signal 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 [25]; 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 [26].

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 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 every few years 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 is 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

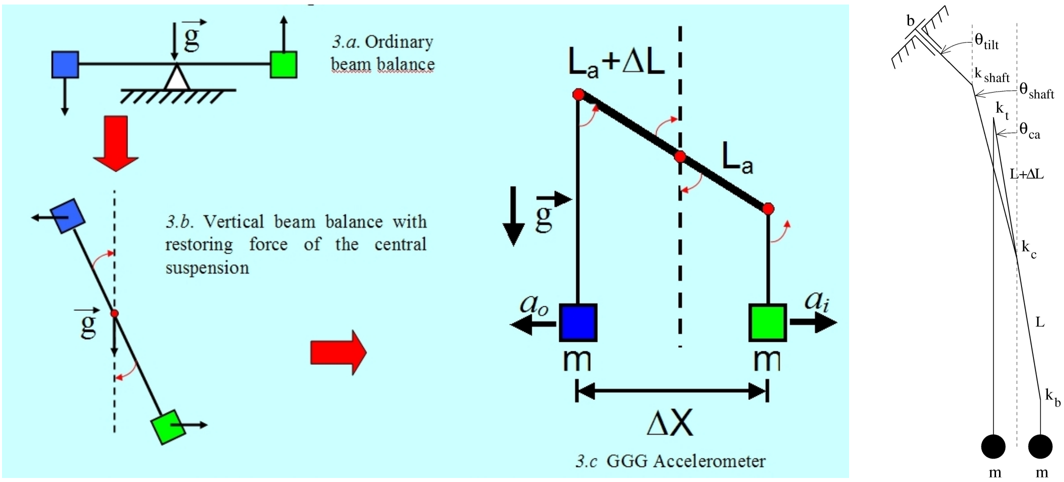

Figure 2: Simplified representation of the GGG balance. (*left*): The GGG accelerometer is designed to be sensitive to differential forces acting in plane perpendicular to the spin axis, which is in the vertical direction. The two test masses are coupled as in a vertical beam balance with a natural period of differential oscillation relative to each other T_d (see text). (*left*): The upper part of the shaft, rotating on bearings (b) is tilted by the angle θ_{tilt} by the terrain and bearings tilt noise; the 2D flexible joint k_{shaft}, placed on the shaft below the bearings, attenuates θ_{tilt} so that the lower part of the shaft is tilted, at low frequencies, by the attenuated angle $\theta_{shaft} = \frac{k_{shaft}}{M_{tot} g L_{shaft}} \theta_{tilt} \ll \theta_{tilt}$ The coupling arm (ca) equilibrium position corresponding to the shaft tilt is $\theta_{ca} = \frac{k_c}{2mL^2} \frac{T_d^2}{4\pi^2} \theta_{shaft}$. Low frequency horizontal acceleration disturbances are equivalent to tilt disturbances ($\Delta a_{horiz-acc} = g\theta_{tilt}$)

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.

Below we briefly describe how GGG works and report the sensitivity it has achieved.

The basic dynamical features of GGG are shown in Fig. 2 and described in the caption. They allow us to express with simple analytical formulas both the differential period T_d of natural oscillation of the test bodies relative to each other:

$$T_d^2 = \frac{4\pi^2}{\frac{k_t + k_c + k_b}{2mL^2} - \frac{g}{2L}\frac{\Delta L}{L}} \tag{2}$$

(m the mass of each test body, g the local gravitational acceleration, L the length of half the balance coupling arm, $\Delta L/L$ the level of unbalance of the balance, k_t, k_c, k_b the elastic constants in [Nm/rad] –along each direction– of the 2D flexible joints shown in the Figure) and the differential acceleration between the test bodies resulting from a tilt angle θ_{tilt} affecting the shaft above the weak joint (of elastic constant k_{shaft}) which suspends the total system of mass M_{tot} from a height L_{tot}:

$$a_{tilt} = \frac{k_c}{mgL} \frac{k_{shaft}}{M_{tot} g L_{shaft}} g\theta_{tilt} \tag{3}$$

The input tilt disturbance θ_{tilt} relevant to the experiment is at low frequency and is due to i) local terrain microseismic noise and ii) imperfections in the ball bearings which hold the shaft to spin it (note that both these noise sources are absent in space):

$$\theta_{tilt} = \theta_{terrain} + \theta_{ballbearing} \tag{4}$$

The horizontal acceleration noise affecting the test masses at low frequencies is $\Delta a_{horiz-acc} = g\theta_{tilt}$, and for this reason (which in fact relies on the equivalence principle itself, whereby the inertial and gravitational mass are the same at this level) we refer for simplicity to tilt noise only.

Fig. 3 shows a more detailed sketch of the apparatus and two pictures of it, to illustrate also thermal insulation of the vacuum chamber. By active thermal control the ambient temperature variations are reduced by a factor 100 (see Fig. 4)

Figure 3: In order to isolate the GGG rotating accelerometer from low frequency terrain and ball bearings noise (tilts as well as horizontal accelerations) the current design (*left*) exploits the attenuation provided at low frequencies by the 2D flexible joint (labeled 11r) isolating the upper part of the shaft (9r) –which is subject to ground tilts and ball bearings (8) noise– from the lower part (12r) which holds the GGG balance. Thus, the isolated part of the shaft (12r) is driven by its weight closer to the direction of local gravity (which defines the vertical direction) more than its tilted top part. The central picture shows the experimental apparatus while opening the vacuum chamber. The picture to the right shows the vacuum chamber closed with thermal insulation in place.

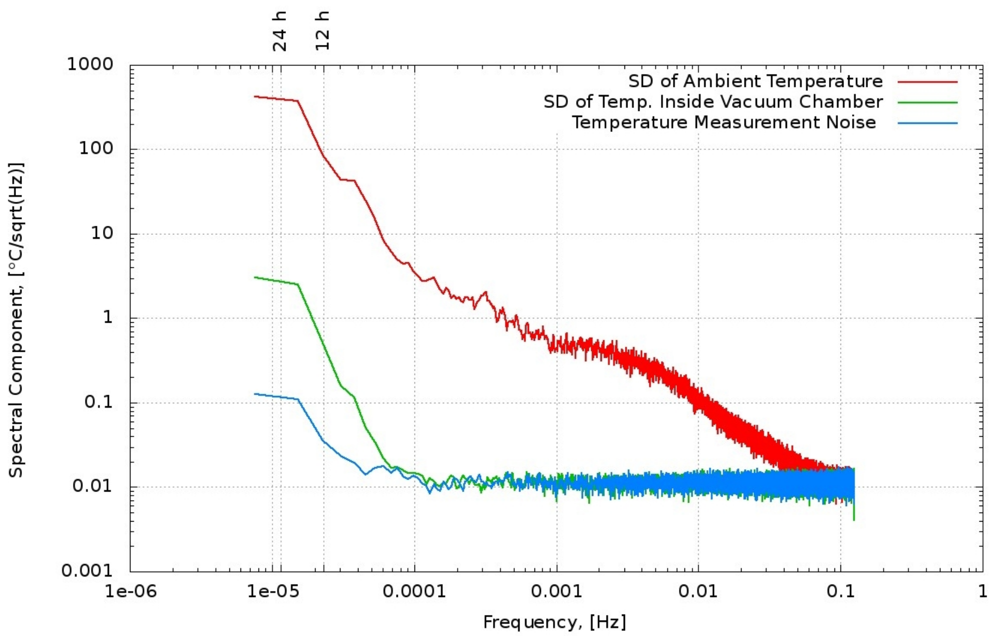

Figure 4: GGG temperature stability relies on a PID (Proportional Integral Derivative), heating only, temperature control acting on the temperature of the vacuum chamber walls. Ambient temperature variations (red curve) are attenuated inside the vacuum chamber (green curve) by about two orders of magnitude, limited only by the temperature readout noise at frequencies higher than 10^{-4} Hz.

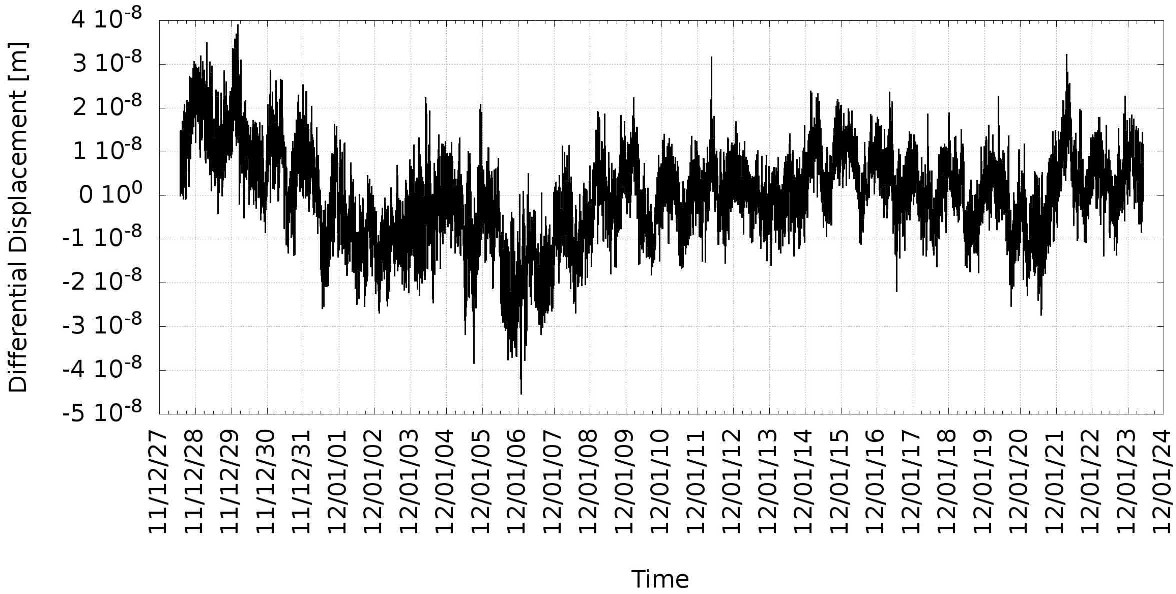

Figure 5: Time series of the relative displacements of the GGG test masses (frequencies above ν_{cut} = 1 mHz filtered out) in one direction of the horizontal plane of the lab during the ongoing run for a timespan $T_{meas} \simeq 28$ d. We have analyzed all data collected till 24 January 2012 – 1 day before the closing date for this proposal

The latest experimental results are reported in Fig. 6. From a 28-d run (ongoing) the acceleration displacement noise at the low frequency of interest (extrapolated to 30-d) is $\simeq 8 \cdot 10^{-11}\,\mathrm{ms}^{-2}$. Fig. 5 reports the time series of the relative displacements of the test masses over the 28-d of the run (till 1 day before the proposal submission deadline); they amount to several 10^{-8} m, for cylinders of 10 kg each spinning at 0.19 Hz. These results demonstrate that weak coupling of large proof masses and sensitivity to small forces are compatible with rapid rotation; in fact, it is rapid rotation that makes sensitivity to small forces possible.

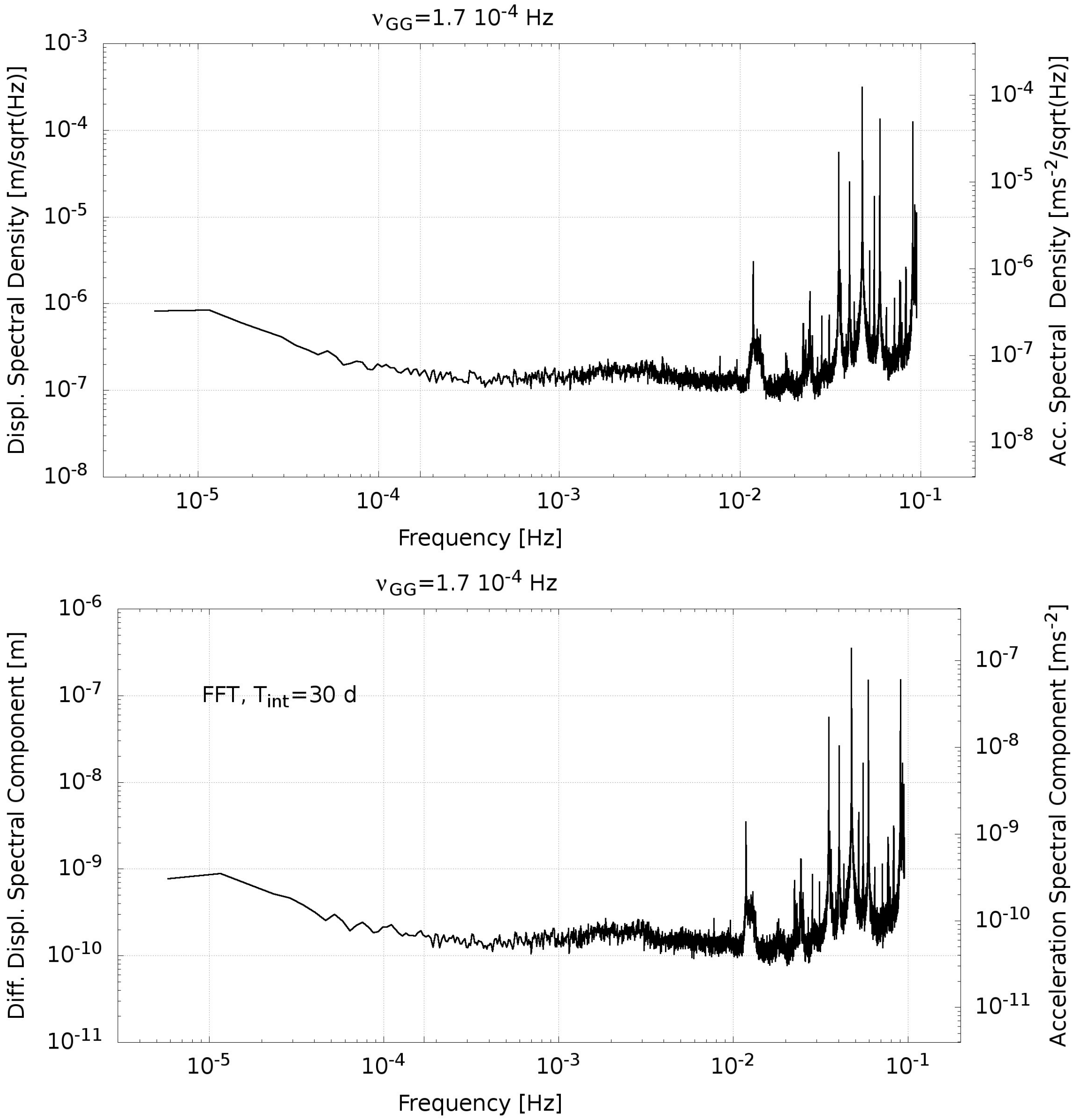

Figure 6: The GGG noise performance as measured from an ongoing run of duration $T_{\text{meas}} \simeq 28$ d. Top plot: Spectral density of the relative displacements and acceleration of the test cylinders in one direction of the horizontal plane of the lab; the GGG differential accelerometer is spinning at $\nu_{spin} = 0.19$ Hz with natural coupling frequency of 0.1 Hz. The measured relative displacement is $\simeq 2 \cdot 10^{-7} \text{m}/\sqrt{\text{Hz}}$ and the measured relative acceleration is $\simeq 7.9 \cdot 10^{-8} \text{ms}^{-2}/\sqrt{\text{Hz}}$ at the frequency $\nu_{\text{GG}} \simeq 1.7 \cdot 10^{-4}$ Hz, the orbital frequency relevant for GG in space. Bottom plot: measured relative test masses displacement and acceleration noise integrated over the full run duration (extrapolated to $T_{\text{int}} \simeq 30$ d). At ν_{GG} we measure an integrated differential displacement noise of $\simeq 2 \cdot 10^{-10}$ m and a differential acceleration noise of $\simeq 8 \cdot 10^{-11}$ m/s^2.

3 B1–b: Methodology

Table 1 shows that the acceleration sensitivity measured by GGG at present (Fig. 6) is still 6 orders of magnitude away from the sensitivity required tin space for GG to meet its goal. However, the noise budget in the same table shows that there are no fundamental limitations for GGG to reach $a_{GGG} = 10a_{GG} \simeq 8 \cdot 10^{-16}\,\mathrm{ms}^{-2}$ (slightly better than torsion balances).

The main limitations are terrain and bearings low frequency tilt noise. Terrain tilt input noise at ν_{GG} has been measured ([27], [28]), 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. Fig. 7 reports the long term measurements of tilt noise performed with ISA tiltmeter by V. Iafolla at IFSI lab (in a very quiet location a few meters underground and in a well isolated room) and by ourselves in downtown Florence –also with an ISA accelerometer provided by V. Iafolla. At $1.7 \cdot 10^{-4}$ Hz the lowest tilt noise is recorded underground and it is 25 times smaller than the one measured in Florence. In our error budget we have assumed an input tilt noise only a factor 2.5 smaller than the value measured downtown Florence. This is a rather conservative assumption because both our current lab in San Piero and the EGO location in Cascina are certainly more quiet than downtown Florence.

The budget Table 1 shows however that ball bearing must be replaced by air bearing. 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. A preliminary design is reported in Fig. 8 and discussed in the caption. 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. The roadmap Table 2 gives details of the intermediate steps that we shall follow. It also shows that at full performance the capacitance bridges are no longer adequate and must be replaced by a low noise laser gauge read out; this effort can be successfully led by the PI G. Zavattini based on his experience in Fabry-Perot interferometry, with collaboration and advise from Dr. M. Shao (JPL, CA, USA) who has already developed, built and demonstrated a very low noise laser gauge. Dr. M. Shao will be the PI of the GG mission proposal to the EXPLORER program of NASA.

At present the capacitive readout has a sensitivity of $3 \cdot 10^{-8}$ m/$\sqrt{\mathrm{Hz}}$ and will be improved by about a factor 10 in the first 18-month period of the Synergy grant. Although good, this is far from the sensitivity necessary for GG to reach $\eta = 10^{-17}$. Laser interferometry seems to be the best solution.

Besides the sensitivity of the readout system it is also necessary that it have a large dynamic range, well above 10 microns. The two cylinders in the GG and GGG systems will oscillate one respect to the other by a few tens of microns.

To reach the goal of GG it is necessary that the readout system have a sensitivity in displacement of $1 - 2 \cdot 10^{-12}$ m/$\sqrt{\mathrm{Hz}}$ at 1-2 Hz corresponding to the rotation frequency of the test masses. Optical systems such a Fabry-Perot interferometers have much higher sensitivities but require that the movement of the objects being monitored be within the tunability of the laser. Generally for gaps of the order of a centimeter this means a dynamic range of fraction of micron. For these reasons a differential laser gauge following the development done by Mike Shao will be adopted. With such a system a noise level of the order of $1 - 2 \cdot 10^{-12}$ m/$\sqrt{\mathrm{Hz}}$ at a frequency of 1 Hz has been demonstrated with an almost unlimited dynamic range.

The implementation of the laser gauge will be in steps. At first a system with about 0.2 nm/$\sqrt{\mathrm{Hz}}$ will be installed on GGG as a prototype system. At this stage the limiting effect of the sensitivity of GGG will be due to the air bearings. Improvements will then be made so as to gain a factor of about 8 on the bearing tilt noise and therefore the gauge will also be improved to avoid limiting the overall sensitivity of GGG. Finally we will demonstrate and reach the nominal gauge sensitivity required of $1 - 2 \cdot 10^{-12}$ m/$\sqrt{\mathrm{Hz}}$ at 1-2 Hz necessary for GG.

The issue of systematic errors which may degrade the performance of the laser gauge when applied to the two coaxial rotating cylinders seems to be under control. Periodic oscillations of the cylinders at their natural coupling frequency (period = 540 seconds in GG, from 10-40 seconds for GGG) will be present but have a frequency well above the frequency at which we will be searching for a signal: $1.7 \cdot 10^{-4}$ Hz. With $Q \simeq 20000$ (for which experimental evidence is available) this should not be an issue.

A critical issue which must be kept in mind is the effect of mirror roughness. Studies by Mike Shao have shown that a high quality surface will introduce a displacement noise of about 1 picometer for each micron of transverse beam motion. With superpolished surfaces this can be a factor 10 better.

Note that, as the roadmap Table 2 shows, the remarkable acceleration sensitivity goal of GGG, of $8 \cdot 10^{-16}\,\mathrm{ms}^{-2}$, can be achieved 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 the success of the experiment in space and to strengthen its European contribution.

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 improve GGG to meet the goal set in Table 1.

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	$a_{GGG} = 10a_{GG}$ (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: $a_{tilt} = \frac{k_c}{mgL}\frac{k_{shaft}}{M_{tot}gL_{shaft}}g\theta_{tilt}$, $\theta_{tilt} = \theta_{terrain} + \theta_{airbearing}$					
terrain	8.2	5.1	3.3	2.1	$\theta_{terrain} \simeq 8 \cdot 10^{-6}\,\frac{\mathrm{rad}}{\sqrt{\mathrm{Hz}}}$ $\theta_{airbearing} \simeq 4 \cdot 10^{-6}\,\frac{\mathrm{rad}}{\sqrt{\mathrm{Hz}}}$ $k_c \simeq k_{shaft} \simeq 0.04$ Nm/rad $m = 10$ kg $L = 0.5$ m $M_{tot} \simeq 80$ kg $L_{shaft} \simeq 4$ m
air bearing	4.1	2.5	1.7	1.0	
Thermal noise sources[24],[25]					
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 1: GGonGround goal and noise budget

GGonGround Roadmap		
Time (Months)		
		Performance achieved
	t_0	$a_0 = 8 \cdot 10^{-11}\,\mathrm{ms^{-2}}$ (INFN lab San Piero, Pisa; ASI and INFN funding; Fig. 6)
		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 2: GGonGround Roadmap

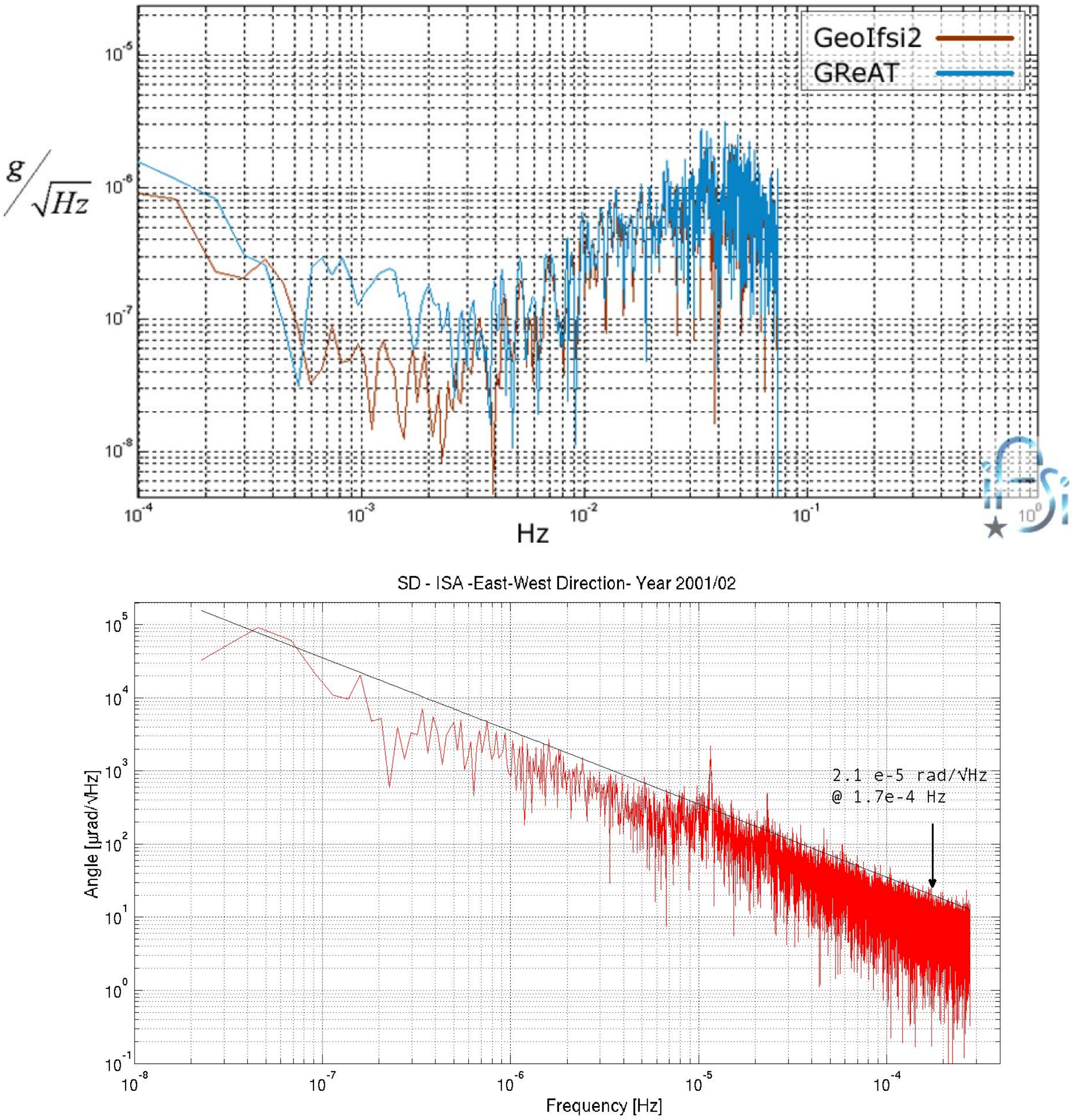

Figure 7: Top: terrain tilt noise as measured by V. Iafolla ISA accelerometer in two different locations at IFSI lab (Roma Tor Vergata) (g is equivalent to rad), showing at the frequency $\nu_{GG} = 1.7 \cdot 10^{-4}$ Hz a noise of $9 \cdot 10^{-7}$rad/$\sqrt{\text{Hz}}$ in a quiet location and of $3 \cdot 10^{-7}$rad/$\sqrt{\text{Hz}}$ in an underground room. Bottom: terrain tilt noise as measured in Florence (over 16 months) with an ISA tiltmeter, showing $2.1 \cdot 10^{-5}$rad/$\sqrt{\text{Hz}}$ at ν_{GG}. In the GGG noise budget we assume for the proposed EGO lab in Cascina (Pisa) a level of terrain tilt noise only a factor 2.5 smaller.

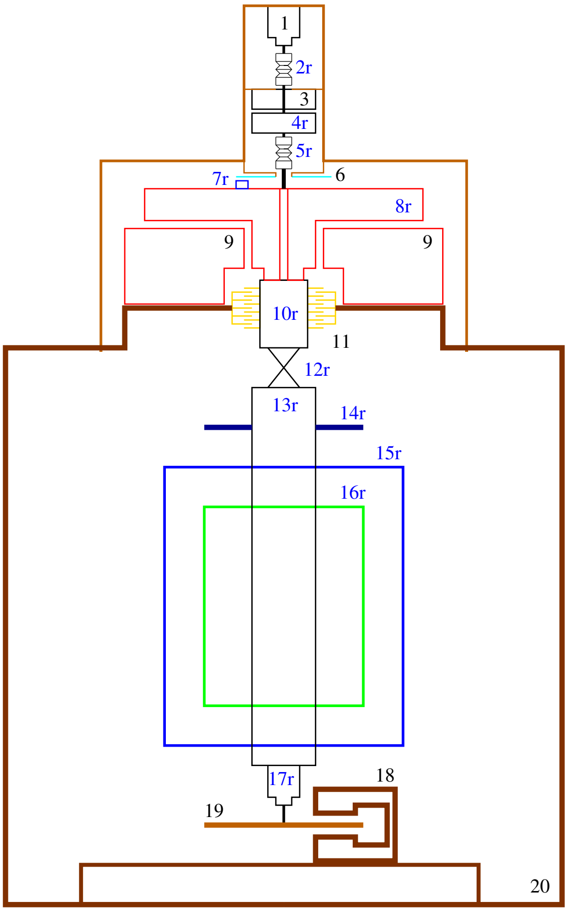

Figure 8: Design for the implementation of the air bearing on GGG. Precision grade ball bearings are manufactured with typical ∼ 100 nm geometric tolerances: balls are manufactured with ∼ 100 nm sphericity and ∼ 500 nm diameter tolerance. Very roughly, a 5 cm diameter ball bearing can then cause a shaft fitted to the inner race to tilt by some μrad. The complexity of the ball bearing result in $\simeq$ μrad shaft tilt noise in the low frequency region of interest for GGG. On the other side, air bearings require very tight bearing gaps for proper operation (10 μm) which translates into extremely high accuracy motion with best noise performance. Typical rotary runout can be as low as 1 nm and tilt characteristics as low as 0.02 μrad. Because the air bearing has two surfaces and only two surfaces, the tilt noise is essentially concentrated at the rotation frequency, while the noise performance is order of magnitude better at low frequency. In GGG the air bearing (8r and 9) is intended to allow for the quiet rotation of the shaft (10r) while providing for lateral (due to its cylindrical part) and vertical (due to its planar part) stiffness against forces acting on it. The air bearing requires a small but continuous compressed air flow, so that it has been placed outside the vacuum chamber (20). The GGG sensitive balance, composed of the two rotating hollow cylindrical test bodies (15r and 16r) differentially coupled in the horizontal plane, is suspended to the 2D flexible joint (12r) with the purpose of isolating this part from terrain tilts and horizontal accelerations. The 2D flexible joint (12r) connects the suspended part of the shaft (13r) to the air bearing rotating part (8r). The ferrofluid vacuum feedthrough (11) allows for the rotational motion transfer to the vacuum inside the chamber. It will be an Hollow Shaft Feedthrough housing the not–suspended part of the GGG shaft (10r). Stiffness against horizontal forces on the shaft (10r) due to the magnets needed by the vacuum feedthrough is provided by the cylindrical part of the air bearing, so that the ball bearing normally used on this type of feedthrough are avoided in this application. The GGG shaft will then be rotating on the air bearing only.

References

[1] A. Einstein, Jahrbuch der Radioaktivität und Elektronik, 4, 411-462 (1907)
[2] S. Schlamminger *et. al.*, Phys. Rev. Lett. 100, 041101 (2008)
[3] J. G. Williams, S. G. Turyshev & D. H. Boggs, Phys. Rev. Lett. 93, 261101 (2004)
[4] E. G. Adelberger*et al.*, Progress in Particle and Nuclear Physics 62, 102 (2009)
[5] A. M. Nobili *et al.*, General Relativity & Gravitation 40, 1533Ű1554 (2008)
[6] S. Fray *et. al.*, Phys. Rev. Lett. 93, 240404 (2004)
[7] A. Peters, K.Y. Chung & S. Chu, Nature 400, 949 (1999)
[8] P. K. Chapman, A. J. Hanson, *Proc. Conf. on Exp. Tests of Grav. Theories*, JPL Pub. 228 (1971)
[9] P. W. Worden, Jr., *PhD Thesis*, Stanford University, Stanford (CA) (1976)
[10] P. W. Worden, Jr., Acta Astronautica, 5, 27 (1987)
[11] A. M. Nobili *et al.*, Phys. Rev. D Rapid Commun. 63, 101101(R) (2001)
[12] R. Pegna *et al.Up-converting low frequency signals above resonance,* in preparation for Rev. Sci. Instr. (2011)
[13] J. P. Den Hartog, *Mechanical Vibrations*, Dover Publ. Inc N.Y. 1985 (first published in 1934)
[14] S. H. Crandall, J. Sound Vib. 11(1), 3-18, (1970)
[15] A. M. Nobili *et al.*, J. Astronaut. Sc. 43, 219-242 (1995)
[16] A. M. Nobili *et al.*, New Astronomy 3 175Ű218 (1998)
[17] A. M. Nobili *et al.*, Classical Quantum Gravity 16, 1463-1470 (1999)
[18] A. M. Nobili *et al.*, New Astronomy 7 521-529 (2002)
[19] *GG Phase A Study Report*, ASI (1998), *GG Phase A-2 Study Report* (2009)
[20] A. M. Nobili *et al.*, New Astronomy 8 371-390 (2003)
[21] G. L. Comandi *et al.*, Rev. Sci. Instrum. 77 034501 1-15 (2006)
[22] G. L. Comandi *et al.*, Rev. Sci. Instrum. 77 034502 1-15 (2006)
[23] A. M. Nobili *et al.*, Int. J. of Modern Physics D, 16 2259-2270 (2007)
[24] R. Pegna *et al.*, Phys. Rev. Lett. 107, 200801 (2011)
[25] A. M. Nobili *et al.*, *Integration time in very high sensitive EP tests in space,* to be submitted
[26] A. M. Nobili, *et al., Null checks in space experiments to test EP,* to be submitted
[27] G. L. Comandi, *PhD Thesis,* University of Pisa, Pisa, Italy (2004)
[28] V. Iafolla, *private communication* (2012)

European Reasearch Council

ERC Synergy Grant 2012
Research Proposal (Part B2)

GG ("Galileo Galilei") and GG on Ground: a very high sensitive experiment to probe the foundations of General Relativity

GGonGround

Corresponding Principal Investigator: **Anna M. Nobili**
Principal Investigator: **Guido Zavattini**
Corresponding Host Institution: **EGO**
Proposal full title: **GG ("Galileo Galilei") and GG on Ground: a very high sensitive experiment to probe the foundations of General Relativity**
Proposal short name: **GGonGround**
Proposal duration in months: **72**

1 GGonGround project proposal: Part B2

2 B2–a1: Curriculum Vitae of corresponding PI Anna M. Nobili

Born in Italy on September 1949

Positions in Italy and abroad

- 1992-present: associate professor in Astronomy, University of Pisa, Italy (subjects taught: Elements of celestial mechanics, Physics I, Space Mechanics)
- 1991-1992: visiting scientist at Obervatoire de Medoun, Paris, France (on leave from Pisa University)
- 1988-1989: visiting scientist ("Bepi Colombo" ESA fellow) at Cornell University, Space Sciences, NY, USA (on leave from Pisa University)
- 1984-1985: visiting scientist at University of Glasgow, Glasgow, UK (on leave from Pisa University)
- 1981-1982: visiting scientist at Queen Mary College, London, UK (on leave from Pisa University)
- 1979-1992: permanent researcher at University of Pisa, Italy
- 1976-1979: temporary researcher at University of Pisa, Italy
- 1974-1976: temporary researcher at University of Bologna, Italy
- 1973-1974: research fellow at SNS (Scuola Normale Superiore) Pisa, Italy
- (1973: Laurea degree in Physics *summa cum laude*)
- 1968-1970: Physics student at SNS (Scuola Normale Superiore) Pisa, Italy (to my knowledge, I was the second female student in the history of SNS to be admitted for Physics)

Responsibility in national and international research projects

- 2004-present: PI of GGG (GG on Ground) national experiment funded by the II National Scientific committee of INFN (Istituto Nazionale di Fisica Nucelare)
- 2008-2010: PI of GG Phase A2 Study with development of GGG experimental apparatus, funded by ASI (Agenzia Spaziale Italiana)
- 2007-2010: member of the ASI funded national project "Cosmology and fundamental Physics in space " as PI of the Fundamental Physics part
- 2001-2003: PI of the national project on "The fundamentals of gravity: measuring the universal constant of gravity G and testing the Equivalence Principle" selected and funded by the Italian Ministry of Research as a project of national interest
- 2001-2002: PI of GG Advanced Phase A funded by ASI to investigate feasibility in sun-synchronous orbit
- 1998-2002: PI of project "PGB-Enabling vibration free activity onboard the International Space Station (ISS)", funded by ASI and selection for flight on the ISS; it was canceled in 2003 as a result of the Columbia shuttle disaster (co-owner of an Italian patent on PGB)
- 1997-1998: PI of GG Phase A Study funded by ASI after national competition for a small mission
- 1996: PI of GG Pre-Phase A Study funded by ASI in preparation for a STEP-GG competitive review at ESA
- 1989-1993: member of ESA-NASA science team on STEP (Satellite Test of the Equivalence Principle) mission - also PI of sub-group an G-measurement with STEP; funded by ESA
- 1987-1994: PI of European project COGEOS on the observation of geosynchronous satellites for geodynamics; funded by the European Commission
- 1986-1988: member of Italian-British project LONGSTOP on the stability of the outer planets

Research interests

I have worked in solar system dynamics and was among the first to discover chaos in the solar systems (Nobili & Burns, Solar system chaos, Science 244, 1425, 1989; Milani & Nobili, An example of stable chaos in the Solar System, Nature, 357, 569-570, 1992). In space geodesy I have contributed to understanding the small forces which affect the motion of laser tracked satellites (I am co-author of a book on "Non gravitational forces and satellite geodesy", Adam Hilger Ltd., Bristol and Boston 1987).

I have always tried to use my understanding of the space environment for a precision experiment in fundamental physics. At first, I tried to measure the fundamental constant of gravity G by *manufacturing* a very elegant planet-satellite system inside a spacecraft in geosysnchronous orbit (Nobili et al., ESA Journal 14, 389-408, 1990). The interest for testing the equivalence principle in space was much stronger than that for measuring G, and I was offered by ESA the opportunity to work in the joint ESA-NASA science team which was set-up to investigate the Stanford proposed mission STEP (Satellite Test of the Equivalence Principle) aiming at a breakthrough improvement in testing the equivalence principle (to 10^{-17}). In those years I became more and more convinced that a radically new type of sensor could make the experiment and the mission much simpler – first of all, by not requiring cryogenics. This is how in the mid 1990s the "Galileo Galilei (GG)" project was initiated.

The GG concept was so innovative and unconventional that at first it was not accepted. It involves macroscopic proof masses in rapid rotation while trying to measure extremely small forces between them, which at first glance is not a good idea. A high level review panel of ESA made written statements which turned out to be wrong by many orders of magnitude. Papers were published to demonstrate the validity of the idea and the feasibility of the space experiment, but at some point I became convinced that it was necessary to provide experimental evidence. GG on Ground (GGG) was initiated. The apparatus has now reached an interesting level of sensitivity, with a significant recent improvement due to the contribution of Raffaello Pegna. More importantly, we can convincingly argue that it is possible to improve it by serval orders of magnitude, thus making the case for the experiment in space really strong. But *"new blood"* must be injected into the project, because an advanced low noise laser gauge read out must be implemented. The PI Guido Zavattini, with the collaboration of Mike Shao from JPL, is up to the task. I am fully dedicated to this project and determined to bring the mission in orbit. The dedication of Guido Zavattini to challenging experiments in fundamental physics is apparent from his CV; if this proposal is approved, this will become his new challenging experiment.

Awards

In 2006 I have been awarded the prize *Premio Pisa donna 2006* by the city of Pisa

Funding

I have devoted considerable efforts to fund my research projects, taking the responsibility to lead the project proposals. I have been funded by the Italian Ministry of Research, by the European Commission, by the Italian Space Agency (ASI) and by INFN (Istituto Nazionale di Fisica Nucleare). Funds provided by ASI in the years 2008-2010 –in addition to INFN funds– have allowed us to build a new ad hoc vacuum chamber which accommodates a new weakly suspended GGG apparatus. In the current year GGG is funded by INFN; application for next year is due by the fall when INFN panel (Commissione Nazionale Scientifica II) reviews all projects and decides about next year funding. INFN resources are devoted to the equipment only.

3 B2–b1: 10-yr track-record of corresponding PI Anna M. Nobili

10 papers published in refereed journals during the last 10 years:

1. **R. Pegna, A.M. Nobili, M. Shao, S.G. Turyshev, G. Catastini, A. Anselmi, R. Spero, S. Doravari, G.L. Comandi, A. De Michele**, Abatement of thermal noise due to internal damping in 2D oscillators with rapidly rotating test masses, *Phys. Rev. Lett.* 107, 200801–5, 2011 **Citations: 0**

2. **A.M. Nobili, G.L. Comandi, S. Doravari, D. Bramanti, R. Kumar, F. Maccarrone, E. Polacco, S. G. Turyshev, M. Shao, J. Lipa, H. Dittus, C. Laemmerzhal, A. Peters, J. Mueller, C. S. Unnikrishnan, I. W. Roxburgh, A. Brillet, C. Marchal, J. Luo, J. van der Ha, V. Milyukov, V. Iafolla, D. Lucchesi, P. Tortora, P. De Bernardis, F. Palmonari, S. Focardi, D. Zanello, S. Monaco, G. Mengali, L. Anselmo, L. Iorio & Z. Knezevic**, "Galileo Galilei" (GG) a small satellite to test the equivalence principle of Galileo, Newton and Einstein, *Exp Astron* 23, 689–710, 2009 **Citations: 7**

3. **A.M. Nobili, G.L. Comandi, D. Bramanti, S. Doravari, D. Lucchesi, F. Maccarrone**, Limitations to testing the equivalence principle with satellite laser ranging, *General Relativity and Gravitation*, 40, 1533–1544, 2008 **Citations: 2**

4. **A.M. Nobili, G.L. Comandi, S. Doravari, F. Maccarrone, D. Bramanti, E. Polacco**, Experimental validation of a high accuracy test of the Equivalence Principle with small satellite "Galileo Galilei–GG", *International Journal of Modern Physics* D, 16, 2259–2270, 2007 **Citations: 3**

5. **G.L. Comandi, R. Toncelli, M.L. Chiofalo, D. Bramanti and A.M. Nobili**, Dynamical Response of the Galileo Galilei rotor for a Ground test of the Equivalence Principle: theory, simulation and experiment. Part II: the rejection behavior, *Review of Scientific Instruments*, 77, 034502(1–10), 2006 **Citations: 0**

6. **G.L. Comandi, M.L. Chiofalo, R. Toncelli, D. Bramanti, E. Polacco and A.M. Nobili**, Dynamical Response of the Galileo Galilei rotor for a Ground test of the Equivalence Principle: theory, simulation and experiment. Part I: the normal modes, *Review of Scientific Instruments*, 77, 034501(1–15), 2006 **Citations: 0**

7. **G.L. Comandi, A.M. Nobili, D. Bramanti, R. Toncelli, E. Polacco, M.L.Chiofalo**, "Galileo Galilei on the Ground – GGG": experimental results and perspectives, *Physics Letters* A, 318, 213–222, 2003 **Citations: 1**

8. **A.M. Nobili, D. Bramanti, G.L. Comandi, R. Toncelli, E. Polacco, M.L. Chiofalo**, "Galileo Galilei – GG": design, requirements, error budget and significance of the ground prototype, *Physics Letters* A, 318, 172–183, 2003 **Citations: 5**

9. **A.M. Nobili, D. Bramanti, G.L. Comandi, R. Toncelli, E. Polacco**, A rotating differential accelerometer for testing the equivalence principle in space: results from laboratory tests of a ground prototype, *New Astronomy*, 8, 371–390, 2003 **Citations: 3**

10. **A.M. Nobili, D. Bramanti, G.L. Comandi, R. Toncelli, E. Polacco**, Radiometer effect in the Microscope space mission, *New Astronomy*, 7, 521–529, 2002 **Citations: 3**

Overall I am co-author of 71 papers published in refereed journals, 1 book, 36 invited papers/reviews, and 1 Italian patent

In the last 10 years I have given about 20 invited presentations at international conferences and have organized 2 international workshops in Pisa

4 B2–a2: Curriculum Vitae of PI Guido Zavattini

Born in Switzerland, April 1963

Present Position: Associate Professor in Physics

Studies
- I graduated in Physics at the University of Pisa on 2 March 1989 with 110/110 votation
- PhD program in Physics at the University of Bologna: 3/1990-3/1993
- PhD title: 23/9/1993
- Post-Doc at INFN-Trieste: 3/1993-3/1994

FERRARA UNIVERSITY:
29/12/2008 - present: Associate Professor in Physics at the University of Ferrara
28/2/2008: Qualified as Associate Professor in Physics (FIS/07)
15/8/2002 - 15/8/2003: On leave at the University of California at Davis, Davis, California, USA
1/9/1994 – 29/12/2008: University researcher

OTHER PROFESSIONAL POSITIONS
4/2007 - present: Member of the Scientific and Technical Advisory Committee (STAC) for the VIRGO project
7/98 - 7/2002: Ferrara coordinator for the II National Scientific committee for INFN
7/2004 - present: Ferrara coordinator for the II National Scientific committee for INFN

FOREIGN LANGUAGES
English and Italian: Mother tongue
French: Excellent

Principle research activities
FUNDAMENTAL PHYSICS
THE PVLAS EXPERIMENT (Trieste 1993 - 1994; Ferrara 1994 - present)
Funding: INFN (Istituto Nazionale di Fisica Nucleare) grant and MIUR (Ministero dell'Istruzione, Università e della Ricerca) grant.

I am the spokesperson and PI for both the INFN and MIUR grants.

The PVLAS experiment, financed by INFN, aims at the first measurement of the magnetic birefringence of vacuum induced by an intense magnetic field.

This effect, predicted by QED, is connected to photon-photon scattering by means of the "vacuum polarization"

Furthermore the PVLAS experiment will put new laboratory limits on the mass and coupling constant of hypothetical neutral particles which couple to two photons. The hypothetical particles could contribute to dark matter solution.

The experiment is in a phase of being upgraded in sensitivity after a long period of data taking and analysis.

The best limits on the vacuum magnetic birefringence and consequently on the low energy photon-photon cross sections have been set by this experiment. Furthermore the experiment has produced new precise measurements of the Cotton-Mouton constant for various gases.

<u>Experience</u>:
- Design, production and optimization of the phase locking system for a Nd:YAG laser to a very high finesse cavity
- Modification of the Pound-Drever-Hall phase locking scheme to a cavity.
- Optimization of a very sensitive ellipsometer based on a Fabry-Perot cavity.

- Design and implementation of an ellipsometer with a 6.4 m long cavity with finesse F $=10^5$ at the National Laboratories of INFN.
- Measurement of the intrinsic birefringence of interferential mirrors.
- Sensitivity measurements with the ellipsometer.
- Use of superconducting magnet.
- Data analysis.
- Study of the consequences of the intrinsic birefringence of cavity mirrors within a sensitive ellipsometer.

GAL Experiment (Pisa 1988-1989, Thesis work)

Experiment on the equivalence between gravitational and inertial mass.

The aim of the experiment was to measure the relative difference in free-fall gravity for different materials to a level of $\Delta g/g < 10^{-10}$

- Development at Pisa of a collimator capable of measuring parallelism between beams to a level 1e-6 rad.
- Development at CERN of an interferometer with parallel, vertical arms, each 7 m long.
- Precesion optics and mechanics.

My experience with Fabry-Perot interferometers and highly sensitive optical systems qualifies me for the development of the differential laser gauge necessary for measuring the relative movement of the two test masses in the proposal. Furthermore Ferrara will have the collaboration of Mike Shao who has already developed and tested a similar laser gauge system with the desired performances.

OTHER FIELDS OF INTEREST

MEDICAL PHYSICS (Ferrara, 1994 - present)

PET (Positron emission tomography) and SPECT (Single Photon Emission Tomography) allow functional imaging of organs *in-vivo*.

At the Department of Physics of the University of Ferrara collaborators and I developed an integrated high resolution PET-SPECT small animal tomograph for small animal imaging. The system is based on YAP:Ce (Ytirum Aluminum Perovskite doped with Cerium) scintillator matrices coupled to position sensitive photomultiplier tubes. The capability of imaging both in PET and SPECT remains unique.

At present the integration of a CT scanner is underway on the same scanner so as to provide both functional and morphological images simultaneously. The prototype has already been tested on a benchtop system with promising results.

We are also in the process of designing a new PET scanner for small animals based on multilayers of silicon double sided detectors. Simulations have shown the enormous capabilities of such a scanner both in spatial resolution as in sensitivity. Such a scanner would be limited only by the positron range of the radionuclides eliminating all other sources of error.

Optical fluorescence tomography

At the University of California at Davis, we began a new in-vivo imaging technique for small animals based on the fluorescent light emitted by fluorophores which can be bound to biological molecules.

In fact light with wavelength longer than 600 nm is principally diffused by biological tissues and not absorbed. This technique has the advantage of using fluorophores which do not decay in time, as do radionuclides used in PET and SPECT. Processes can therefore be monitored for longer periods of time.

5 B2–b2: 10-yr track-record of PI Guido Zavattini

Reviewed papers:
Co-Author of 82 papers

1) M. Bregant, G. Cantatore, F. Della Valle, G. Ruoso, G. Zavattini Frequency locking to a high-finesse Fabry-Perot cavity of a frequency doubled Nd:YAG laser used as the optical phase modulator *Review of Scientific Instruments* **73** no. 12 (2002) pp. 4142-4144. **Citations: 4**

2) M. Bregant, G. Cantatore, S. Carusotto, R. Cimino, F. Della Valle, G. Di Domenico, U. Gastaldi, M. Karuza, E. Milotti, E. Polacco, G. Ruoso, E. Zavattini, G. Zavattini Measurement of the Cotton-Mouton effect in krypton and xenon at 1064 nm with the PVLAS apparatus. *Chemical Physics Letters*, **392** (2004) pp. 276-280. **Citations: 12**

3) M. Bregant, G. Cantatore, S. Carusotto, R. Cimino, F. Della Valle, G. Di Domenico, U. Gastaldi, M. Karuza, E. Milotti, E. Polacco, G. Ruoso, E. Zavattini, G. Zavattini A precise measurement of the Cotton Mouton effect in Neon. *Chemical Physics Letters*, **410** (2005) pp. 288-292. **Citations: 11**

4) G. Zavattini, G. Ruoso, E. Milotti, M. Karuza, G. Di Domenico, F. Della Valle, R. Cimino, G. Cantatore, On Measuring Birefringences and Dichroisms using Fabry-Perot Cavities. *Applied Physics B,* **83** (2006) pp. 571-577. **Citations: 5**

5) G. Zavattini, M. Bregant, G. Cantatore, S. Carusotto, R. Cimino, F. Della Valle, G. Di Domenico, U. Gastaldi, M. Karuza, E. Milotti, E. Polacco, G. Raiteri, G. Ruoso, E. Zavattini, PVLAS. *In: Venice 2007, Neutrino Telescopes. Venezia, 06/03/2007 - 09/03/2007, Padova: Papergraph, p. 373-395.*

6) E. Zavattini, G. Zavattini, G. Ruoso, et al., New PVLAS results and limits on magnetically induced optical rotation and ellipticity in vacuum. *Physical Review D,* **77** (2008) p 032006. **Citations: 59**

7) M. Bregant, G. Cantatore, S. Carusotto, R. Cimino, F. Della Valle, G. Di Domenico, U. Gastaldi, M. Karuza, V. Lozza, E. Milotti, E. Polacco, G. Raiteri, G. Ruoso, E. Zavattini and G. Zavattini Limits on low energy photon-photon scattering from an experiment on magnetic vacuum birefringence. *Phys Rev. D,* **78** (2008) p 032006. **Citations: 10**

8) M. Bregant, G. Cantatore, S. Carusotto, R. Cimino, F. Della Valle, G. Di Domenico, U. Gastaldi, M. Karuza, V. Lozza, E. Milotti, E. Polacco, G. Raiteri, G. Ruoso, E. Zavattini and G. Zavattini, New precise measurement of the Cotton-Mouton effect in helium, *Chem. Phys. Lett,* **471** (2009) pp 322-325. **Citations: 4**

9) G. Zavattini and E. Calloni, Probing for new physics and detecting non-linear vacuum QED effects using gravitational interferometer antennas, *Europ. Physic. Journal C* **62** (2009) pp 459-466. **Citations: 4**

10) F. Della Valle, G. Di Domenico, U. Gastaldi, E. Milotti, R. Pengo, G. Ruoso and G. Zavattini, Towards a direct measurement of vacuum magnetic birefringence: PVLAS achievements. *Optics Communications* **283** (2010) pp 4194-4198. **Citations: 1**

6 B2–c: Extended Synopsis of GGonGround project proposal

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 tested experimentally by Galileo in Pisa. Newton regarded testing it as so important that he 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– and extending it globally, nine 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 that is 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: thw time of fall of just a few seconds and release errors the test masses. 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 these techniques. Tests based on dropping cold atoms have achieved $\eta = 10^{-7}$ [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 a 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 in *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 from ASI and INFN ([19] $\div$ [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; in fact, 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 which competes 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

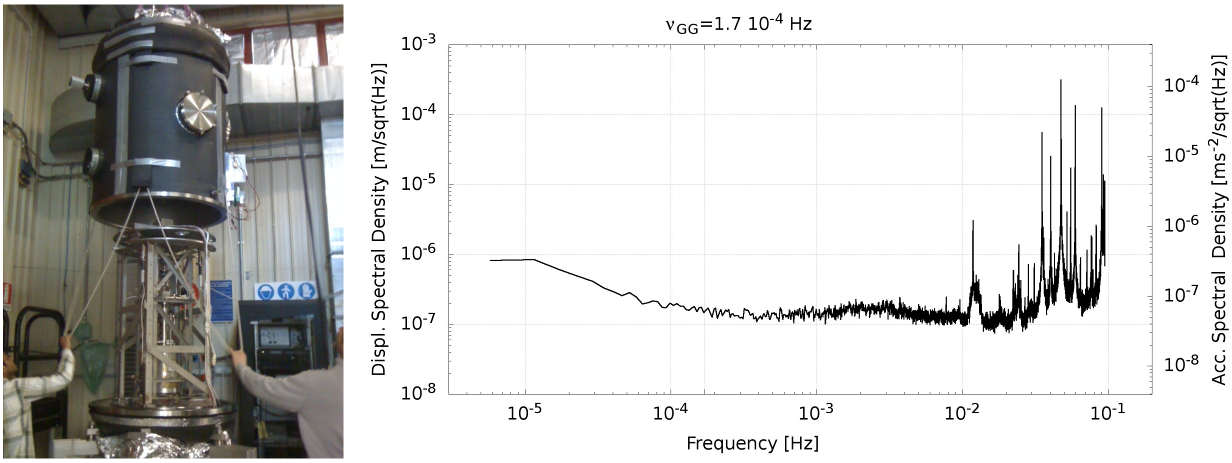

Figure 1: *Left:* the GGG apparatus (at INFN lab in San Piero-Pisa, built with ASI and INFN funding). The proof masses are concentric cylinders (10 kg each) with the symmetry axis in the vertical direction, weakly coupled in the horizontal plane by high quality $CuBe$ joints in 2D. Together they form 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:* Spectral density of the relative displacements and the relative accelerations of the test cylinders in the horizontal plane in a 28 d ongoing run 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 $2 \cdot 10^{-7}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ and the measured acceleration noise is $7.9 \cdot 10^{-8}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ (the measured natural period is 10 s). In 30 d the differential acceleration noise is $\simeq 8 \cdot 10^{-11}\,\mathrm{ms}^{-2}$, 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 every few years 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 is 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 1. Fig. 1 shows that GGG has reached a sensitivity of $\simeq 8{\cdot}10^{-11}\,\mathrm{ms}^{-2}$ in 30 d, while GG must reach $a_{GG} = 8{\cdot}10^{-17}\,\mathrm{ms}^{-2}$ to meet its goal. We state with confidence that GGG can improve by 5 orders of magnitude its current performance to reach $a_{GGG} = 10a_{GG} \simeq 8{\cdot}10^{-16}\,\mathrm{ms}^{-2}$

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)	$8 \cdot 10^{-17}$ ($\eta = 10^{-17}$, $h \simeq 600\,\mathrm{km}$)	$6 \cdot 10^{-13}$ ($T_d \simeq 540\,\mathrm{s}$)	1
GGonGround goal	$a_{GGG} = 10 a_{GG}$ (upconverted to $0.2 \div 3$ Hz)	$8 \cdot 10^{-16}$	$3.2 \cdot 10^{-14}$ ($T_d \simeq 40\,\mathrm{s}$)	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: $a_{tilt} = \frac{k_c}{mgL}\frac{k_{shaft}}{M_{tot}gL_{shaft}}g\theta_{tilt}$, $\theta_{tilt} = \theta_{terrain} + \theta_{airbearing}$					
terrain	8.2	5.1	3.3	2.1	$\theta_{terrain} \simeq 8 \cdot 10^{-6}\,\frac{\mathrm{rad}}{\sqrt{\mathrm{Hz}}}$ $\theta_{airbearing} \simeq 4 \cdot 10^{-6}\,\frac{\mathrm{rad}}{\sqrt{\mathrm{Hz}}}$ $k_c \simeq k_{shaft} \simeq 0.04\,\mathrm{Nm/rad}$ $m = 10\,\mathrm{kg}$ $L = 0.5\,\mathrm{m}$ $M_{tot} \simeq 80\,\mathrm{kg}$ $L_{shaft} \simeq 4\,\mathrm{m}$
air bearing	4.1	2.5	1.7	1.0	
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 1: GGonGround goal and noise budget

GGonGround Roadmap		
Time (Months)		
		Performance achieved
	t_0	$a_0 = 8 \cdot 10^{-11}\,\mathrm{ms}^{-2}$ (INFN lab San Piero, Pisa; ASI and INFN funding; Fig. 1)
		First 18–month period targets
6	$t_0 + 6$	$a_1 = 2.8 \cdot 10^{-12}\,\mathrm{ms}^{-2}$ ($T_d = 14.8\,\mathrm{s}$ $\mathrm{r_{capRO}} = 1.45 \cdot 10^{-8}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; can be done with capacitance read out and ball bearings, requires weaker joints by a factor 4)
12	$t_0 + 12$	$a_2 = 7.7 \cdot 10^{-14}\ ms^{-2}$ ($T_d = 40\,\mathrm{s}$ $\mathrm{r_{capRO}} = 3 \cdot 10^{-9}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; can be done with capacitance readout and ball bearings, requires 10 times longer suspension shaft)
18	$t_0 + 18 = t_1$	$a_3 = 5.6 \cdot 10^{-15}\,\mathrm{ms}^{-2}$ ($T_d = 40\,\mathrm{s}$ $\mathrm{r_{laserRO}} = 2.2 \cdot 10^{-10}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; 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	$t_1 + 18 = t_2$	$a_4 = 7.7 \cdot 10^{-16}\,\mathrm{ms}^{-2}$ ($T_d = 40\,\mathrm{s}$ $\mathrm{r_{laserRO}} = 3.0 \cdot 10^{-11}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; 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 2: GGonGround Roadmap

(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 Fabry-Perot interferometry, with collaboration and advise from Dr. M. Shao (JPL, CA, USA) who has already developed, built and demonstrated a very low noise laser gauge.

The roadmap Table 2 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 the success of the experiment in space and to strengthen its European contribution.

Required funding (9592600 € total for 6 yr) and PIs time on the the project are given in the Budget Tables. Both PIs are strongly dedicated to this project, for their time is 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 relevant to 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.

References

[1] A. Einstein, Jahrbuch der Radioaktivität und Elektronik, 4, 411-462 (1907)
[2] S. Schlamminger *et. al.*, Phys. Rev. Lett. 100, 041101 (2008)
[3] J. G. Williams, S. G. Turyshev & D. H. Boggs, Phys. Rev. Lett. 93, 261101 (2004)
[4] E. G. Adelberger*et al.*, Progress in Particle and Nuclear Physics 62, 102 (2009)
[5] A. M. Nobili *et al.*, General Relativity & Gravitation 40, 1533Ū1554 (2008)
[6] S. Fray *et. al.*, Phys. Rev. Lett. 93, 240404 (2004)
[7] A. Peters, K.Y. Chung & S. Chu, Nature 400, 949 (1999)
[8] P. K. Chapman, A. J. Hanson, *Proc. Conf. on Exp. Tests of Grav. Theories*, JPL Pub. 228 (1971)
[9] P. W. Worden, Jr., *PhD Thesis*, Stanford University, Stanford (CA) (1976)
[10] P. W. Worden, Jr., Acta Astronautica, 5, 27 (1987)
[11] A. M. Nobili *et al.*, Phys. Rev. D Rapid Commun. 63, 101101(R) (2001)
[12] J. P. Den Hartog, *Mechanical Vibrations*, Dover Publ. Inc N.Y. 1985 (first published in 1934)
[13] S. H. Crandall, J. Sound Vib. 11(1), 3-18, (1970)
[14] A. M. Nobili *et al.*, J. Astronaut. Sc. 43, 219-242 (1995)
[15] A. M. Nobili *et al.*, New Astronomy 3 175Ū218 (1998)
[16] A. M. Nobili *et al.*, Classical Quantum Gravity 16, 1463-1470 (1999)
[17] A. M. Nobili *et al.*, New Astronomy 7 521-529 (2002)
[18] *GG Phase A Study Report*, ASI (1998), *GG Phase A-2 Study Report* (2009)
[19] A. M. Nobili *et al.*, New Astronomy 8 371-390 (2003)
[20] G. L. Comandi *et al.*, Rev. Sci. Instrum. 77 034501 1-15 (2006)
[21] G. L. Comandi *et al.*, Rev. Sci. Instrum. 77 034502 1-15 (2006)
[22] A. M. Nobili *et al.*, Int. J. of Modern Physics D, 16 2259-2270 (2007)
[23] R. Pegna *et al.*, Phys. Rev. Lett. 107, 200801 (2011)
[24] A. M. Nobili *et al., Integration time in very high sensitive EP tests in space,* to be submitted
[25] A. M. Nobili, *et al., Null checks in space experiments to test EP,* to be submitted
[26] G. L. Comandi, *PhD Thesis,* University of Pisa, Pisa, Italy (2004)
[27] V. Iafolla, *private communication* (2012)