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Research Proposal (Part B1)

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

GGonGround

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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 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 1e4 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 skill- is the route for GG to 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], ($\eta \equiv \Delta a_\oplus / a_\oplus$, $a_\oplus \simeq 1.69 \cdot 10^{-2}\,\mathrm{ms}^{-2}$ 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 $h \simeq 600$ 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]: thermal noise due to internal damping which competes with the low frequency signal

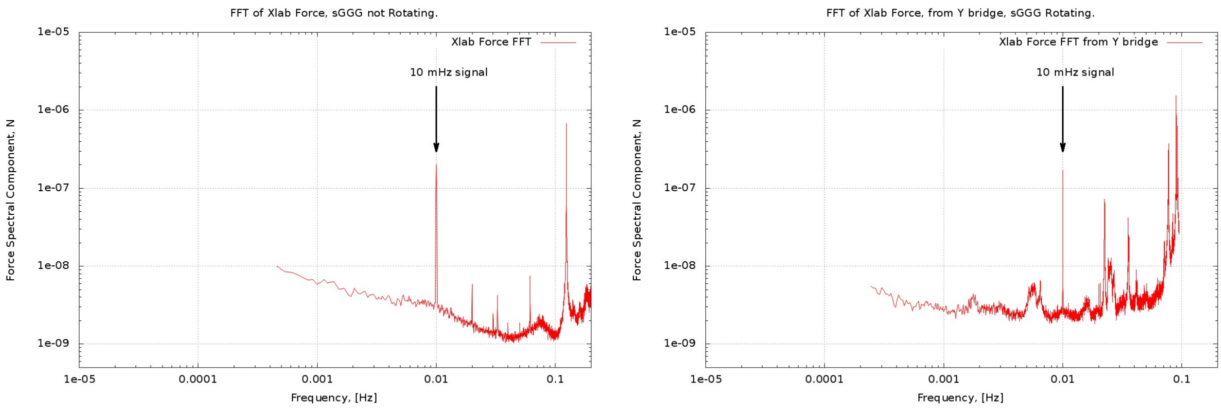

Figure 1: We have experimentally demonstrated that in a 2D oscillator in supercritical rotation like GGG modulation of low frequencies signals at frequencies above resonance is possible without signal attenuation. Left plot: GGG is not rotating and a differential force signal at 0.01 Hz is applied to 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: GAG 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, which is up-converted close to the spin frequency and therefore at frequencies 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 this differential displacements of the test cylinders– have been demodulated back to the non rotating horizontal plane of the lab for comparison with non rotating case shown above along the X direction. If GGG were an oscillator in 1-D only, a similar rotation of the oscillator above its natural frequency would have been attenuated the signal by a factor 2.56. We note in passing that in the non rotating case (top plot) readout electronics noise increases at lower frequencies as expected, while in the rotating case the relevant readout electronics noise is that at the rotation (that is at the *modulation*) frequency.

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 [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

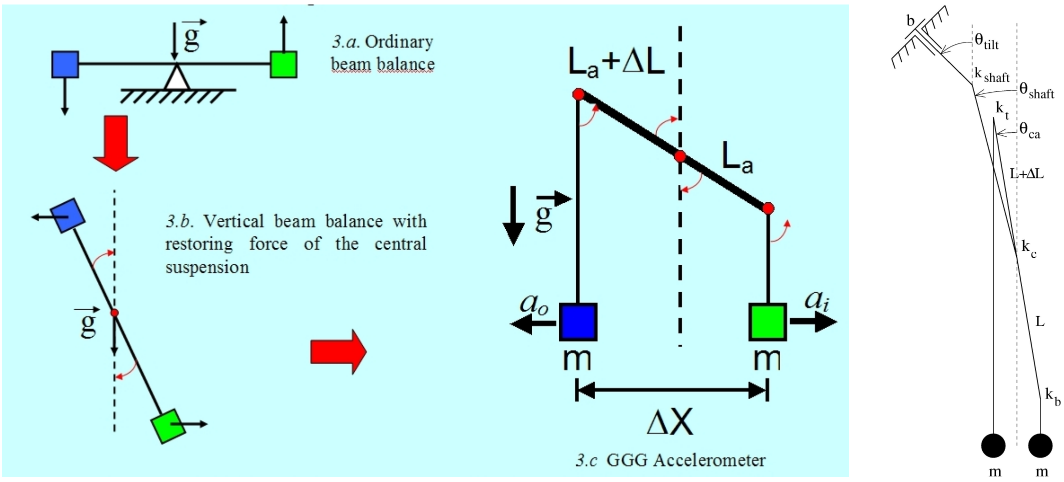

Figure 2: Simplified representation of the GGG balance. (*left*): The GGG accelerometer is designed to be sensitive to differential forces acting in plane perpendicular to the spin axis, which is in the vertical direction. The two test masses are coupled as in a vertical beam balance with a natural period 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 simply $\Delta a_{horiz-acc} = g\theta_{tilt}$, 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 defined 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.

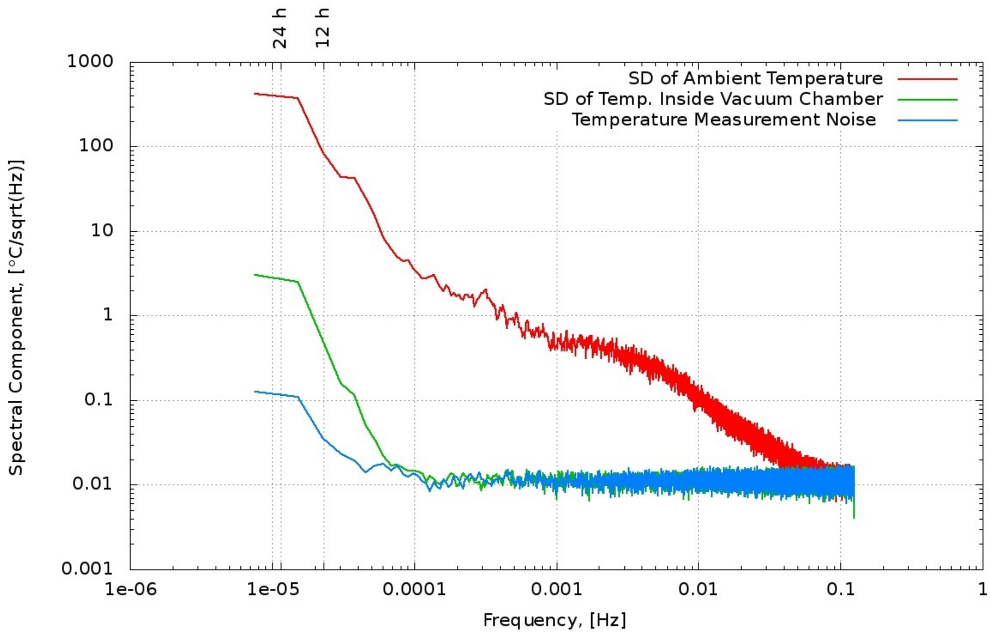

Figure 4: GGG temperature stability relies on a PID (Proportional Integral Derivative), heating only, temperature control acting on the temperature of the vacuum chamber walls. Ambient temperature variations (red curve) are attenuated inside the vacuum chamber (green curve) by about two orders of magnitude,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

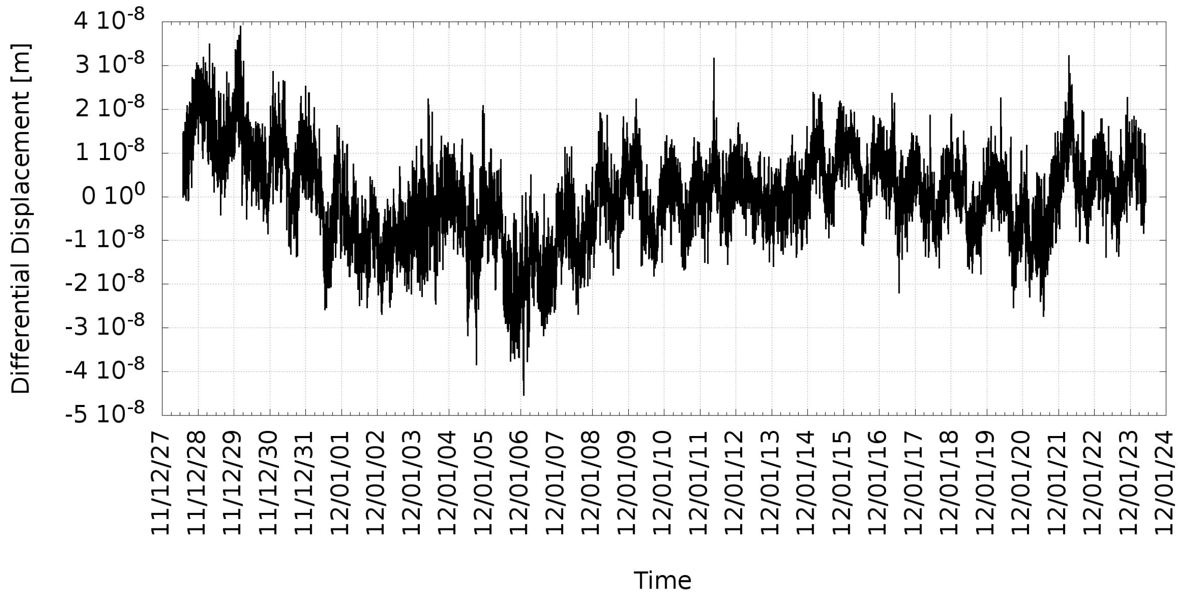

Figure 5: Time series of the relative displacements of the GGG test masses (frequencies above ν_{cut} = 1 mHz filtered out) in one direction of the horizontal plane of the lab during the ongoing run for a timespan $\mathrm{T_{meas}} \simeq 28$ d. We have analyzed all data collected till 24 January 2012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

The 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.

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 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.

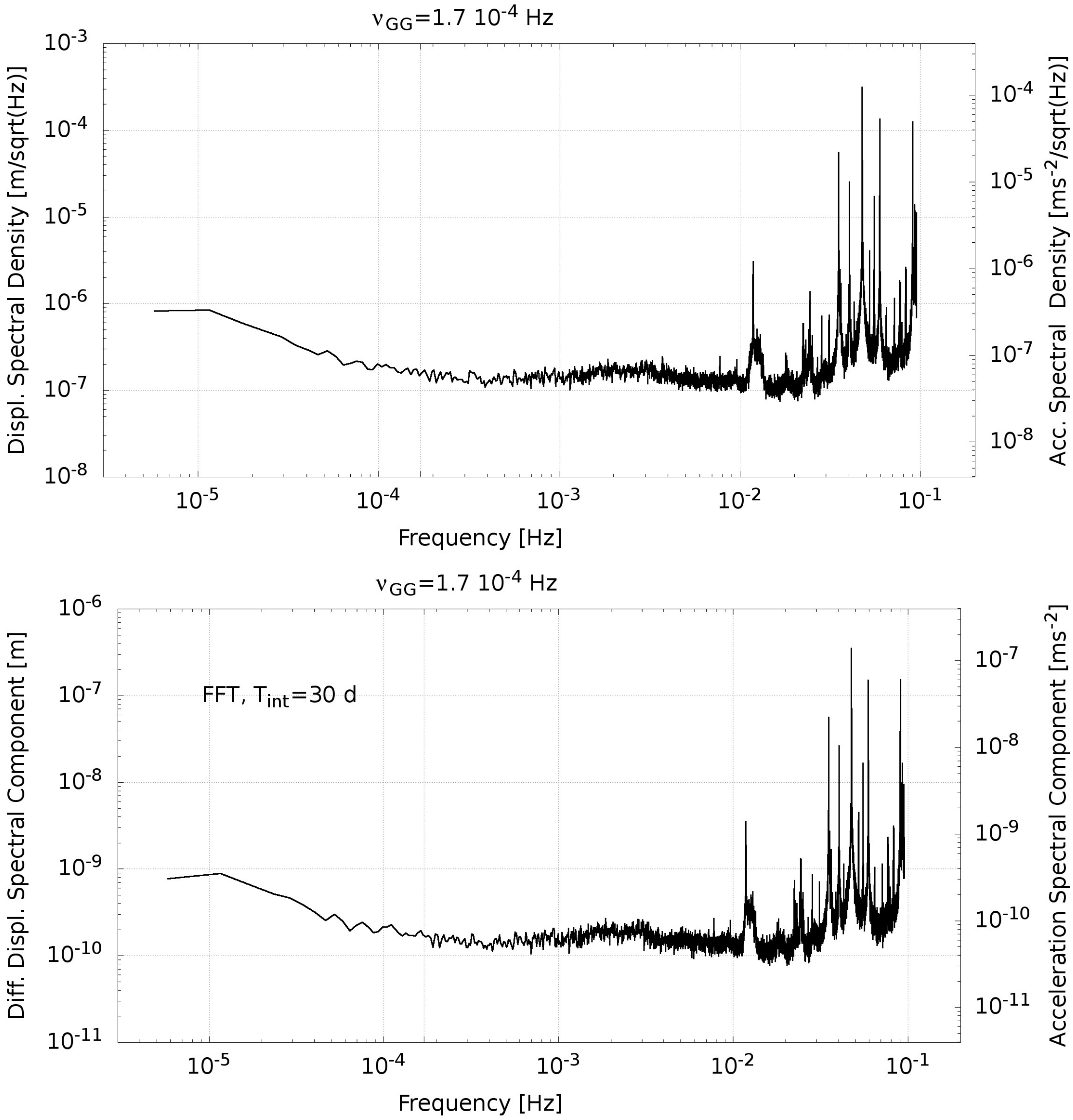

Figure 6: The GGG noise performance as measured from an ongoing run of duration $\mathrm{T_{meas}} \simeq 28$ d. Top plot: Spectral density of the relative displacements and acceleration of the test cylinders in one direction of the horizontal plane of the lab; the GGG differential accelerometer is spinning at $\nu_s = 0.19$ Hz with natural coupling frequency of 0.1 Hz. The measured relative displacement is $\simeq 2 \cdot 10^{-7}\mathrm{m}/\sqrt{\mathrm{Hz}}$ and the measured relative acceleration is $\simeq 7.9 \cdot 10^{-8}\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ at the frequency $\nu_{\mathrm{GG}} \simeq 1.7 \cdot 10^{-4}$ 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 $\mathrm{T_{int}} \simeq 30$ 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 larger 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 quite that 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 sicussed 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)	$8 \cdot 10^{-17}$ ($\eta = 10^{-17}$, $h \simeq 600\,\mathrm{km}$)	$6 \cdot 10^{-13}$ ($T_d \simeq 540\,\mathrm{s}$)	1
GGonGround goal	$a_{GGG} = 10a_{GG}$ (upconverted to $0.2 \div 3$ Hz)	$8 \cdot 10^{-16}$	$3.2 \cdot 10^{-14}$ ($T_d \simeq 40\,\mathrm{s}$)	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[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	$t_0 + 6$	$a_1 = 2.8 \cdot 10^{-12}\,\mathrm{ms}^{-2}$ ($T_d = 14.8\,\mathrm{s}$ $\mathrm{r_{capRO}} = 1.45 \cdot 10^{-8}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; 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

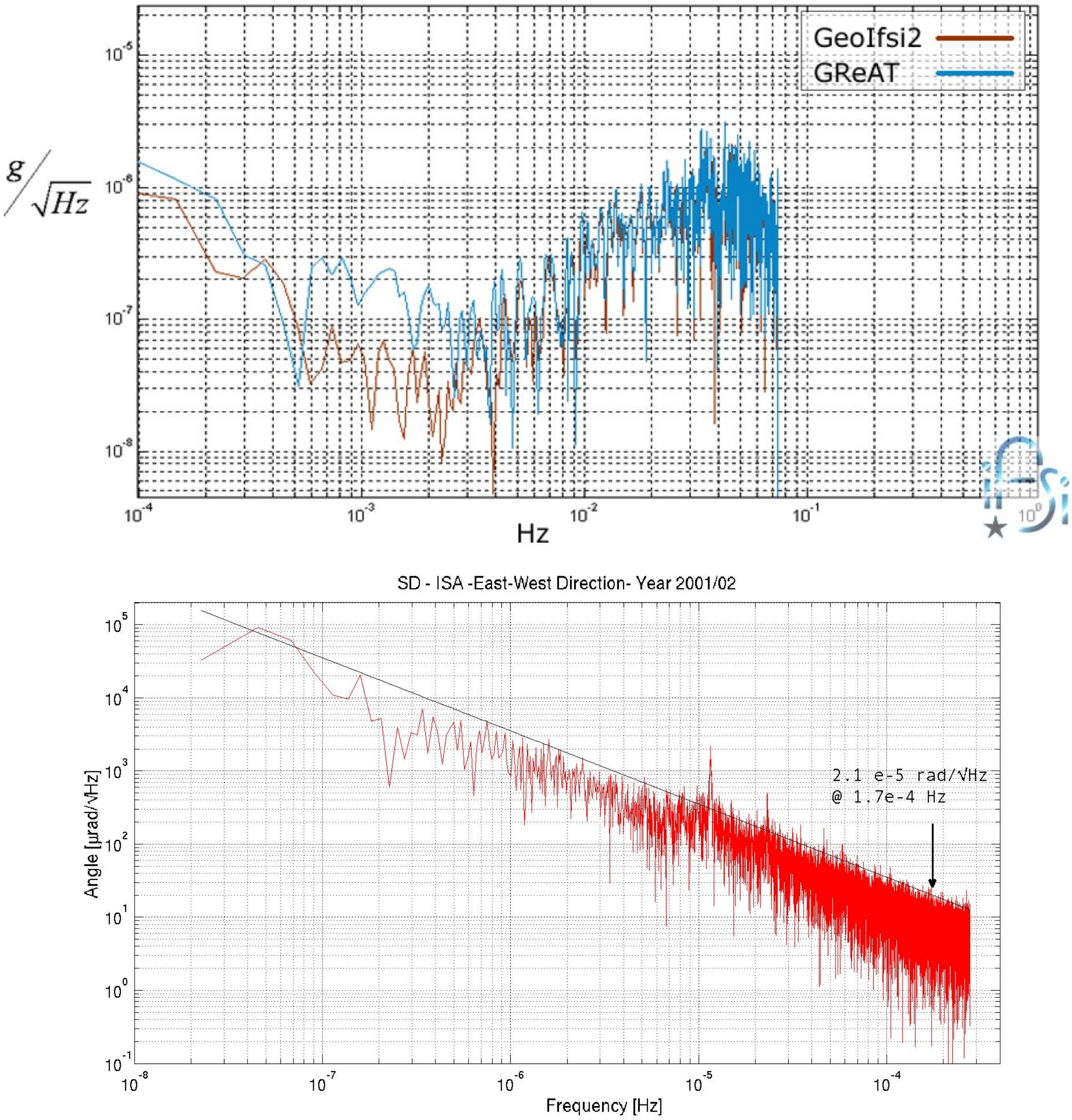

Figure 7: Top: terrain tilt noise as measured by V. Iafolla ISA accelerometer in two different locations at IFSI lab (Roma Tor Vergata) (g is equivalent to rad), showing at the frequency $\nu_{GG} = 1.7 \cdot 10^{-4}$ Hz a noise of $9 \cdot 10^{-7}\mathrm{rad}/\sqrt{\mathrm{Hz}}$ in a quiet location and of $3 \cdot 10^{-7}\mathrm{rad}/\sqrt{\mathrm{Hz}}$ in an underground room. Bottom: terrain tilt noise as measured in Florence (over 16 months) with an ISA tiltmeter, showing $2.1 \cdot 10^{-5}\mathrm{rad}/\sqrt{\mathrm{Hz}}$ 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.

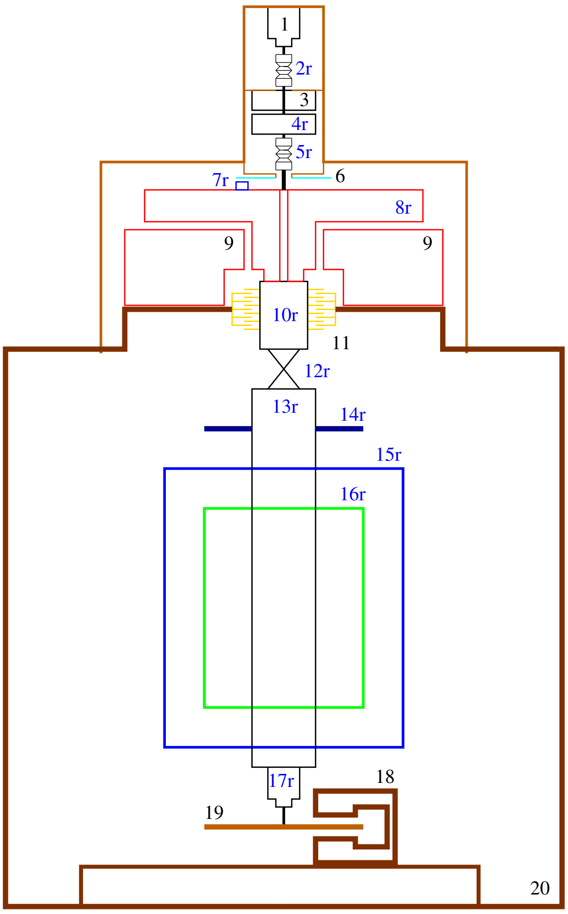

Figure 8: Design for the implementation of the air bearing on GGG. Precision grade ball bearings are manufactured with typical $\sim$ 100 nm geometric tolerances: balls are manufactured with $\sim$ 100 nm sphericity and $\sim$ 500 nm diameter tolerance. Very roughly, a 5 cm diameter ball bearing can 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 ($10\,\mu$m) 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 $0.02\,\mu$rad. 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. 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 to insulate this part with respect to 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.

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4 B1–c: Resources and budget tables

Budget Table (in €) for the Corresponding Principal Investigator Anna M. Nobili

	Cost Category	Months 1–18	Months 19–36	Months 37–54	Months 55–72	Total
Direct Costs	Personnel:					
	PI	44000	44000	36000	36000	160000
	Senior Staff (1)	118500	118500	118500	118500	474000
	Post Docs (1)	67500	67500	67500	67500	270000
	Students (PhD, 2)	60000	60000	60000	60000	240000
	Other (Dr. R. Pegna)	118500	118500	118500	118500	474000
	Other (1 mech. engineer)	67500	67500	67500	67500	270000
	Other (Dr. G. Catastini)			66000	66000	132000
	Other (Dr. D.M. Lucchesi)	13500	13500	13500	13500	54000
	Other (1 Junior Staff)	105000	105000	105000	105000	420000
	Other (1 admin. assistant)	53550	53500	53550	53550	214200
	Total Personnel:					**2708200**
	Other Direct Costs:					
	Equipement (eligible fraction only)	235000	275000	275000	275000	1060000
	Consumables	25000	25000	25000	25000	100000
	Travel	92700	92700	100950	100950	387300
	Publications, dissemination etc..	49500	49500	49500	49500	198000
	Other (removal and lab set up)	50000				50000
	Total Other Direct Costs	452200	442200	450450	450450	**1795300**
	Total Direct Costs	1100250	1090250	1156500	1156500	**4503500**
Indirect Costs	Max 20% of Direct Costs	220050	218050	231300	23130	900700
Subcontracting Costs (auditing)	(No Overheads)	10000	10000	10000	10000	40000
Total Costs of Project:	(By Year and Total)	1330300	1318300	1397800	1397800	**5444200**
Requested Grant:	(By Year and Total)	1330300	1318300	1397800	1397800	**5444200**

Working time the PI **A.M. Nobili** dedicates to the project over the period of the grant

		Months 1–18	Months 19–36	Months 37–54	Months 55–72	Average
		73.3%	**73.3%**	**60%**	**60%**	**67%**

Budget Table (in €) for the Principal Investigator Guido Zavattini						
	Cost Category	Months 1–18	Months 19–36	Months 37–54	Months 55–72	Total
Direct Costs	Personnel:					
	PI	24000	36000	36000	36000	132000
	Senior Staff (1)	118500	118500	118500	118500	474000
	Post Docs (1)	67500	67500	67500	67500	270000
	Students (PhD, 1)	30000	30000	30000	30000	120000
	Other (Dr. Mike Shao)	37500	37500	37500	37500	150000
	Other (2 Junior Staff)	210000	210000	210000	210000	840000
	Total Personnel:	487500	499500	499500	499500	**1986000**
	Other Direct Costs:					
	Equipement (eligible fraction only)	210000	230000	200000	200000	840000
	Consumables	25000	25000	25000	25000	100000
	Travel	102000	125000	92000	92000	411000
	Publications, dissemination etc	30000	30000	30000	30000	120000
	Other					
	Total Other Direct Costs	367000	410000	347000	347000	**1471000**
	Total Direct Costs	854500	909500	846500	846500	**3457000**
Indirect Costs	Max 20% of Direct Costs	170900	181900	169300	169300	691400
Subcontracting Costs	(No Overheads)					
Total Costs of Project:	(By Year and Total)	1025400	1091400	1015800	1015800	**4148400**
Requested Grant:	(By Year and Total)	1025400	1091400	1015800	1015800	**4148400**

Working time the PI **G. Zavattini** dedicates to the project over the period of the grant						
		Months 1–18	Months 19–36	Months 37–54	Months 55–72	Average
		40%	**60%**	**60%**	**60%**	**50%**

Summary Table for the Entitre Budget (in €)						
	Cost Category	Months 1–18	Months 19–36	Months 37–54	Months 55–72	Total
Direct Costs	Personnel:					
	PI	68000	80000	72000	72000	292000
	Senior Staff	237000	237000	237000	237000	948000
	Post Docs	135000	135000	135000	135000	540000
	Students	90000	90000	90000	90000	360000
	Other	605550	605550	671550	671550	2554200
	Total Personnel:	1135550	1147550	1205550	1205550	**4694200**
	Other Direct Costs:					
	Equipement	445000	505000	475000	475000	1900000
	Consumables	50000	50000	50000	50000	200000
	Travel	194700	217700	192950	192950	798300
	Publications, dissemination etc	79500	79500	79500	79500	318000
	Other	50000				50000
	Total Other Direct Costs	819200	852200	797450	797450	**3266300**
	Total Direct Costs	1954750	1999750	2003000	2003000	**7960500**
Indirect Costs	Max 20% of Direct Costs	390950	399950	400600	400600	1592100
Subcontracting Costs (auditing)	(No Overheads)	10000	10000	10000	10000	40000
Total Costs of Project:	(By Year and Total)	2355700	2409700	2413600	2413600	**9592600**
Requested Grant:	(By Year and Total)	2355700	2409700	2413600	2413600	**9592600**

5 B–d: Ethical and security-sensitive issues

	Research on Human Embryo/ Foetus	NO	Page
	Does the proposed research involve human Embryos?	NO	
	Does the proposed research involve human Foetal Tissues/ Cells?	NO	
	Does the proposed research involve human Embryonic Stem Cells (hESCs)?	NO	
	Does the proposed research on human Embryonic Stem Cells involve cells in culture?	NO	
	Does the proposed research on Human Embryonic Stem Cells involve the derivation of cells from Embryos?	NO	
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**YES**	

	Research on Humans	NO	Page
	Does the proposed research involve children?	NO	
	Does the proposed research involve patients?	NO	
	Does the proposed research involve persons not able to give consent?	NO	
	Does the proposed research involve adult healthy volunteers?	NO	
	Does the proposed research involve Human genetic material?	NO	
	Does the proposed research involve Human biological samples?	NO	
	Does the proposed research involve Human data collection?	NO	
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**YES**	

	Privacy	NO	Page
	Does the proposed research involve processing of genetic information or personal data (e.g. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	NO	
	Does the proposed research involve tracking the location or observation of people?	NO	
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**YES**	

	Research on Animals	NO	Page
	Does the proposed research involve research on animals?	NO	
	Are those animals transgenic small laboratory animals?	NO	
	Are those animals transgenic farm animals?	NO	
	Are those animals non-human primates?	NO	
	Are those animals cloned farm animals?	NO	
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**YES**	

	Research Involving non-EU Countries (ICPC Countries)	NO	Page
	Is the proposed research (or parts of it) going to take place in one or more of the ICPC Countries?	NO	
	Is any material used in the research (e.g. personal data, animal and/or human tissue samples, genetic material, live animals, etc) : a) Collected in any of the ICPC countries?	NO NO	
	b) Exported to any other country (including ICPC and EU Member States)?	NO	
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**YES**	

	Dual Use	NO	Page
	Research having direct military use	NO	
	Research having the potential for terrorist abuse	NO	
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**YES**	

Security-Sensitive Issues

There are no security-sensitive issues