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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

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

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1 GGonGRound proposal: Part B1

Example of link to a webpage: Galileo Galilei Web Page. Example of link to a webpage: GGonGround Synergy Grant Web Page.

The scientific proposal [max 15 pages, excluding the Budget Tables (obligatory), Ethical Issues Table (obligatory) and Annex (only if applicable), and the Security Aspects Letter (only if applicable)] Describe the scientific, technical, and/or scholarly aspects of the project demonstrating the ground-breaking nature of the research, its potential impact and research methodology. Describe the significant synergies, complementarity and added value of the group beyond the current work of the Principal Investigators to enable it to jointly achieve the project's scientific objectives. Indicate the fraction of each PI's working time that will be devoted to this project, a full estimation of the real project cost and any ethical considerations raised by the project. Indicate innovative ways of working together and how the core time spent together will be utilised.

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

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

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

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

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

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

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

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

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

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

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

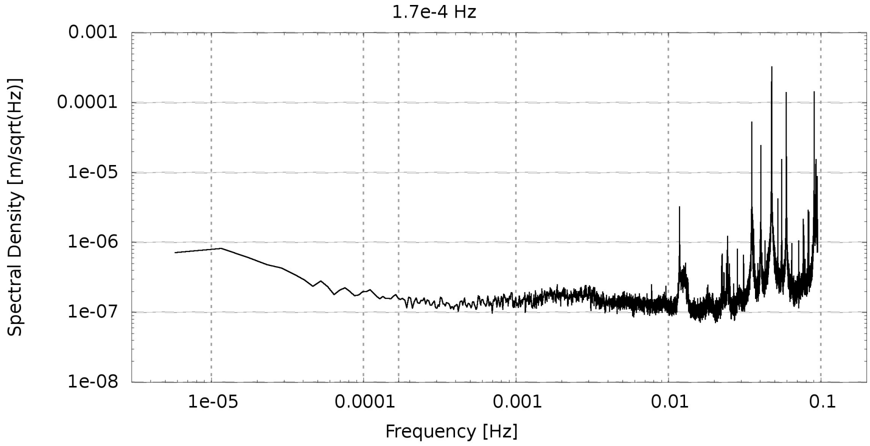

Figure 1: *Left:* the GGG apparatus (at INFN lab in San Piero-Pisa, built with ASI and INFN funding). The proof masses are concentric cylinders (10 kg each) with the symmetry axis in the vertical direction, weakly coupled in the horizontal plane by high quality $CuBe$ joints in 2D. Together they form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

that weak coupling of large proof masses and sensitivity to small forces are compatible with rapid rotation; indeed, it is rapid rotation that makes sensitivity to small forces possible.

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

Recent collaboration with JPL (Jet Propulsion Laboratory, CalTech-NASA) has shown that an optical read-out based on the very low noise laser interferometry gauge developed and demonstrated at JPL will allow GG to fully exploit its very short integration time. The collaboration has led to an agreement between JPL and ASI to submit GG to the EXPLORER program as a NASA led mission and the partnership of ASI, with M. Shao (JPL) as PI and A. M. Nobili as Co-PI. EXPLORER is a long time program of NASA dedicated to flying small size missions in a few years; the Nobel prize winner COBE was one of them. The 2010 Decadal Astronomy has ranked the EXPLORER program as its second highest priority and has advised NASA to further strengthen it. EXPLORER is the right framework for a small mission like GG –which is well below the size of ESA missions– and given that ASI cannot afford a full mission but would be willing contribute to a NASA led mission with a significant Italian rôle.

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

Synergy between the Corresponding PI Nobili, who has led GG and GGG so far, and the PI Zavattini, who will lead the efforts for implementing a low noise laser gauge can considerably improve GGG to meet the goal set in Table 3. Fig. 2 shows that GGG has reached a sensitivity of $8.5\cdot 10^{-11}\,\mathrm{ms}^{-2}$ 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 $a_{GGG} = 10 a_{GG} \simeq 8\cdot 10^{-16}\,\mathrm{ms}^{-2}$ (slightly better than torsion balances) because –as the noise budget in the same table shows– there are no fundamental limitations. The main limitations are terrain and bearings low frequency tilt noise. Terrain tilt input noise at ν_{GG} has been measured ([26], [27]), its effect on the test cylinders is understood (it is expressed by a simple analytical formula with few parameters) and there is no doubt that the current suspensions can be improved (only a factor 4 is needed) and the apparatus properly modified to meet the goal. Air bearing is known to be several orders of magnitude less noisy than ball bearing (the vacuum chamber enclosing the torsion balance rotates on air bearing) and a solution is under study for GGG in which only the experiment rotates, not the chamber. This is feasible and can be realized by A. M. Nobili with the collaboration of Dr. R. Pegna who has significantly contributed to the current GGG performance and can effectively co-lead this activity. At full performance the capacitance bridges are no longer adequate and must be replaced by the laser gauge; this effort can be successfully led by the PI G. Zavattini based on his experience in Fabri-Perot interferometry, with collaboration and advise from Dr. M. Shao (JPL, CA, USA) who has already developed, built and demonstrated a very low nose laser gauge.

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

Required funding (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, their time being limited only by teaching duties (AMN will leave teaching the second year). Funding is dominated by personnel cost due to the lack of funds in Italy to employ researchers and the very limited number of permanent ones; and also to the wide variety of disciplines 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.

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a. State of the art and objectives: Specify clearly the objectives of the proposal, in the context of the state of the art in the field. When describing the envisaged research it should be indicated how and why the proposed work is important for the field, and what impact it will have if successful, such as how it may open up new horizons or opportunities for science, technology or scholarship. Specify any particularly challenging or unconventional concepts and approaches of the proposal, including multi - or interdisciplinary aspects.

3 B1–b: Methodology

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: $a_{tilt} = \frac{k_c}{mgL}\frac{k_{shaft}}{M_{tot}gL_{shaft}}g\theta_{tilt}$					
terrain	8.2	5.1	3.3	2.1	$\theta_{terrain} \simeq 8 \cdot 10^{-6}\,\frac{\mathrm{rad}}{\sqrt{\mathrm{Hz}}}$ $\theta_{ab} \simeq 4 \cdot 10^{-6}\,\frac{\mathrm{rad}}{\sqrt{\mathrm{Hz}}}$ $k_c \simeq k_{shaft} \simeq 0.04\,\mathrm{Nm/rad}$ $m = 10\,\mathrm{kg}$ $L = 0.5\,\mathrm{m}$ $M_{tot} \simeq 80\,\mathrm{kg}$ $L_{shaft} \simeq 4\,\mathrm{m}$
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	$a_0 = 8.5 \cdot 10^{-11}\,\mathrm{ms}^{-2}$ (INFN lab San Piero, Pisa; ASI and INFN funding; Fig. 2)
		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

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b. Methodology Describe the proposed methodology and feasibility in detail including, as appropriate, key intermediate goals. Explain and justify the methodology in relation to the state of the art, including any particularly novel or unconventional aspects addressing 'high-gain/high-risk' balance, i.e. if successful the payoffs will be very significant, but there is a higher-than- normal risk that the research project does not entirely fulfil its aims.

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**

c. Resources (incl. project costs) It is strongly recommended to use the budget table template to facilitate the assessment of resources by the panels (see Annex 3). The summary and the breakdown of the budget following the template is subdivided in personnel costs, equipment and infrastructure, consumables, travel, publication costs, and any envisaged subcontracts. This table has to be provided by each PI and a final table will summarise the overall budget breakdown for the roject. These figures should be summarised in the financial information form A3 as well (although according to host institutions and not according to PIs).

Describe the size and nature of the Synergy group, including each PI and where appropriate, their key team members and their roles. The participation of team members engaged by another institution besides that of the participating PIs should be justified in relation to the additional financial cost this may impose to the project (see section 1.1.3 of this guide). Describe other necessary resources, such as infrastructure and equipment. Specify any existing resources that will contribute to the project. It is advisable to include a short technical description of the equipment requested, a justification of its need as well as the intensity of its planned use. Please ensure that a short narrative description is provided for all budget lines for which funding is requested.

State the amount of funding considered necessary to fulfil the objectives for the duration of the project. This should be a reasoned estimate of the projects costs. Each PI should take into account the percentage of their dedicated time (each PI is expected to devote at least 30% of their total working time to the ERC-funded project while spending at least 50total working time in an EU Member State or Associated Country) to run the ERC-funded activity when calculating their personnel costs. Include the direct costs of the project plus a flat rate financing of indirect costs on the basis of 20% of the total eligible direct costs (excluding subcontracting and the costs of reimbursement of resources made available by third parties which are not used on the premises of the beneficiary) towards overheads.

The project cost estimation should be as accurate as possible. The evaluation panels assess the estimated costs carefully; unjustified budgets will be consequently reduced.

There is no minimum contribution per year; the requested contribution should be in proportion to the actual needs to fulfil the objectives of the project.

5 B–d: Ethical and security-sensitive issues

	Research on Human Embryo/ Foetus	YES	Page
	Does the proposed research involve human Embryos?		
	Does the proposed research involve human Foetal Tissues/ Cells?		
	Does the proposed research involve human Embryonic Stem Cells (hESCs)?		
	Does the proposed research on human Embryonic Stem Cells involve cells in culture?		
	Does the proposed research on Human Embryonic Stem Cells involve the derivation of cells from Embryos?		
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**YES**	

	Research on Humans	YES	Page
	Does the proposed research involve children?		
	Does the proposed research involve patients?		
	Does the proposed research involve persons not able to give consent?		
	Does the proposed research involve adult healthy volunteers?		
	Does the proposed research involve Human genetic material?		
	Does the proposed research involve Human biological samples?		
	Does the proposed research involve Human data collection?		
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**YES**	

	Privacy	YES	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)?		
	Does the proposed research involve tracking the location or observation of people?		
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**YES**	

	Research on Animals	YES	Page
	Does the proposed research involve research on animals?		
	Are those animals transgenic small laboratory animals?		
	Are those animals transgenic farm animals?		
	Are those animals non-human primates?		
	Are those animals cloned farm animals?		
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**YES**	

	Research Involving non-EU Countries (ICPC Countries)	YES	Page
	Is the proposed research (or parts of it) going to take place in one or more of the ICPC Countries?		
	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?		
	b) Exported to any other country (including ICPC and EU Member States)?		
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**YES**	

	Dual Use	YES	Page
	Research having direct military use		
	Research having the potential for terrorist abuse		
	I CONFIRM THAT NONE OF THE ABOVE ISSUES APPLY TO MY PROPOSAL	**YES**	

Security-Sensitive Issues
There are no security-sensitive issues

6 Proposal Part B2–Section 1

The Principal Investigators

Each of the Principal Investigators must provide a list reflecting their track record. This can be either an 'early achievement track-record' (for PIs 2 to 12 years after their PhD) or a '10-year track-record' (for advanced researchers) chosen by the applicants based on which is most appropriate for their career stage. The evaluation experts will be instructed to judge each PI against the benchmarks relevant to his/her career stage. The experts will also pay particular attention to the joint effort of the group that may be built around specialised infrastructure, or that allow for new combinations of skills and disciplines, or the bringing together of researchers from different institutions, sectors or countries.

7 Proposal Part B2–A. Curriculum Vitae

a. Curriculum Vitae (max 2 pages for each PI):

In addition to the standard academic and research record, the CV should include a succinct 'funding ID' which must specify any current research grants and their subject, as well as any ongoing application for work related to the proposal. This facilitates the proper assessment of the proposal and the granting process in case the proposal is retained for funding. Any research career gaps and/or unconventional paths should be clearly explained. Peer reviewers will take this into consideration when assessing the PI's quality and career progression.

8 Proposal Part B2–B Track-Record

b. Track-Record

Early achievement track-record (max 2 pages for each PI):
The PI should list: his/her activity as regards: 1. Publications in major international peer-reviewed multi-disciplinary scientific journals and/or in the leading international peer-reviewed journals, peer-reviewed conferences proceedings and/or monographs of their respective research fields, indicating the ten best, those without the presence as co-author of their PhD supervisor, and information about the citation response they have attracted. 2. Granted patent(s) (if applicable).
3. Invited presentations to peer-reviewed, internationally established conferences and/or international advanced schools (if applicable).
4. Prizes and Awards (if applicable).
or
10-Year track-record (max 2 pages for each PI):
The PI should list his/her activity over the past 10 years (dated from the deadline of the call) as regards:
1. A list of the top 10 publications, as senior author (or in those fields where alphabetic order of authorship is the norm, joint author), listing all authors, in major international peer- reviewed multi-disciplinary scientific journals and/or in the leading international peer-reviewed journals and/or peer-reviewed conferences proceedings of their respective research fields, also indicating the number of citations (excluding auto-citations) they have attracted.
2. Research monographs, chapters in collective volumes and any translations thereof (if applicable).
3. Granted patents (if applicable).
4. Invited presentations to peer-reviewed, internationally established conferences and/or international advanced schools (if applicable).
5. Research expeditions that the applicant has led (if applicable).
6. Organisation of International conferences in the field of the applicant (membership in the steering and/or programme committee) (if applicable).

7. International Prizes/Awards/Academy memberships (if applicable).
8. Memberships to Editorials Boards of International Journals (if applicable).

The above mentioned page limits for sections 2a and 2b apply individually, i.e. maximum 4 pages per PI.

9 GGonGround - Extended Synopsis

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

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

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

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

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

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

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

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

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

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

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

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

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

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

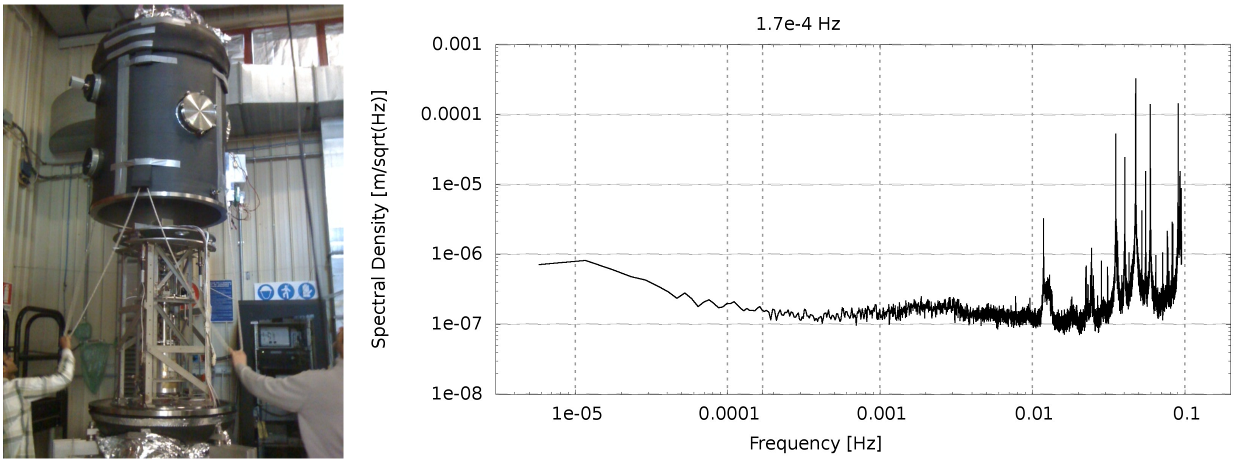

Figure 2: *Left:* the GGG apparatus (at INFN lab in San Piero-Pisa, built with ASI and INFN funding). The proof masses are concentric cylinders (10 kg each) with the symmetry axis in the vertical direction, weakly coupled in the horizontal plane by high quality $CuBe$ joints in 2D. Together they form a very peculiar beam balance in which the beam is vertical –hence the balance is sensitive to differential forces in the horizonal plane– and the masses are concentric. The relative displacements of the cylinders in the horizontal plane are read by 2 orthogonal capacitance bridges whose plates are located halfway in between them. The balance rotates around the vertical axis upconverting low frequency signals to the spin frequency. The rotating shaft is held by ceramic ball bearings. An additional 2D weak joint is located just below the bearings in order to reduce low frequency tilts and horizontal accelerations from terrain microseismic noise and bearings noise on the shaft. Note that both terrain and bearings noise are absent in space because the spacecraft is isolated (no terrain) and after initial spin up by the launcher no motor or bearings are needed (angular momentum conservation). *Right:* Linear spectral density of the relative displacements of the test cylinders in the horizontal plane of the lab in a 20 d run (still ongoing) after demodulation from the rotating frame ($\nu_{spin} = 0.19$ Hz). The frequency of interest is the orbital frequency $\nu_{GG} = 1.7 \cdot 10^{-4}$ Hz of the GG satellite at which a violation signal is expected in space. At ν_{GG} the measured displacement noise is $2 \cdot 10^{-7}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$; in 30 d and with the measured natural oscillation period of 10 s, the differential acceleration noise is $8.5 \cdot 10^{-11}\,\mathrm{ms}^{-2}$, 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 in a few years; the Nobel prize winner COBE was one of them. The 2010 Decadal Astronomy has ranked the EXPLORER program as its second highest priority and has advised NASA to further strengthen it. EXPLORER is the right framework for a small mission like GG –which is well below the size of ESA missions– and given that ASI cannot afford a full mission but would be willing contribute to a NASA led mission with a significant Italian rôle.

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

Synergy between the Corresponding PI Nobili, who has led GG and GGG so far, and the PI Zavattini, who will lead the efforts for implementing a low noise laser gauge can considerably improve GGG to meet the goal set in Table 3. Fig. 2 shows that GGG has reached a sensitivity of $8.5 \cdot 10^{-11}\,\mathrm{ms}^{-2}$ 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 $a_{GGG} = 10 a_{GG} \simeq 8 \cdot 10^{-16}\,\mathrm{ms}^{-2}$

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)	$8 \cdot 10^{-17}$ ($\eta = 10^{-17}$, $h \simeq 600$ km)	$6 \cdot 10^{-13}$ ($T_d \simeq 540$ s)	1
GGonGround goal	$a_{GGG} = 10 a_{GG}$ (upconverted to $0.2 \div 3$ Hz)	$8 \cdot 10^{-16}$	$3.2 \cdot 10^{-14}$ ($T_d \simeq 40$ s)	30

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

Table 3: GGonGround goal and noise budget

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

Table 4: GGonGround Roadmap

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

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

Required funding (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, their time being limited only by teaching duties (AMN will leave teaching the second year). Funding is dominated by personnel cost due to the lack of funds in Italy to employ researchers and the very limited number of permanent ones; and also to the wide variety of disciplines 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.

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