EQUIVALENCE PRINCIPLE TEST IN SPACE

The discovery of "Dark Energy" and the fact that only 5% of the mass of the Universe is explained by current Physics laws have led to a serious impasse. A very high-accuracy space test of the Equivalence Principle with the GG ("Galileo Galilei") mission would prove or rule out the existence of a new long-range interaction in Nature and be a crucial asset for the future of Physics and Cosmology.

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1 Models of the Universe and the current physical theories

In 1930, in London, at a banquet honoring Einstein, George Bernard Shaw – Nobel prize for Literature in 1925 – said:

> "Napoleon, and other great men of his type, they were makers of empire. But there is an order of men who get beyond that, they are not makers of empire but they are makers of Universe. Their hands are not stained by the blood of any human being on Earth. Ptolomy made a Universe which lasted 14 hundred years. Newton also made a Universe which has lasted 3 hundred years. Einstein made a Universe and I can't tell you how long that will last."

An old movie shot at the banquet still exists – from which the picture shown in fig. 1 is taken – showing George Bernard Shaw strongly addressing the audience, while Einstein listens to his praises in a shy attitude, till he breaks into a laugh after the last sentence "… and I can't tell you how long that will last". The speech expresses, in the words of the great Irish writer, the scientific fact that our understanding of the Universe relies upon our knowledge of gravity. Eleven years earlier, on November 7, 1919, the London Times announced the successful measurement of the bending of starlight by the Sun, which yielded twice as much as expected by Newton – a value close to Einstein's prediction. The news was the headline, and read: "Revolution in Science. New Theory of the Universe. Newtonian Ideas Overthrown".
Ever since Newton's "*Philosophiae Naturalis Principia Mathematica*" was published in London in 1687 gravity is known to govern the physics of the cosmos. In the following two centuries, based on Newton's law of gravity, the best scientists of their time developed sophisticated mathematical tools which allowed them to predict the position of planets in the sky. By comparison with extremely accurate and systematic observations carried out at major astronomical observatories – particularly in Europe – theoretical predictions and observations were found to agree with each other amazingly, superceding Ptolomy's model which had lasted 14 hundred years. Celestial Mechanics became the paradigm of exact science, so much that the existence of Neptune could be inferred, and the planet actually observed in 1846 at the predicted position (though with a bit of luck), on the basis of its gravitational influence on the motion of Uranus which had been found by observations to deviate more and more with time from the theoretical prediction. In point of fact, the contribution from theory was crucial, while the capability to observe Neptune was already there 234 years earlier, when Galileo did indeed see Neptune [1], [2]. Newton's theory of gravity dominated for more than 200 years, even beyond the publication of Einstein's theory of General Relativity [3]. Despite the consistency and beauty of this new theory of gravity, and its profound revolutionary nature with respect to Newton's theory, its observable consequences were minute and hard to measure. Even Einstein's beautiful explanation of the small additional perihelion advance of Mercury predicted by his theory – and until then "missing" in the predictions of Celestial Mechanics as based on Newton's gravity (see, *e.g.* [4]) – was anyway adding only a small contribution to a much larger and astonishingly good prediction of the effects of planetary perturbations to the motion of the perihelion of Mercury.
On a larger scale, since 1929 it became apparent that the Universe is expanding. By comparing measurements of velocities (by means of redshifts) and measurements of distances (using Cepheids as standard candles), Edwin Hubble proved that the Universe is actually expanding. Gravity would slow down that expansion, and so the question was to establish whether the density of matter is sufficient to "close" the Universe or else it will keep expanding forever. About 10 years ago, two teams of astronomers found that there is too little matter in the Universe to stop its expansion and, moreover, that the outward motion is indeed speeding up. The conclusion was based on more than 20 years measurements of the distance of extremely far away galaxies using very bright supernovae as standard candles (the Cepheids being too dim at such distances). The discovery was named by the journal *Science* "Breakthrough of the Year 1998" in Astronomy (see [5]).
A new, unknown, form of mass-energy – the so-called "dark energy" – is required.
It is indeed quite remarkable that completely different astronomical measurements, namely those of the cosmic microwave background anisotropy performed by BOOMERanG [6] and WMAP [7], have led to the same conclusion. In the future, a dedicated space survey as proposed with the ESA mission EUCLID should provide the scientific community with considerable new insights. In the US, the JDEM mission – jointly funded and developed by NASA and the Office of High Energy Physics at the Department of Energy (DOE) – will make precise measurements of the expansion rate of the Universe to understand how this rate has changed with time; these measurements will yield vital clues about the nature of "dark energy".
In 2005 a "Dark-Energy Task Force" (DETF) has been established in the US by the Astronomy and Astrophysics Advisory Committee and the High-Energy Physics Advisory Panel to advise the Department of Energy, NASA and the National Science Foundation on future "dark energy" research. In 2006 DETF published its final report [8]. The executive summary of the report begins as follows:

> "Over the last several years scientists have accumulated conclusive evidence that the Universe is expanding ever more rapidly. Within the framework of the standard cosmological model, this implies that 70% of the Universe is composed of a new, mysterious dark energy, which unlike any known form of matter or energy, counters the attractive force of gravity. Dark energy ranks as one of the most important discoveries in cosmology, with profound implications for astronomy, high-energy theory, general relativity, and string theory.
> One possible explanation for dark energy may be Einstein's famous cosmological constant. Alternatively, dark energy may be an exotic form of matter called quintessence, or the acceleration of the Universe may even signify the breakdown of Einstein's Theory of General Relativity. With any of these options, there are significant implications for fundamental physics."

A few pages below, the section of the DETF report on "Goals and Methodology for Studying Dark Energy" ends with the following sentence:

> "Just as dark-energy science has far-reaching implications for other fields of physics, advances and discoveries in other fields of physics may point the way toward understanding the nature of dark energy; for instance, any observational evidence for modifications of General Relativity."

In addition, the existence of "dark matter" – whose nature is not yet understood – has been postulated long before the discovery of "dark energy". Invoked by most astronomers,

Fig. 1 George Bernard Shaw (right, standing), Nobel prize for Literature in 1925, giving a speech at banquet honoring Albert Einstein (left, seated) in London in 1930.

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"dark matter" probably consists of undiscovered elementary particles whose aggregation produces the gravitational pull capable of holding together galaxies and clusters of galaxies in agreement with observations. The amount required is more than 20% of the total. Hence, only about 5% of the mass of the Universe is understood at present.
In this framework it is apparent that the challenge for theoretical physics – especially for General Relativity as the best theory of gravity to date – is enormous.
The theory of General Relativity (GR) and the Standard Model of particle physics, taken together, form our current view of the physical world. While the former governs physics in the macroscopic and cosmic scales the latter governs the physics of the microcosm. According to GR gravity is not a force but a manifestation of the space-time curvature. The relation between space-time curvature and space-time content (mass-energy and momentum) being given by Einstein's field equations. The theory has been extensively tested and no astronomical observation or experimental test has been found to deviate from its predictions. Thus it is the best description we have of gravitational phenomena that we observe in Nature. The Standard Model of particle physics, since the 1970s gives a unified formalism for the other three fundamental interactions (strong, weak and electromagnetic) between the fundamental particles that make up all matter. It is a quantum field theory which is consistent with both Quantum Mechanics and Special Theory of Relativity. It has been spectacularly successful at describing physics down to a distance scale of about 10^{-18} m and no experiment to date contradicts it. Considerable new insights, down to even smaller scales, are expected from the Large Hadron Collider (LHC).
However, merging these two very successful theories to form a single unified theory poses significant difficulties. While in the Standard Model particle fields are defined on a flat Minkowski space-time, GR postulates a curved space-time which evolves with the motion of mass-energy (mass tells spacetime how to curve, curved space-time tells particles how to move). In addition quantum mechanics becomes inconsistent with GR near singularities and in general current theories break down whenever gravity and quantum mechanics both become important.
It is apparent that in spite of their own success, GR and the Standard Model need to be reconciled with each other. As for GR, the need to put it to more and more stringent tests comes therefore not only from facing the challenge of a Universe whose mass-energy is mostly unknown, but also from the absence of a quantum theory of gravity.
This need has been clearly identified by the "Committee on the Physics of the Universe" which was appointed by the National Research Council of the US National Academies to investigate the subject and advise the major national research funding agencies. The results of the panel's work have been published in the book "Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century" [9].
The 3rd of the eleven questions identified in the book is

"Did Einstein Have the Last Word on Gravity?

Black holes are ubiquitous in the universe, and their intense gravity can be explored. The effects of strong gravity in the early universe have observable consequences. Einstein's theory should work as well in these situations as it does in the solar system. A complete theory of gravity should incorporate quantum effects – Einstein's theory of gravity does not – or explain why they are not relevant."

The last chapter of the book, under the title "Realizing the Opportunities", is devoted to giving recommendations as to how to proceed in order to answer the 11 questions identified. The recommendations focus on very large scientific projects; however, a specific section is devoted to the importance of setting up an effective program by balancing few big long-term projects with more numerous, more affordable, small ones addressing specific crucial issues. The section is ([9], p. 162)

"Striking the Right Balance

In discussing the physics of the universe, one is naturally led to the extremes of scale – to the largest scales of the universe as a whole and to the smallest scales of elementary particles. Associated with this is a natural tendency to focus on the most extreme scale of scientific projects: the largest space observatories, the most energetic particle accelerators. However, our study of the physics of the universe repeatedly found instances where the key advances of the past or the most promising opportunities for the future come from work on a very different scale. Examples include laboratory experiments to test gravitational interactions, theoretical work and computer simulations to understand complex astrophysical phenomena, and small-scale detector development for future experiments.
Two of our scientific questions – 'Did Einstein have the last word on gravity?' and 'Are there additional space-time dimensions?'– are being addressed by a number of laboratory and solar-system experiments to test the gravitational interaction. Tests of the principle of equivalence using laboratory torsion balances and lunar laser ranging could constrain hypothetical weakly coupled particles with long or intermediate range. These experiments have reached the level of parts in 10^{13} and could be improved by another order of magnitude. Improvement by a factor of around 10^5 could come from an equivalence principle test in space. […] null experimental results provide important constraints on existing theories, and a positive signal would make for a scientific revolution."

2 Equivalence Principle: the founding pillar of General Relativity

In 1907 Einstein formulated the "*hypothesis of complete physical equivalence*" between a gravitational field and an accelerated reference frame: in a freely falling system all masses fall equally fast, hence gravitational acceleration has no *local* dynamical effects [10]. Any test mass located inside the famous Einstein elevator – falling with the local acceleration of gravity g near the surface of the Earth – and zero initial velocity with respect to it, remains motionless for the time of fall. An observer inside Einstein elevator will not be able to tell – before hitting the ground – whether he is moving with an acceleration g in empty space, far away from all masses, or else he is falling in the vicinity of a body (the Earth) whose local gravitational acceleration is also g.
This is known as the Weak Equivalence Principle (WEP), whereby the effect of gravity disappears in a freely falling reference frame. Its experimental consequence is the Universality of Free Fall (UFF), namely the fact that in the gravitational field of a source mass (*e.g.*, the Earth) all bodies fall with the same acceleration regardless of their mass and composition. UFF was first tested by Galileo in the early 1600 (see, *e.g.* [11]), and later – with Newton's "*Principia*" – became the consequence of the equation of motion of falling bodies once the equivalence between inertial and gravitational mass was assumed.
In the novel, profound view of Einstein the Equivalence Principle has far reaching implications. In its "Weak" formulation it holds only *locally*: Einstein elevator is free falling *in the vicinity* of the Earth, which amounts to saying that the height of fall is much smaller than the radius of the Earth. The cancellation of gravity in a freely falling frame holds locally for each frame, but the direction of free fall is not the same in all of them. Which is a direct consequence of the fact that the gravitational field of a body (like the Earth) is non uniform, giving rise to the so-called *tidal forces* between test particles whose centers of mass are not coincident. With his formulation of the WEP Einstein has moved from Newton's concept of one global reference frame with gravitational forces and the UFF, to many free falling local frames without gravitational forces.
In his further development of the theory of General Relativity [3], Einstein formulated what is known as the Einstein Equivalence Principle (EEP), which is an even more powerful and far-reaching concept. EEP states the following (see, *e.g.*, [12]):

i) WEP is valid
ii) The outcome of any local non-gravitational experiment is independent of the velocity of the freely falling reference frame in which it is performed (Local Lorentz Invariance)
iii) The outcome of any local non-gravitational experiment is independent of where and when in the Universe it is performed (Local Position Invariance).

EEP is regarded as the "heart and soul" of GR because it is the validity of this "principle" (indeed, only a working "hypothesis" in Einstein's own words) to ensure the fact that in GR the effects of gravity are replaced by a curved 4-dimensional space-time. Since EEP assumes the WEP to be valid, it is apparent that the WEP is the founding pillar of General Relativity.
Since a decade or so General Relativity is challenged as ever before – more than by its lack of quantization or unification with the other fundamental interactions – by observations at larger galactic and cosmic scales which are presently taken care of through the introduction of "dark matter" and "dark energy". *As long as these components are neither detected through non gravitational means, nor explained as resulting from new physical phenomena, it remains of the uttermost importance to test General Relativity*.
The most remarkable composition-independent tests of GR have been performed both in weak-field conditions, by means of radio links with Cassini spacecraft [13], and in strong-field regime, by timing the double pulsar [14]. This is a unique system in which both neutron stars are detectable as radio pulsars and is becoming the best available test bed for general relativity and alternative theories of gravity in the strong-field regime [15]. Though all experimental tests of GR are valuable as they contribute to assess its validity and provide further constrains, it is expected that testing the very foundation of GR, namely the weak equivalence principle, has a stronger probing power than testing its numerous predictions. Also, a good control of the real environment of the experiments is of crucial importance as the effects of any deviation are bound to be extremely small.
As for the consequences for Physics and Cosmology, it is worth stressing that a violation of the WEP – detected as a deviation from the Universality of Free Fall – would necessarily imply the existence of a new long-range interaction: a revolutionary scientific result. We also note in passing that a time variation of the fine-structure constant over the last Hubble time – which would be a sign of new physics beyond the Standard Model – and a violation of the Equivalence Principle have been recently demonstrated to be directly related to each other [16] .

3 The case for an Equivalence Principle test in space

Most to our amazement, we are led to look back at Galileo's pioneering tests of the Universality of Free Fall carried about 400 years ago when he first realized that pendulum suspended test masses would provide much more accurate tests than test masses dropped from a height (see, *e.g.,* [11]). With his pendulum experiments Galileo was able to test the UFF to 10^{-3} (see also [17]), similarly to what Newton did several decades later and reported in the opening paragraph of his "*Principia*". After Galileo and Newton pendulum tests became able to prove UFF to 10^{-5}, but it was not until the test masses

were suspended on torsion balances rather than on simple pendulums that the accuracy of the UFF improved enormously. The first to envisage using this very successful instrument for the specific purpose of testing the UFF were Roland von Eötvös and his students in Budapest. In a remarkable series of experiments initiated at the turn of the XX century, and with test masses of many different compositions, they were able to prove the UFF to 10^{-8} – 10^{-9} [18]. This accomplishment became possible for two reasons. The first is because the torsion balance is an extremely sensitive instrument: if the suspension wire is very thin the torsion elastic constant is extremely small and the balance is capable to respond with a relatively large torsion angle to even a minute force acting differently on the two masses of the balance; if in addition the mechanical quality is good, so that losses in the system are small, the torsion angle can be detected with a reasonable integration time. The second is that a torsion balance, while being extremely sensitive to forces which are different on the two masses (causing a torsion of the wire), it is ideally insensitive to forces equally acting on them: no deviation from UFF, no differential effect, no signal. The sensitivity of the balance, which can be assessed beyond question by suspending test masses of equal composition, sets the limit to which UFF can be tested with any such instrument.
However, torsion balance tests of UFF in the Eötvös design suffered a major limitation. He set forth to look for a deviation from UFF on the test masses of his torsion balance "falling" in the gravitational field of the Earth, in which case the driving signal (whose relative difference on the two masses of different composition is under detection) is indeed larger than in the field of the Sun, but it is a constant DC signal directed along the North-South direction of the horizontal plane (see [19], sect. 2). The balance was therefore placed with its arm in the East-West direction in order to maximize the effect, but there was no way to check the zero of the test. The only crude check was to physically reverse the balance by 180° (or the location of the test masses on the balance). It was only in the mid 60s and early 70s that the importance was perceived of using a torsion balance for testing the UFF in the gravitational field of the Sun – instead of that of the Earth – since the rotation of the Earth itself, on which the balance sits, provides a modulation of the expected signal at the 24 h Earth rotation period going to zero twice per period (each time the arm of the balance points towards or away from the Sun; see [19], sect. 2). In so doing, there is a small loss in the strength of the driving signal (yet, a much smaller loss than in moving from dropping masses from a height to masses suspended from simple pendulums or torsion balances). Nevertheless, the gain was enormous showing no deviation from the UFF to 10^{-11} [20] and 10^{-12} [21]: an improvement by almost 3 orders of magnitude as compared to Eötvös tests was obtained thanks to the signal modulation.
Exploiting the Earth's rotation to modulate the torsion balance signal was thus very important. Yet, it has two drawbacks: in the first place, the diurnal frequency of the signal modulation is also the frequency of major disturbances (*e.g.,* due to thermal variations and local terrain tilts, to name just the most dangerous); secondly, it is too low to provide significant benefits in terms of reduction of the *1/f* noise of the electronics involved in the mechanical transducer and read-out system. Next step was therefore to rotate the torsion balance itself at a spin rate chosen and controlled by the experimentalists, and faster than the Earth's rotation. Though the task was far from being an easy one, as macroscopic apparata designed to detect extremely small forces are known to be heavily disturbed once put into rotation, the "Eöt–Wash" group at the University of Washington in Seattle, US, which embarked on this project was able to re-obtain 10^{-12} [22] in 1994 and recently to improve by 1 order of magnitude, to 10^{-13} [23] finding no violation.
In the meantime, it had been suggested since the early 70s that an Equivalence Principle test carried out onboard a spacecraft in low Earth orbit would provide several orders of magnitude improvement over ground-based tests [24, 25]. The advantages of space for EP (*i.e.* UFF) testing are apparent. Primarily they are

- that in low Earth orbit the driving signal from Earth is 3 orders of magnitude stronger than for torsion balances, thus ensuring that much improvement for the same instrument sensitivity as on ground;
- that the test masses set-up benefits greatly from the absence of weight (weaker suspensions, higher sensitivity);
- that the satellite carrying the experimental apparatus is essentially an isolated system, hence it is subject to far less disturbances than any vacuum chamber enclosing a torsion balance in a ground lab.

Scientists and space agencies aim at reaching 10^{-15} (μSCOPE mission, by the French Space Agency CNES [26], 10^{-17} ("Galileo Galilei"- GG mission, by the Italian Space Agency ASI [27]) and 10^{-18} (STEP mission by NASA, USA, envisaging a cryogenic apparatus [28]). To date only μSCOPE is under construction, to fly in the next few years. More recently, the use of cold atoms rather than classical macroscopic test masses has been proposed for a space experiment, hoping to reach 10^{-16} [29]. Even balloon-borne (GReAT – ASI and SAO collaboration [30]) and sub-orbital experiments (POEM, NASA [31]) have been extensively investigated.
It is apparent that only an experiment in space can improve current EP tests by several orders of magnitude leading either to the discovery of a new fundamental force of Nature or to very severe constraints on physical theories.

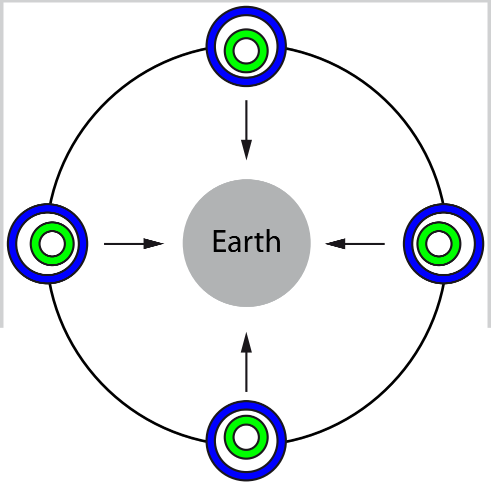


Fig. 2 The EP violation signal in GG. Section in the plane perpendicular to the spin/symmetry axis of the GG outer (dark blue) and inner (green) test cylinders (of different composition and weakly coupled in the plane) as they orbit around the Earth inside a co-rotating, passively stabilized spacecraft (not shown). The centers of mass of the test cylinders are shown to be displaced towards the center of the Earth as in the case of a violation of the equivalence principle in the field of the Earth (indicated by the arrows). The signal is therefore at the orbital frequency (1.75×10^{-4} Hz), but is modulated at the 1 Hz rotation frequency of the system.

4 The GG ("Galileo Galilei") space mission and the GGG ("GG on the Ground") prototype: state of the art

GG is under investigation by ASI (Agenzia Spaziale Italiana) with the space industry TAS-I (Thales Alenia Space - Italy) as prime contractor. The GGG ground prototype of the instrument designed to fly in GG is under developement at INFN (Istituto Nazionale di Fisica Nucleare) in Pisa - San Piero a Grado with a significant contribution from ASI.
GG has been designed to exploit all advantages of space so as to achieve a very high-accuracy test of the Equivalence Principle (to 10^{-17}) without cryogenics. The whole system (2 concentric hollow test cylinders, the capacitance read-out in between them and the spacecraft) of cylindrical symmetry co-rotates (at 1 Hz) around the symmetry axis which is almost perpendicular to the orbit plane of the satellite around the Earth. A sketch of the EP violation signal in GG is shown in fig. 2. Rotation at 1 Hz serves 2 purposes: to modulate the signal and to passively stabilize the spacecraft. Unlike on Earth, in space no motor is required, hence there is no noise from motor and bearings.
The GG spacecraft is shown in figs. 3 and 4. Figure 5 shows

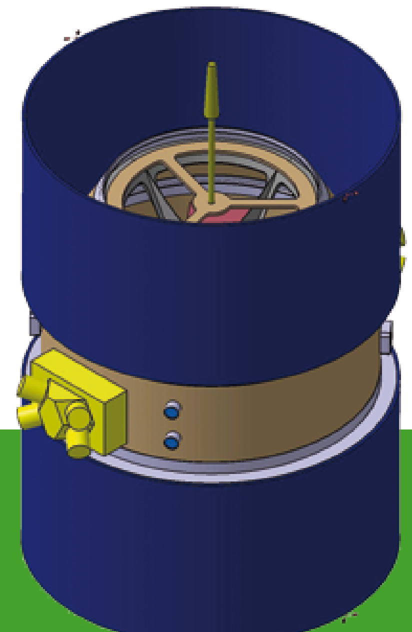


Fig. 3 The GG cylindrical spacecraft (1.45 m central diameter) showing the solar panels (blue), the main body (light brown, see fig. 4) with one of the two antennas along the symmetry axis.

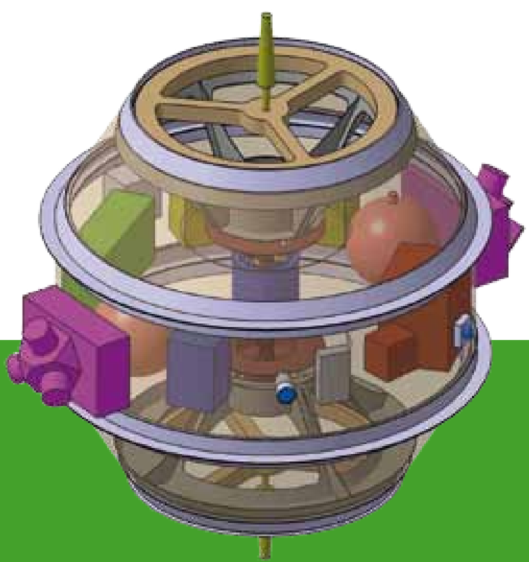
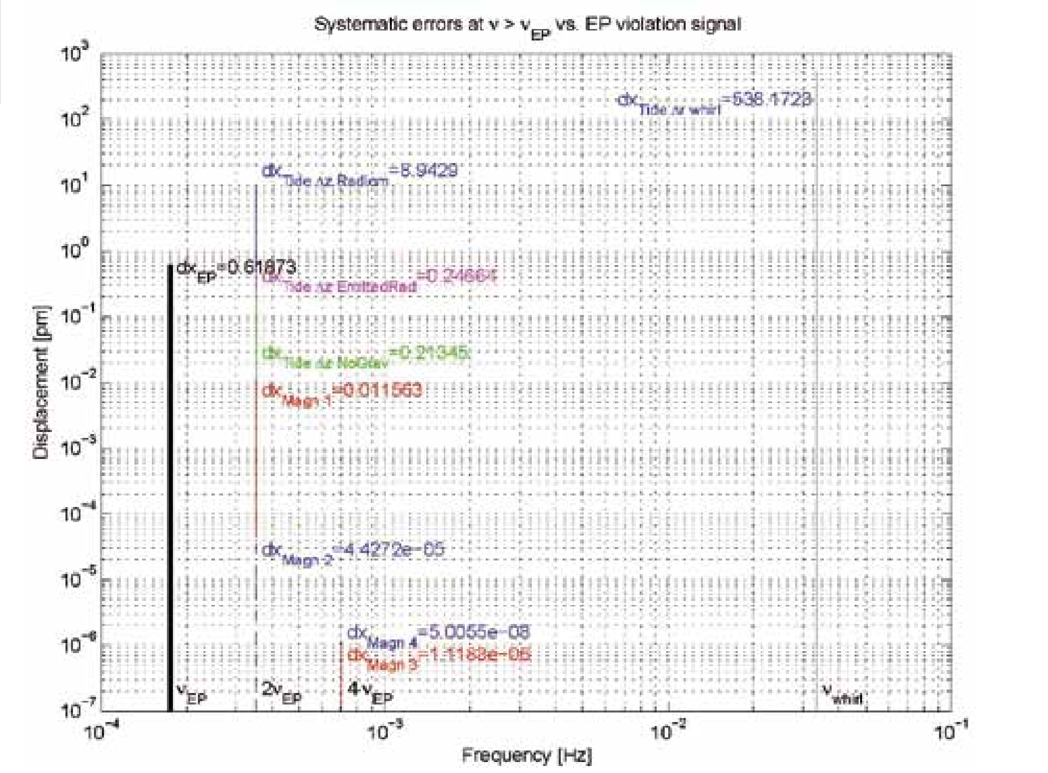


Fig. 4 Transparent view of the spacecraft body (shown in fig. 3 with the solar panels). At its center the outer test cylinder of the GG accelerometer is visible in blue.

Fig. 7 Graphical representation of the GG error budget as obtained from the Space Experiment Simulator. The mission requirements are embedded in the simulator during a science run; the time series of the relative displacements of the test cylinders (which should be zero if the Universality of Free Fall and the Weak Equivalence Principle hold!) allows us to establish systematic and random errors. The plot reports major systematic errors only, caused by various (classical) perturbations, as a function of their frequency (in the inertial frame) to be compared with the signal expected for an EP violation to 10^{-17} (indicated by the thick line, first from left). The relative displacement caused on the test masses by the signal and the various perturbations is expressed in picometers. The frequency of the signal is the satellite orbit frequency, indicated as ν_{EP}. It is apparent that, even though in some cases the perturbing effects are larger than the signal, they are always sufficiently separated in frequency to be distinguished from it.



the spacecraft attitude in low equatorial orbit around the Earth and fig. 6 its accommodation in the bay of the European launcher VEGA, largely funded by Italy and to be operational close to the Equator at the Kourou launch site of ESA (European Space Agency) .

In the most recent study TAS-I has developed an end-to-end simulator of the GG space experiment in order to verify that – with the established design and mission requirements – it can achieve its goal of testing the Equivalence Principle to 10^{-17}. The error budget so obtained is reported in a graphical representation in fig. 7 and discussed in the caption.

The GG accelerometer, *i.e.* the core instrument located at the center of the spacecraft (see fig. 4), can be realized in the lab in a 1-g version by using the spin/symmetry axis for suspending it against local gravity. This is the GGG (GG on the Ground) prototype with two test cylinders 10 kg each as in space, the same number of degrees of freedom and the same capacitance read-out as in space. GGG is shown in fig. 8.

The major differences (disadvantages) compared to space are: i) motor and bearings (not needed in space); ii) seismic vibration noise from the terrain; iii) stiffer suspensions (because of 1-g), hence lower sensitivity. The advantage is obviously easy access to the apparatus.

The output of a 25 days continuous run of the GGG accelerometer spinning at 0.167 Hz is reported in fig. 9, where the relative displacements of the GGG test cylinders in 2 orthogonal directions of the non-rotating horizontal plane of the lab are plotted (in m) as a function of time. The amplitude of the displacements remains between 0.2 and 0.4 μm for the entire 25 days of the run except for a

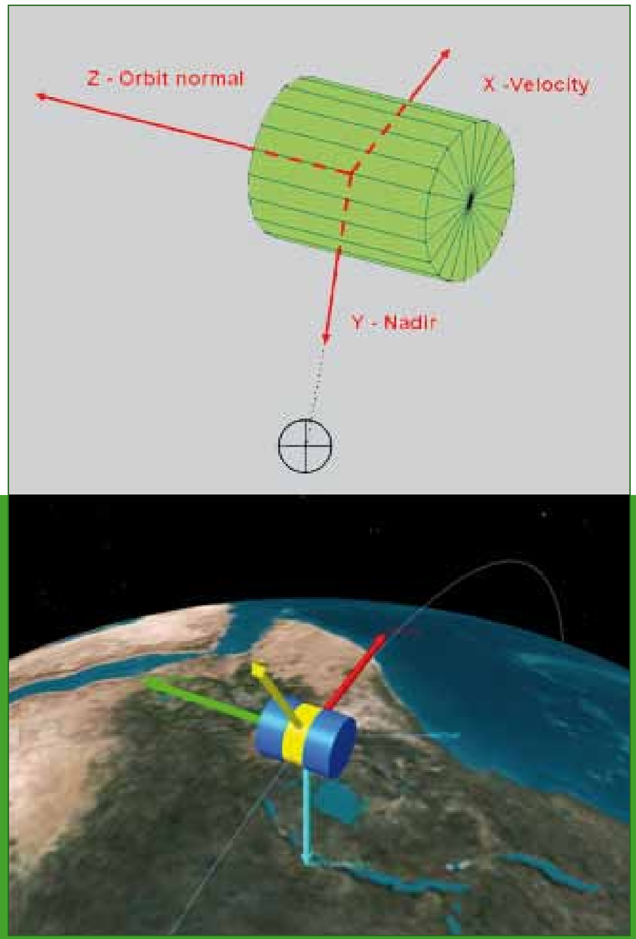


Fig. 5 Sketch of the GG satellite in its low-altitude equatorial orbit around the Earth (the green arrow shows the spin/symmetry axis.

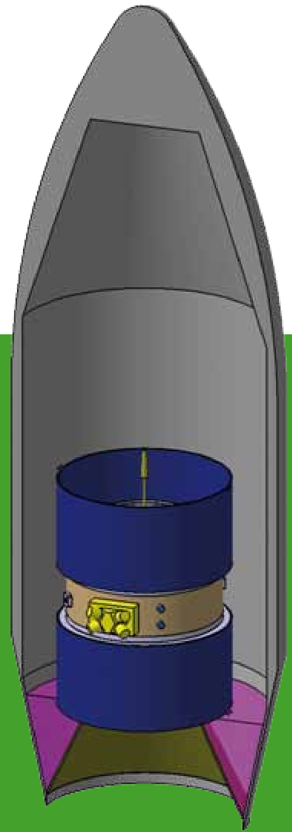
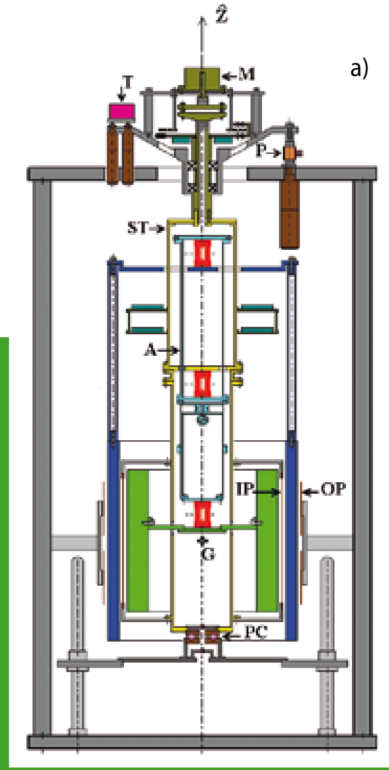


Fig. 6 Sketch of the GG spacecraft accommodated inside the bay of the VEGA launcher.

a)



b)

Fig. 8 a) Sketch of the GGG prototype accelerometer (which is located inside the vacuum chamber shown in b)), with the blue and green concentric test cylinders (10 kg each as in space). The direction of local gravity makes the instrument not as symmetric as in space, nevertheless preserving its main dynamical features and operation.
b) The vacuum chamber enclosing the GGG accelerometer (thermally stabilized and wrapped with Mylar).

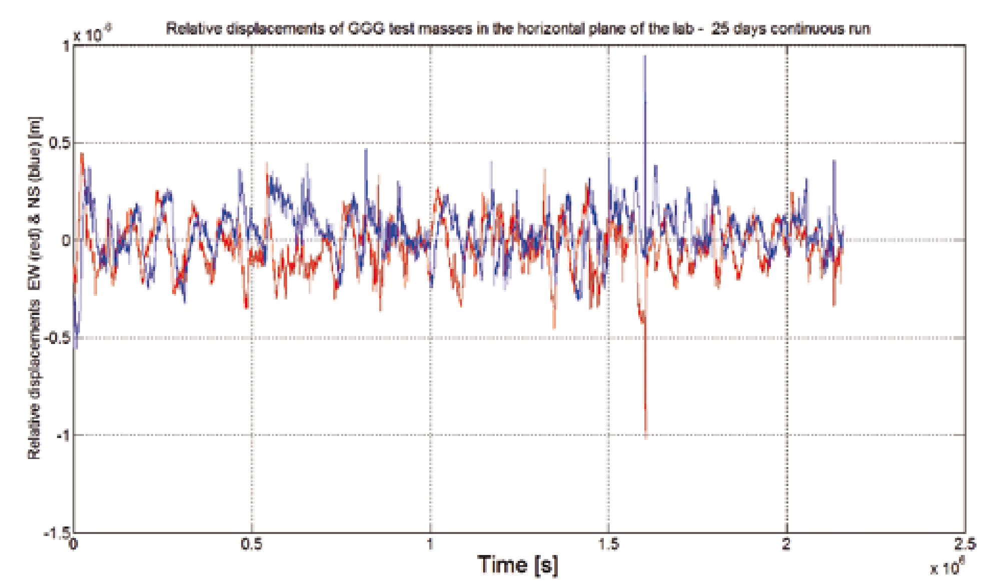


Fig. 9 Relative displacements of the GGG test cylinders in the East-West (EW) and North-South (NS) directions of the horizontal plane of the lab as a function of time during a 25 days continuous run. A single isolated jump occurs; other than that, the amplitude of the displacements is of $2x10^{-7}$ to $4x10^{-7}$ m (the diurnal pattern is apparent).

very sharp jump which may be attributed to an electric/electronic failure since the rotor has immediately resumed normal operation. The FFT of this signal is reported in fig. 10. It shows that, at the frequency of the EP violation signal in space (namely, the orbital frequency of $1.75x10^{-4}$ Hz of the GG satellite around the Earth) the GGG prototype has reached a sensitivity of a few nanometers to be compared with the sensitivity of about a picometer to be achieved in GG (see fig. 7). Since the limitation to the current sensitivity of GGG comes from low-frequency terrain tilts – in spite of active tilt control currently in operation – an appropriate cardanic suspension (not rotating) has been designed for low-frequency passive tilt reduction. The newly designed suspended GGG accelerometer is under completion.

Acknowledgements

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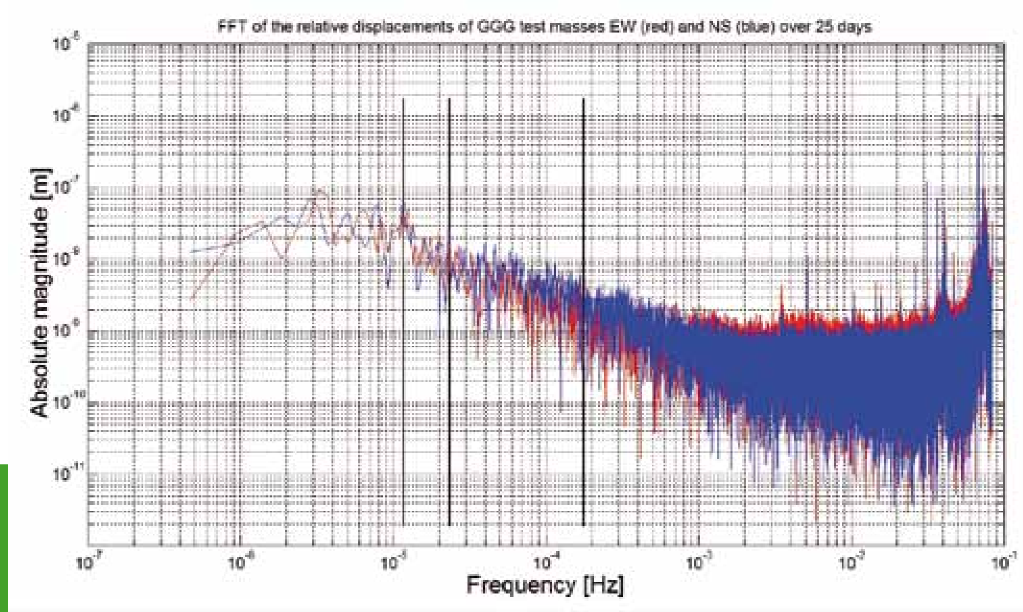

Fig. 10 Fast Fourier Transform of the relative displacements of the GGG test masses whose time variation in the EW and NS directions of the horizontal plane was shown in fig. 9. The 3 vertical black lines indicate (from left to right) the frequencies corresponding to 24 h, 12 h and to the orbital frequency of the GG satellite around the Earth at which an EP violation signal in the gravitational field of the Earth would appear ($1.75x10^{-4}$ Hz). At the latter frequency the GGG sensitivity is of a few nanometers (limited by terrain tilts) while GG should reach the picometer level. A passive cardanic suspension has been designed to reduce low-frequency terrain tilts in GGG in order to demonstrate the capability to achieve a sensitivity close to that required by GG in space for it to fulfill its mission goal of testing the equivalence principle to 10^{-17}.

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