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GReAT (General Relativity Accuracy Test): a free fall test of Weak Equivalence Principle from stratospheric balloon altitude

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Abstract. GReAT (General Relativity Accuracy Test) is a free fall experiment from stratospheric balloon altitude to test the Weak Equivalence Principle (WEP) with an accuracy of $5 \cdot 10^{-15}$. The key components of the experiments are a very high accuracy (sensitivity close to 10^{-14} g/$\sqrt{Hz}$ in a 25-s integration time) differential acceleration detector to detect a possible violation of the WEP and the facility necessary to perform the experiment. The detector will be released to free fall inside an evacuated capsule (Einstein elevator) which has been previously dropped from a stratospheric balloon, and will be slowly rotated about a horizontal axis to modulate the gravity signal and then released inside the capsule, immediately after the capsule's release from the balloon. In this paper, we report the progress in the development of the differential accelerometer that must be able to test the WEP with the declared accuracy. Following a brief description of the overall experiment, we present experimental results obtained with a differential accelerometer prototype, in particular the ability of the sensor to reject common–mode noise components. Finally, we present a new configuration of the differential accelerometer which is less sensitive to higher–order mass moments generated by nearby masses.

Key words. Equivalence Principle – Differential accelerometer

1. Introduction

The Principle of Equivalence is at the very basis of currently accepted theories of gravitation. This particular position among the hypotheses on the machinery of the physical world makes its verification particularly important and justifies the current improvement attempts. Along the years, different kinds of Equivalence Principle were formulated (see Will 2006). The basic one states that the *in-*

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ertial mass (or simply *mass*) is proportional to the *gravitational mass* (or *weight*): it is called **Weak Equivalence Principle** (**WEP**). Another way of stating it is that the trajectory of a test body (i.e. one sufficiently small to neglect tidal effects and not acted upon by other interactions such as electromagnetism) is independent of its internal structure and composition. This means that two different bodies, put in the same gravitational field, will fall the same way: this fact is known as **Universality of Free Fall** (**UFF**). This type of test is in line of principle very simple and was the subject of studies by Galileo Galilei.

The independence of a gravitational trajectory from the particular body being considered opens the way to a geometric view of (curved) space–time. The Einstein's Theory of General Relativity, indeed, is based on a stronger statement, the so–called **Einstein Equivalence Principle** (**EEP**), which includes WEP and introduces further hypotheses. Therefore a noteworthy part of our current knowledge of physical world is based on the WEP, and it is of primary importance to test whether (and at what scale) it could break.

In the last decades several experiments were set–up to test the validity of WEP (for a review see Will (2006)). Apart from Lunar Laser Ranging (LLR) and free fall experiments, the majority of them were performed on–ground, where several sources of noise (among of them seismic noise) ultimately limit their accuracy. For this reason the environment offered by space is suitable for consistent improvements; at least three space experiments — MICROSCOPE, STEP, GG — are under development.

Of course space experiments are very costly and need a rather long time to be developed. The GReAT experiment described in this article has the advantage of combining the relative low–noise environment given by free fall with repeatability, resulting in a competitive performance with respect to other ongoing projects. It aims at reaching an accuracy of five parts in 10^{15} by measuring the differential accelerations acting on two masses free–falling inside a capsule dropped from a balloon at high altitude. In Figure 1 the improvement provided by GReAT (two orders of magnitude) is shown in terms of the Eötvös ratio η, while in Table 1 its performances are compared with those of ongoing space experiments.

In the following a description of the experiment is given, focusing on its various parts. Particular care is taken on the formulation of the error budget. Finally, a current status snapshot is provided.

2. General description

The GReAT experiment (Iafolla et al. 1998, 2000; Lorenzini et al. 2000) aims to test the WEP to a few parts in 10^{15} by releasing in free fall a very sensitive differential accelerometer inside a co–moving capsule. The capsule is already free–falling after having been dropped from a balloon at an altitude $\geq$ 40 km. This experiment will involve the precise measurement of differential accelerations between two masses made of different materials which are the proof–masses of a high–sensitivity differential accelerometer (i.e., the detector). The detector is housed inside an instrument package that will be slowly spun (e.g., at 0.5 Hz), before release inside the capsule, about an horizontal axis to modulate the differential acceleration signal, due to a WEP violation. The experiment, with an estimated accuracy of five parts in 10^{15}, at 95 % confidence level, will improve the accuracy in validating the WEP by about two orders of magnitude with respect to the most accurate tests conducted thus far.

The capsule (see Fig. 2), with external dimensions of about 5 m in length and 1.5 m in diameter, is slightly decelerated by the rarefied atmosphere during the fall and, consequently, it moves slowly upward with respect to the detector that is in *real* free fall. The capsule contains an evacuated cryostat with inner dimensions of about 2 m length and 1 m diameter in which the instrument package free falls. In the up to 28 s interval in which the detector spans the internal length of the cryostat, the capsule falls by less than 4 km and reaches a maximum Mach number of 0.8. At the end of the fall, the capsule is decelerated by a parachute for retrieval and subsequent re–flights.

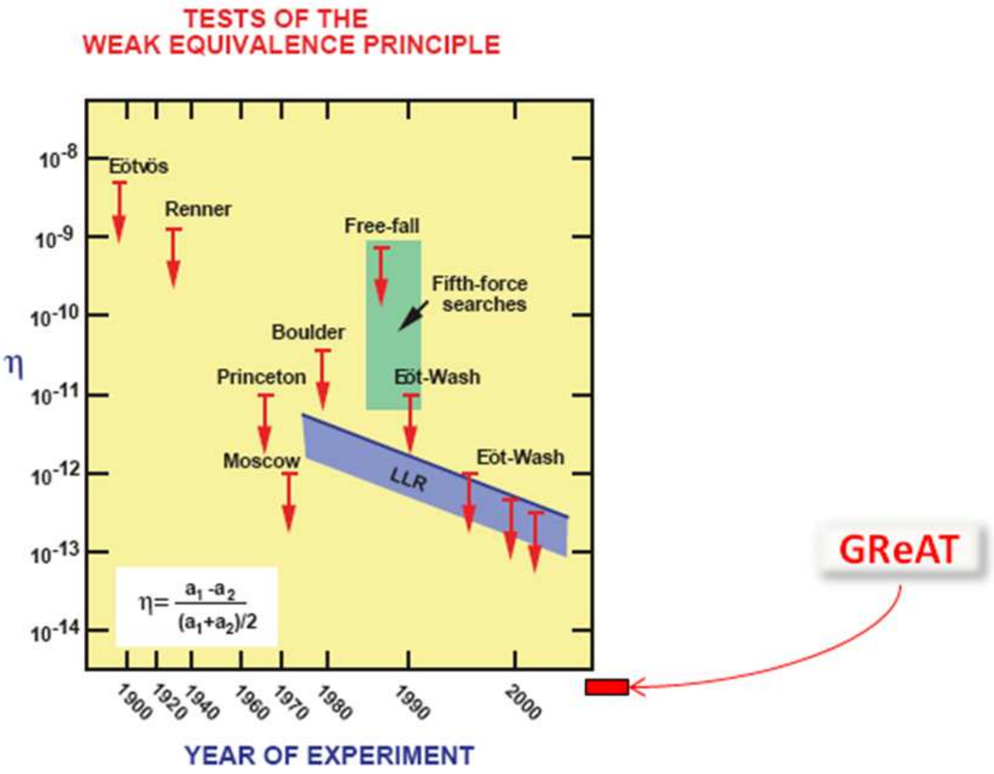

Fig. 1. Tests of WEP in terms of Eötvös ratio η (from Will (2006), modified).

Table 1. Comparison of GReAT performances with these of ongoing space experiments.

Name	Accuracy	Type	Funding institution(s)
STEP	10^{-18}	(drag-free satellite)	NASA
GG	10^{-17}	(drag-free satellite)	INFN/ASI
MicroScope	10^{-15}	(drag-free satellite)	CNES/ESA
GReAT	$5 \cdot 10^{-15}$	(drag-shielded capsule)	ASI/NASA

Cryogenic refrigeration is provided by the cryostat to obtain low Brownian noise, high thermal stability, low thermal gradients, and a high Q–factor of the acceleration detector. These are necessary conditions to achieve the desired measurement accuracy. The overall mass of the capsule is 1500 kg as a baseline; this mass is a fairly standard load for high–altitude balloons. Heavier capsules will provide a little longer free fall times with the same internal dimensions.

Our detector will be a differential accelerometer with a noise spectral density of about 10^{-14} g/$\sqrt{Hz}$. The detector will measure the differential acceleration between two sensing masses of different materials by measuring the variation of the capacitance between these masses when they move differentially under the influence of an external acceleration (e.g., owing to a violation of the WEP). The detector is based on the experimental heritage of high–accuracy acceleration detectors developed in the last twenty years at IFSI. Its further development requires technology within the current state–of–the–art.

3. Description of the experimental apparatus

The elements of the experimental apparatus are as follows:

1. Helium–filled balloon
2. Gondola attached to the balloon with the mechanism to keep the capsule aligned along the vertical and release it together with other house–keeping equipment
3. Shielding capsule (see Figure 2)
4. Liquid–helium, evacuated cryostat
5. Instrument package which houses the detector inside a high–vacuum chamber
6. Spin/release mechanism for spinning the instrument package and releasing it into the capsule
7. Differential acceleration detector
8. Two video cameras for recording the motion of the instrument package inside the capsule
9. Telemetry system for the down link from the capsule to the ground
10. Transonic parachute for decelerating the capsule at the end of the fall.

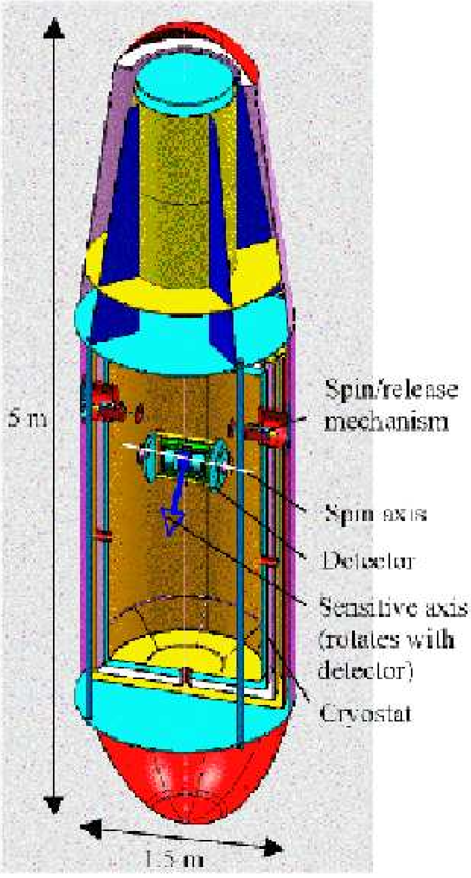

Fig. 2. Sketch of capsule during free fall.

4. Experiment Sequence

Upon reaching the balloon floating altitude of ≥ 40 km and checking the equipment status, the capsule is first released from the balloon; the instrument package, that is slowly spinning about its longitudinal (horizontal) axis, is released from the top of the capsule immediately thereafter. While falling towards the Earth (see Figure 2) from an altitude of 40 km, the capsule will be slightly decelerated by the rarefied atmosphere and the free–falling experimental package will take 28 s to reach the bottom of a 2 m–long cryostat (Fuligni & Iafolla 1992; Lorenzini 1991) with a (baseline) capsule mass of 1500 kg. Figure 3 shows the distance of fall (m) of the instrument package relative to the drag–decelerated capsule, the Mach number and the capsule drop (km) vs. time. The Mach number of the capsule is 0.8 (velocity ≈ 270 m/s) after 28 s of fall. The capsule falls by about 4 km in these 28 s. After the instrument package has reached the capsule's floor, the capsule is decelerated by a parachute for retrieval and reflight. Supersonic parachutes which can operate to Mach numbers as high as 2 are available off–the–shelf (e.g., Irvin Company) and they have already been used successfully in 1996 to decelerate (at Mach = 0.8) an experimental re–entry cap-

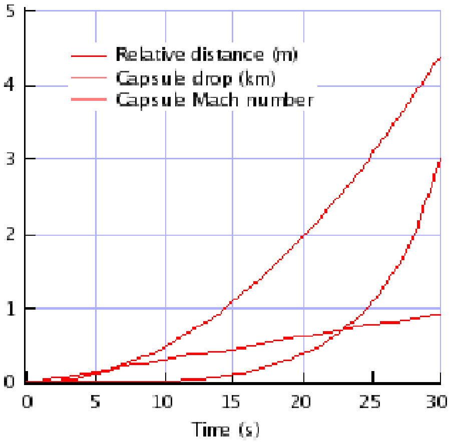

Fig. 3. Acceleration noise inside capsule.

sule (the ARC project) dropped from a balloon launched by the Trapani (Sicily) balloon base.

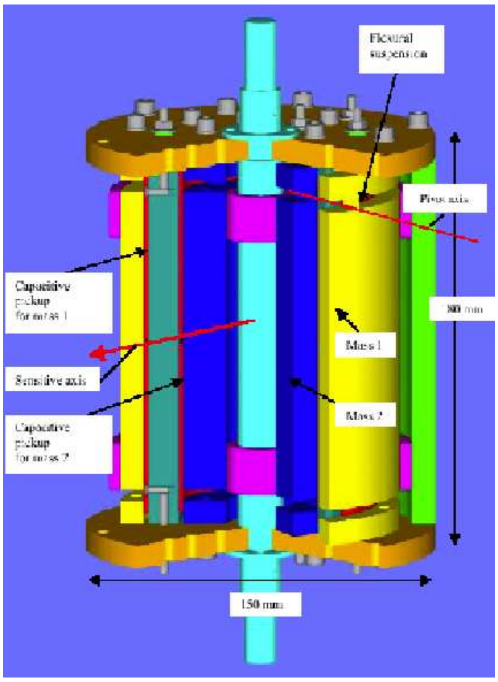

Fig. 4. Outline of differential accelerometer prototype built by IFSI-INAF.

5. Differential Acceleration Detector

The differential acceleration detector (see Figure 4) measures the differential capacitance, and consequently the relative displacement along the sensitive axis x, between two double–faced capacitors: capacitor probe 1 is formed by sensing mass 1 and fixed plates As and A’s; capacitor probe 2 is formed by sensing mass 2 and fixed plates Bs and B’s. The displacement of sensing mass 1, for example, is detected by the series capacitors A and A’ which forms one branch of a capacitive bridge while two additional reference capacitors form the other branch. The bridge is pumped by a quartz oscillator at a stable frequency of about 20 kHz in order to reduce the relevant noise temperature of the preamplifier (Bordoni et al. 1981). The difference between the output signals from the capacitive probes 1 and 2 is amplified by a low–noise preamplifier, sent to a lock–in amplifier for phase–detection and eventually to a low–pass filter. There are also two more sets of fixed plates for each sensing mass that are used for feedback control.

Figure 4 shows the configuration of one of the differential detector prototypes built by IFSI-INAF. The final design of the differential acceleration detector for the flight tests will capitalize on the experience gained in the laboratory from the various prototypes and numerical simulations carried out by our partners at the Harvard-Smithsonian Center for Astrophysics (CfA). The two sensing masses in Figure 4 consist of solid hollow right cylinders with spherical ellipsoids of inertia so as to cancel the 2nd–order gravity–gradient torques (quadrupole moments). The design of the proposed capacitive detector can accommodate a variety of sensing masses with different dimensions and materials. The differential detector must be designed as much as possible in a way that allows modifications from one flight to the next based on the lessons learned from the previous flight experience (much the same way as the adjustments made on instruments under development in a laboratory). Moreover, the centers of mass (CM) of the sensing masses are as close as technically possible to one another to minimize the effect of gravity–gradient forces, rotational motion, and

Table 2. Current error budget for the PE test.

Noise Source	Max. differential acceleration	Frequency content
Brownian noise	1×10^{-14} g/ $\sqrt{Hz}$	white
Amplifier noise	4×10^{-15} g/ $\sqrt{Hz}$	white
Capsule's vibrations	10^{-17} g/ $\sqrt{Hz}$	white
Drag in capsule	6×10^{-17} g	$1/t_{fall}$
Proof–masses magnetic disturbances	$< 10^{-17}$ g	f_S
Radiometer effect	2×10^{-16} g	f_S
Earth's gravity gradient torques	10^{-16} g 10^{-12} g	f_S $2f_S$
Higher–order gravitational coupling to capsule mass	$< 10^{-16}$ g	$f_S, 2f_S, 3f_S, \ldots$
Others	$< 10^{-17}$ g	various
Error sum (rms), t_{int} = 20 s	2.4×10^{-15} g	f_S

Symbols: t_{fall} = free–fall time, t_{int} = integration time, f_S = signal frequency

linear accelerations upon the differential output signal. The two sensing masses are made of different materials. IFSI has already built a (zero–violation–signal) differential detector with sensing masses of the same material (e.g., aluminum-aluminum), as part of the instrument technological development. This prototype could be flown in a test balloon flight to characterize the noise environment during free fall.

The two sensing masses are constrained by torsion springs to rotate about a common axis and their resonant frequencies are electrostatically controlled for frequency matching. On the one hand, the lower the resonant frequency the more sensitive the detector and the smaller the dynamic range. On the other hand, the higher the resonant frequency, the larger the dynamic range and the shorter the time constant of the transient oscillations. The value of the resonant frequency stems from a trade–off between sensitivity on one side and fast transient response and large dynamic range (and also tolerance of centrifugal forces) on the other side. A value of the resonant frequency in between 2-5 Hz strikes a balance between the above competing requirements. Once the instrument is built with a specific mechanical resonant frequency, this frequency can be lowered by supplying a constant voltage to the feedback capacitor fixed plates. All the other modal frequencies of the instrument are at least two orders of magnitude higher than the controlled torsional frequency. This wide frequency separation allows most of the signal energy to excite the degree of freedom of interest. The sensing masses of this detector are not subjected to electrostatic charging because they are grounded to the instrument's case through the torsional springs. A high Q–factor is obtained by means of liquid helium refrigeration and by eliminating dissipation sources, i.e., the torsion springs, the instrument's case and the capacitor moving plates are integrally machined from the same block of material.

6. Experiment Error Budget

Error sources are internal and external to the detector. The most important internal sources are: (1) amplifier noise; (2) thermal noise (Braginsky & Manukin 1974; Giffard 1976); and (3) viscous drag due to residual gas inside the capacitors (Worden et al. 1990). The most important external noise sources are: (1) the Earth's gravity gradient force and torque; (2) the Earth's magnetic field interaction with the ferrous impurities in the sensing masses;

and similarly (3) paramagnetism of the proof–masses coupled to the magnetic moment of the capsule–fixed electrical equipment.

The proposed experimental technique is such that the hypothetical WEP violation signal has either a frequency well separated from narrow–band noise sources or a strength much larger than the broad–band noise sources. Table 2 provides a summary of the most important noise sources and their frequency content for an instrument with a quality factor $Q > 10^5$. Our error analysis shows that a proposed detector that meets the characteristics specified here will be capable to carry out a test of the Equivalence Principle with an accuracy of 5 parts in 10^{15}, with 95% confidence level, in a 20 s integration time.

7. Conclusion

Among the ongoing experiments to test the WEP, GReAT offers an improvement in accuracy with respect to current limits on Eötvös ratio η with moderate cost and has the advantage of reusability. Its development is based on a well–established expertise on acceleration sensors and an overall design studied conceived for a strong isolation of detector with respect to all the main sources of noise. The experimental activity and the simulations performed so far show that an hypothetical WEP–violating signal greater than the accuracy level could be neatly distinguished. From the technological point of view, the implementation of the support facility for GReAT will represent a new platform for micro– and pico–gravity experiments.

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