GGG

A rapidly rotating differential accelerometer as a prototype of the GG experiment in space

Anna Nobili - INFN, Pisa July 2013

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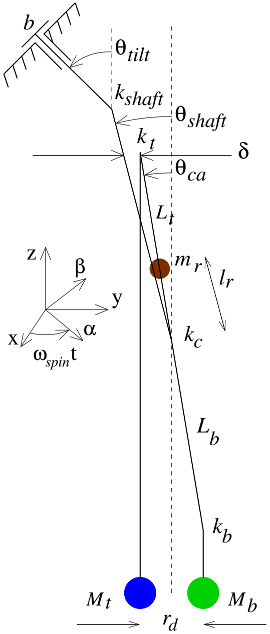
GGG: a rapidly rotating differential accelerometer sensitive in 2D (I)



- **Best GGG measured sensitivity as prototype of GG experiment in space (@ $1.7 \cdot 10^{-4}$ Hz):**

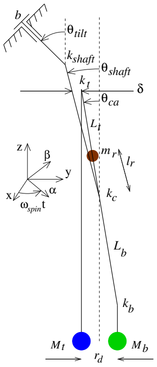
  $$\eta_{GGG@1.7\cdot10^{-4}\mathrm{Hz}} \simeq \frac{7\cdot10^{-11}\,\mathrm{m/s^2}}{8\,\mathrm{m/s^2}} \simeq 8.9\cdot10^{-12}$$

  In space:
  i) sensitivity 3 orders of magnitude better (absence of weight allows weaker coupling)
  ii) no motor & no ball bearings needed, no rotation noise
  iii) lab (i.e. spacecraft) isolated, no terrain tilt noise
  Low noise read-out needed: Laser Interferometry Gauge from JPL (1 pm @ 1 Hz)

  Nobili et al.: "Galileo Galilei" (GG): space test of the weak equivalence principle and laboratory demonstrations, ***Paper invited for the Class. Quantum Grav. Focus Issue on the Weak Equivalence Principle, 2012***

- **Unique to GG/GGG**: 2 degrees of freedom sensor allows rotation above resonance and signal up-conversion (with no attenuation!!!) to much higher frequency where thermal and electronic noise are much lower (far more effective than cryogenics..)
  Pegna, Nobili et al: Abatement of thermal noise due to internal damping in 2D oscillators with rapidly rotating test masses, ***Phys. Rev. Lett., 2011***

GGG: a rapidly rotating differential accelerometer sensitive in 2D (II)



- **GGG best measured sensitivity to a violation of the weak equivalence principle in the field of the Sun (diurnal frequency):**

$$\eta_{GGG@1.16\cdot10^{-5}\mathrm{Hz-Sun}} \simeq \frac{3.4\cdot10^{-10}\,\mathrm{m/s^2}}{a_{Sun-Pisa}} \simeq \frac{3.4\cdot10^{-10}\,\mathrm{m/s^2}}{0.0057\,\mathrm{m/s^2}} \simeq 6\cdot10^{-8}$$

Best result with slowly rotating torsion balances:

$\eta_{TB-Sun} \lesssim 10^{-12}$ (PRL 1999)
$\eta_{TB-Earth} \simeq 10^{-13}$ (PRL 2008)

Torsion balances much more sensitive than GGG prototype on ground, but not suitable for space where GG can improve their best result by 4 orders of magnitude: $\eta_{GGtarget-Earth} \simeq 10^{-17}$

GGG differential accelerometer competitive with:

- Cold atoms dropping test (Fray et al., PRL 2004): $\eta_{ColdAtoms-Earth} \simeq 10^{-7}$ signal a factor $9.8\,m\,s^{-2}/(0.0057\,m\,s^{-2}) \simeq 1700$ stronger than in GGG, hence apparatus $1700\cdot10^{-7}/6\cdot10^{-8} \simeq 2860$ times less sensitive than GGG to differential accelerations

- Cold atoms vs ordinary matter dropping test (Nature 1999):
$\eta_{ColdAtomsVsNormalMatter-Earth} \simeq 7\cdot10^{-9}$
apparatus $1700\cdot7\cdot10^{-9}/6\cdot10^{-8} \simeq 200$ times less sensitive than GGG to differential accelerations

- Ordinary matter dropping test GAL at CERN (Polacco et al. PRL 1992):
$\eta_{GAL-Earth} \simeq 7.2\cdot10^{-10}$
apparatus $1700\cdot7.2\cdot10^{-10}/6\cdot10^{-8} \simeq 21$ times less sensitive than GGG to differential accelerations

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WEP tests vs measurements of the gravitational redshift

On the universality of free fall, the equivalence principle, and the gravitational redshift

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Through the contributions of Galileo, Newton, and Einstein, we recall the universality of free fall (UFF), the weak equivalence principle (WEP), and the strong equivalence principle (SEP), in order to stress that general relativity requires all test masses to be equally accelerated in a gravitational field; that is, it requires UFF and WEP to hold. The possibility of testing this crucial fact with null, highly sensitive experiments makes these the most powerful tests of the theory. Following Schiff, we derive the gravitational redshift from the WEP and special relativity and show that, as long as clocks are affected by a gravitating body like normal matter, measurement of the redshift is a test of UFF/WEP but cannot compete with direct null tests. A new measurement of the gravitational redshift based on free-falling cold atoms and an absolute gravimeter is not competitive either. Finally, we compare UFF/WEP experiments using macroscopic masses as test bodies in one case and cold atoms in the other. We conclude that there is no difference in the nature of the test and that the merit of any such experiment rests on the accuracy it can achieve and on the physical differences between the elements it can test, macroscopic proof masses being superior in both respects.
[http://dx.doi.org/10.1119/1.4798583]

I. INTRODUCTION

The universality of free fall (UFF)—that the acceleration imparted to a body by a gravitational field is independent of the nature of the body—was established by Galileo and Newton as an experimental fact, within the limits of the experiments of their time. If it holds, inertial and gravitational mass are equivalent; this is the weak equivalence principle (WEP). Newton made this "principle of equivalence" the basis of classical mechanics. More than two hundred years later, Einstein extended it to the invariance of physical laws in non-rotating laboratories freely falling in a uniform gravitational field, making it the foundation of his theory of general relativity (GR).

Because UFF is an experimental fact, it can be disproved by experiment. For Einstein, the clever torsion balance experiments carried out by Eötvös in Hungary at the turn of the 20th century[1] were proof enough. And there the matter stood for about fifty years. Experiments testing general relativity and its foundation, the UFF, were few and required measuring tiny effects to excruciating precision. General relativity came to be regarded as a theory that was beautiful but uninteresting to experimental physicists. Things began to change in the late 1950s, at the dawn of the space age, when physicists realized that the means to test GR were becoming available in the laboratory and, even more promising, in space.

In 1958, a few months after the launch of the first artificial satellite by the Soviet Union, a committee appointed by U.S. President Eisenhower—whose advice led to the establishment of NASA the same year—wrote a famous pamphlet[2] in which physics was first in the list of scientific objectives soon to be addressed in space. They proposed a space experiment to measure the gravitational redshift, which they regarded as a crucial test of GR (Ref. 2, p. 7): "Physicists are anxious to run one crucial and fairly simple gravity experiment as soon as possible. This experiment will test an important prediction made by Einstein's general theory of relativity, namely that a

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"On the universality of free fall, the equivalence principle, and the gravitational redshift", Nobili et al.
American Journal of Physics, July 2013

- Universality of Free Fall (UFF) / Weak Equivalence Principle (WEP) confirmed as the crucial experimental facts on which Einstein founded the General Theory of Relativity (UFF/WEP violation would imply the breakdown of GR **or** the existence of a new force of nature)
- Why UFF/WEP tests are by far superior to measurements of the gravitational redshift in probing General Relativity (null high precision tests vs absolute measurements of low precision and accuracy and troublesome interpretation; second order measurements of the gravitational redshift still beyond reach..)
- Tests of UFF/WEP with cold atoms and atom interferometry cannot compete with UFF/WEP null tests using macroscopic test masses. Even a new high precision and accuracy measurement of the gravitational redshift based on free-falling cold atoms and an absolute gravimeter (Mueller et al., Nature 2010; contested by others ...) is not competitive with UFF/WEP tests

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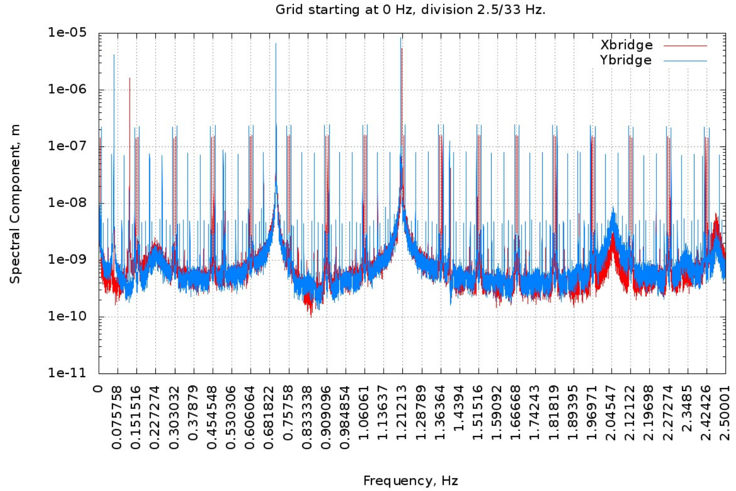
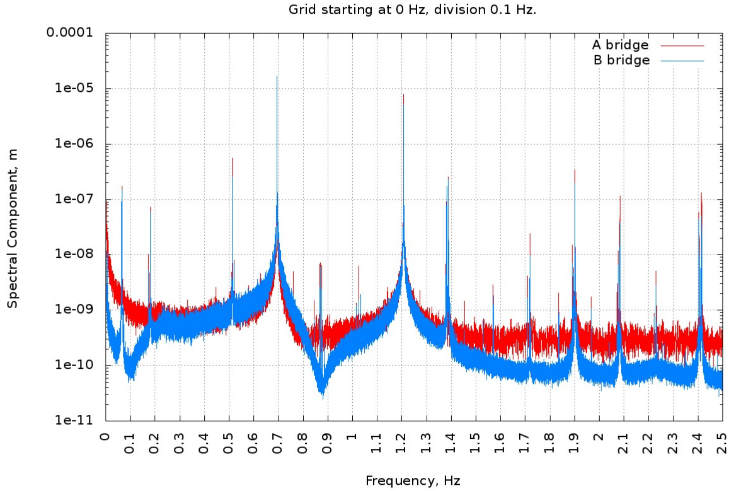
GGG recent improvements (I)

New electronics of the rotating capacitance bridges which read the relative displacements of the test masses in 2 orthogonal directions of the horizontal plane has eliminated spike-like noise with no need for a damper (proved to be artifact noise)

Relative displacements of the TMs measured by the capacitance bridges at zero spin. **Past:**

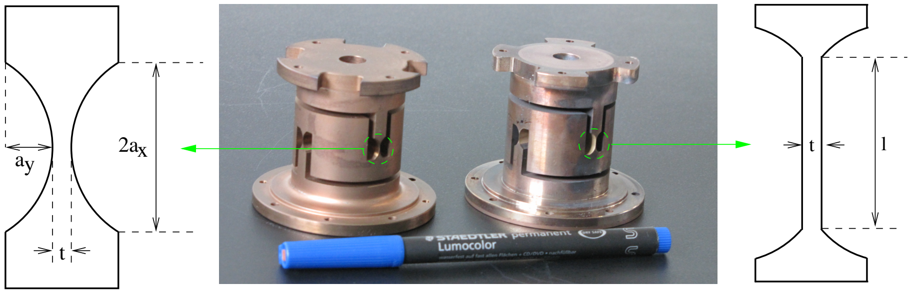


Relative displacements of the TMs measured by the capacitance bridges at zero spin. **Present:**



GGG recent improvements (II)

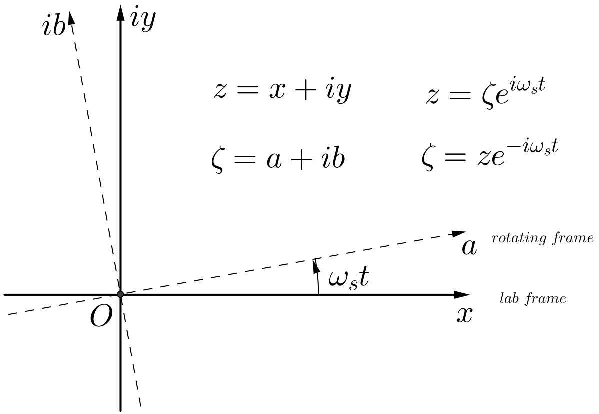
Suspensions damaged by earthquake in 2012.
New suspension with strip (right) rather than elliptic (left) flexure design:



Stiffness measured in the lab, improvement by factor 5 to 10 w.r.t. old design. For the central joint (the most relevant for the differential coupling of the test masses) values for the two directions are much closer to each other. If not, the stiffer dominates resulting in lower sensitivity, & more complex dynamics *(T.R. Saravanan, PhD thesis, 2013)*
Passive rotating 2D joint ensures good attenuation of low frequency tilt noise.

GGG recent improvements (III)

Sign of spin angular velocity $+\omega_s$ known $\Rightarrow$ the (low frequency) "signal" read by the rotating capacitance bridges must be close to $-\omega_s$: **a 2D read-out with the same noise level allows a complex FFT which separates the $+\omega_s$ and $-\omega_s$ lines eliminating half the noise, i.e. factor 2 gain in sensitivity**



.. and if bearings noise dominates it will appear close to $-\omega_s$ line and not to $+\omega_s$ line $\Rightarrow$ bearings noise can be identified and measured unambiguously...

GGG presently dominated by ball bearings noise (not by tilt noise): ceramic bearings deteriorated after long runs, need to be replaced (other groups use more expensive ad hoc air bearings; bearings not needed in GG..)

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- Replace ball bearings in order to exploit passive tilt attenuation provided by 2D rotating joint already implemented and reach the level of read-out electronics noise
- Complete ESA science team document concerning a space test of the WEP on the space station with cold atoms and atoms interferometry
- Complete ongoing discussion with PRD referees on manuscript *Integration time in space experiments to test the equivalence principle*
- ESA has responded positively to the proposal for a Laser Interferometry Gauge (LIG) submitted in collaboration with Guido Zavattini and external support from Mike Shao (JPL). The proposal concerns the study, design and implementation of a laser gauge interferometry on the low noise GGG accelerometer. Discussion on various aspects of proposal and contract due to start at ESA/ESTEC in September. Requires lab to be preserved (INFN, also through ASI, for property of instrumentation University of Pisa for property of the terrain and current infrastructure management.)
- INFN involvement in GG/GGG research to be maintained through "fondi di dotazione", particularly in the coming year until ESA contract is finalized and enforced.