Testing the weak equivalence principle with macroscopic proof masses on ground and in space

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What is special about WEP/UFF?

The "Equivalence Principle" is at the basis of Newtonian gravity

$$m_i\vec{g} = -\frac{GM_\oplus m_g}{r^3}\vec{r} \qquad \left(\frac{m_i}{m_g} = +1 \quad \Rightarrow \vec{g} = -\frac{GM_\oplus}{r^3}\vec{r}\right)$$

"This quantity that I mean hereafter under the name of … mass … is known by the weight … for it is proportional to the weight ***as I have found by experiments on pendulums, very accurately made…*** *"*

Newton, opening paragraph of the Principia, 1687

Newtonian gravity is founded on the **experimental fact** that inertial and gravitational mass are the same.

This is the Equivalence Principle (EP) according to Newton, and so was until Einstein revisited and extended it in 1907-1916. After that, it is known as the Weak Equivalence Principle (WEP), whereby in a gravitational field all bodies fall with the same acceleration – known as the Universality of Free Fall (UFF)

Einstein 1907: "The happiest thought of my life"

"When, in the year 1907, I was working on a summary essay concerning the special theory of relativity for the Jahrbuch fuer Radioaktivitaet und Elektronik, I had to try to modify Newton's theory of gravitation in such a way that it would fit into the theory. Attempts in this direction showed the possibility of carrying out this enterprise, but they did not satisfy me because they had to be supported by hypotheses without physical basis.

At that point, there came to me ***the happiest thought of my life****, in the following form:*

Just as is the case with the electric field produced by electromagnetic induction, the gravitational field has similarly only a relative existence. *For if one considers an observer in free fall, e.g. from the roof of a house, there exists for him during his fall no gravitational field – at least in his immediate vicinity."*

Einstein 1919

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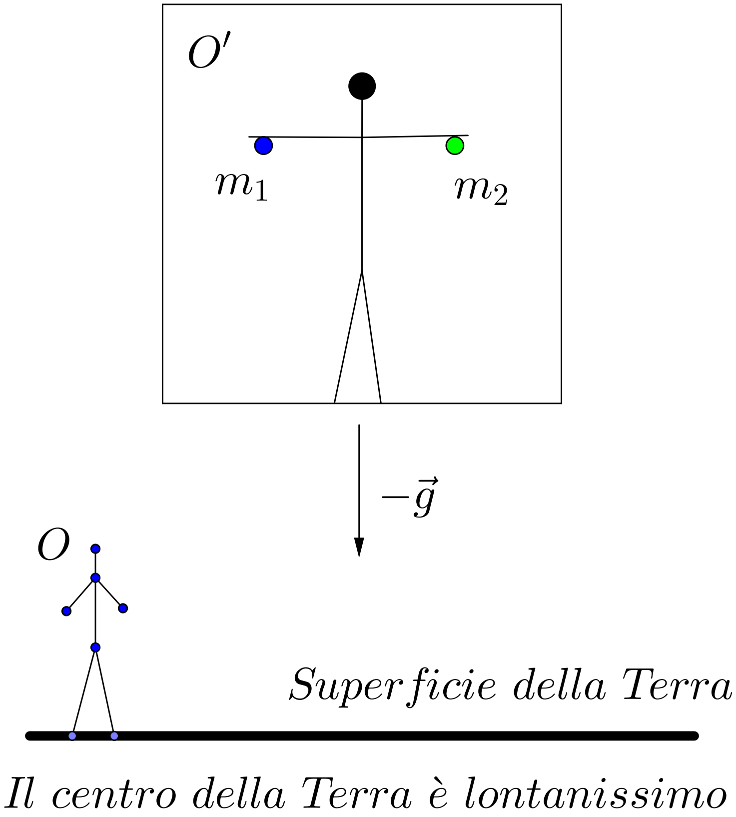
Einstein 1907: “The happiest thought of my life” (II)

“...The breakthrough came suddenly one day. I was sitting on a chair in my patent office in Bern. Suddenly a thought struck me: If a man falls freely, he would not feel his weight. I was taken aback. This simple thought experiment made a big impression on me. This led me to the theory of gravity.”

Einstein 1922



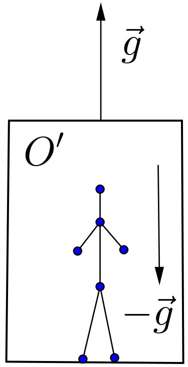
O feels his weight; O' does not

Einstein 1907: "The happiest thought of my life" (III)

"...I continued my thought: A falling man is accelerated. Then what he feels and judges is happening in the accelerated frame of reference. I decided to extend the theory of relativity to the reference frame with acceleration. I felt that in so doing I could solve the problem of gravity at the same time. **... It took me eight more years until I finally obtained the complete solution.**"

Einstein 1922

Il centro della Terra
è lontanissimo



Spazio vuoto

A gravitational field can be (locally) replaced by an accelerated frame!

The "Strong Equivalence Principle" (EEP)

"The strong equivalence principle might be defined as the assumption that in a freely falling, non-rotating, laboratory the local laws of physics take on some standard form, including a standard numerical content, independent of the position of the laboratory in space and time. It is of course implicit in this statement that the effects of gradients in the gravitational field strength are negligibly small, i.e. tidal interaction effects are negligible."

Dicke, 1964

Dicke adds:

"It is well known that this interpretation of the equivalence principle, plus the assumption of general covariance is most of what is needed to generate Einstein's general relativity."

GR is founded on WEP/UFF (I)

Einstein put WEP/UFF at the basis of General Relativity, was very much concerned about its experimental evidence, knew Eötvös and his experiments:

In *"The foundation of the General Theory of relativity"* (1916) § 2 *The need for an extension of the postulate of relativity*, Einstein wrote:

. . . This view is made possible for us by the teaching of experience as to the existence of a field of force, namely the gravitational field, which possesses the remarkable property of imparting the same acceleration to all bodies. Footnote: ***Eötvös has proved experimentally that the gravitational field has this property in great accuracy.***

This footnote was not added in the English translation; it is there in the original paper in German!

...but rumors have it that Einstein did not care about experimental tests and knew nothing about the torsion balance tests performed in the same years by Eötvös and collaborators, who improved Bessel's pendulum experiments by at least 3 orders of magnitude!!

In the Editorial of CQG 2012 Focus Issue devoted to WEP, by Will &. Speake, we read:

"Einstein took WEP for granted in his construction of general relativity, never once referring to the epochal experiments by Baron Eötvös".

GR is founded on WEP/UFF (II)

Should experiments at a very high level of sensitivity no longer support UFF/WEP:

- either GR is somehow amended to accomodate a fact which is in contradiction with its founding pillar
- or a new force of Nature is at play

UFF/WEP tests are small experiments which can lead to new physics

Why are WEP/UFF tests so sensitive?

WEP/UFF experiments can reach very high sensitivity because ...

- They are null experiments: The physical quantity to be measured is the differential acceleration Δa between test masses made of different material falling in the gravitational field of a source body with average acceleration a. No violation, no differential acceleration, $\eta = 0$ ($\eta = \Delta a/a$ is the dimensionless "Eotvos parameter") They are especially sensitive if performed as differential measurements, because the target violation signal is differential: not a good strategy to recover a very small physical quantity from the difference of two much larger ones

- They are NOT absolute measurements (like measuring G or the gravitational redshift): When making an absolute measurement the measured quantity must be compared with its theoretical prediction, hence requires knowledge/measurement of all physical parameters involved in the model, which is much harder...

Why UFF/WEP tests can be more accurate than measurements of gravitational redshift by many orders of magnitude?

$$\eta = \frac{\Delta a}{a}$$

If TMs are coupled the experiment measures Δa directly, hence η: no experiment signal, no violation (to the level of noise); the smaller the signal (or the noise), the better the test.

No prediction must be made to which the measured signal should be compared in order to obtain the physical quantity of interest!
... you must "only" beat random errors and carefully check systematics...

A measurement of gravitational redshift is an *absolute measurement.* The result of the GP-A mission is: (*Vessot et al., PRL 1980*):

$$\left(\frac{\Delta\nu}{\nu}\right)_{GP-A} = [1 + (2.5 \pm 70) \cdot 10^{-6}] \cdot \left(\frac{\varphi_s - \varphi_e}{c^2} - \frac{|\vec{v}_s - \vec{v}_e|^2}{c^2} - \frac{\vec{r}_{se} \cdot \vec{a}_e}{c^2}\right)$$

The measured frequency shift had to be compared with the sum of the 3 terms (gravitational potential difference, second order Doppler shift, residual of first order Doppler), whose values depend on various physical quantities, some of which to be measured during the experiment itself. It is only by comparing the theoretical prediction and the measured shift that the authors could establish the ratio $[1 + (2.5 \pm 70) \cdot 10^{-6}]$ for a measurement of gravitational redshift to 1st order.

It took 4 years to publish the results of an experiment that lasted only about 2 hours!

... more difficult as clocks improve; **measurement to 2nd order still out of reach**; experimental result very hard to interpret (especially for space measurements). What if a discrepancy is found? Would it question GR or call for a better physical model?

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

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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]

Nobili et al., AJP 2013

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Signal strength

Strength of driving signal for WEP experiments on ground and in Low Earth Orbit (in $m\,s^{-2}$)

	Earth's field		Sun's field	
	Ground	LEO	Ground	LEO
mass dropping (*Galileo – like tests*)	9.8 → (*factor 1.2 loss*)	$\simeq 8$	—	—
suspended masses (*regardless of the suspension type : mechanic, electrostatic, superconducting coils...*)	$\simeq 0.016$ → (*factor 2.8 loss* → Sun's field Ground)	$\simeq 8$ (***factor 500 gain!***)	$\simeq 0.0057$	$\simeq 0.0057$

- Best mass dropping test: $7 \cdot 10^{-10}$ *(Carusotto et al. PRL, 1992)*
- Best suspended masses test
  - in the field of the Earth: $\simeq 10^{-13}$ *(Schlamminger et al. PRL, 2008)*
  - in the field of the Sun: 10^{-12} *(Baeßler et al. PRL, 1999)*

- GG target in LEO: 10^{-17} (GG prototype is at: $8.9 \cdot 10^{-12}$ *Nobili et al., CQG 2012*)

Why have torsion balances defeated Galileo-like mass dropping tests?

Release errors in mass dropping tests

Any position difference (error) at initial time in the distance of the TMs to the source body perfectly mimics a violation (velocity errors also matter..):

$$\eta_{class} = 3\frac{\Delta h}{d}$$

True on ground as well as in space, whatever the test masses (macroscopic as well as cold atoms), whatever the time of fall...

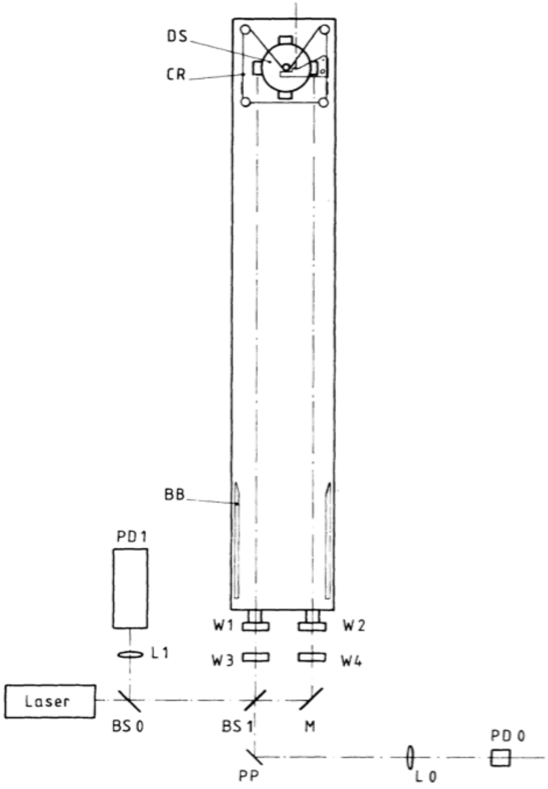
Blaser CQG 2001; Nobiili et al. GRG 2008

So far have wiped out the advantage of a very strong driving signal...

Release errors in the GAL mass dropping test (I)

GAL: a modern *differential* mass dropping experiment at CERN (*Carusotto, Polacco et al. PRL, 1992*)

- Clever idea + low noise laser interferometery read-out to try compete with torsion balance.
- If WEP/UFF holds a disk made of two halves of different material should not rotate.
- Rotation angle measured with modified Michelson interferometer
- The fringe frequency shift, proportional to disk angular acceleration, is the effect to be measured.



Release errors in the GAL mass dropping test (II)

Despite the clever set-up and very low noise laser interferometer read-out did, the torsion balance was far from being defeated!!

Homogeneous Al disk, 70 runs:

$$\frac{\Delta g}{g} = (3.2 \pm 9.5) \cdot 10^{-10}$$

Al-Cu disk, 63+65 drops (disk reversed):

$$\left(\frac{\Delta g}{g}\right)_{\mathrm{Al-Cu}} = (2.9 \pm 7.2) \cdot 10^{-10}$$

Carusotto, Polacco et al. PRL, 1992

SR-POEM: ground demonstration required...

Mass dropping experiment SR-POEM (Sounding Rocket - Principle Of Equivalence Measurement): aims at a few 10^{-17} using SAO very sensitive laser gauge (former POINTS); masses nominally concentric; 8 drops 120 s each, payload reversed between successive drops

Reasenberg et al., CQG 2012

A ground test of POEM is required to establish where it stands, what is limiting it and how much it could gain in a sounding rocket thanks to much longer duration drops

What's magic about the torsion balance?

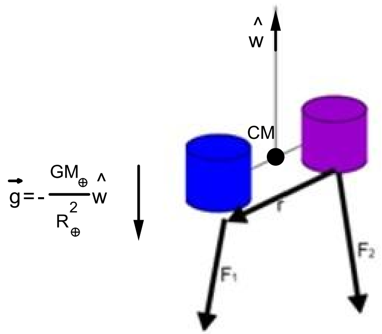
What's magic about the torsion balance (I)

Signal much weaker than in mass dropping, but..

- If fiber is thin, it has very low natural frequency. Torsional stiffness scales as the 4th power of the radius of the fiber (Eöt-Wash group balance 798 s period). TMs very weakly coupled ⇒ highly sensitive to differential effects

What's magic about the torsion balance (II)

- **On ground (not in space!)** the suspension fiber aligns itself with the local gravitational acceleration...



$\vec{F}_1$ and $\vec{F}_2$ are the forces acting on each mass. Their vectorial sum applied to the center of mass CM is balanced by the suspension fiber $\hat{w}$ which, on the ground, aligns itself with the direction of local gravity Only the component of the total torque along $\hat{w}$ does twist the wire. It is found to be:

$$T_w = \frac{\vec{r}\cdot\vec{F}_1\times\vec{F}_2}{|\vec{F}_1+\vec{F}_2|} \quad , \quad \vec{r}=\vec{r}_1-\vec{r}_2$$

- only forces not parallel to each other do twist the wire: which happens if inertial and gravitational mass are not the same for the two bodies under the attraction of the Earth and the centrifugal force due to its rotation...
- forces parallel to each other (of equal as well as different size) do not twist the wire!

What's magic about the torsion balance (III)

Violation signal from Earth DC, but..

- Choosing Sun as source (signal a factor 3 weaker than from Earth): Earth's rotation up-converts DC signal to diurnal frequency... "passive" rotation of the balance. **First exploited by Dicke: 3 orders of magnitude improvement w.r.t Eötvös; 1 more gained by Braginsky & Panov**
- If balance rotates on a turntable ($20'$ reached by Eöt-Wash group) signal from Earth modulated to higher frequency (+ effects of daily disturbances reduced) and signal from Sun modulated too. Small improvement in the field of the Sun; 4 orders of magnitude improvement in the field of the Earth (signal from Earth never modulated before...)

Torsion balance WEP/UFF tests: Improvements over the years

36 yr

14 yr

Authors	Apparatus	Source mass	Materials	$\eta \equiv \Delta a/a$
Eötvös et al. ≈1900 collected in Ann. Phys. **1922**	Torsion balance. Not rotating. No signal modulation	Earth	Many combinations	$10^{-8} \div 10^{-9}$
Roll, Krotkov & Dicke Ann. Phys. **1964**	Torsion balance. Not rotating. 24hr modulation by Earth rotation	Sun	Al – Au	$(1.3\pm1)\text{x}10^{-11}$
Braginsky & Panov JETP **1972**	Torsion balance. 8TMs. Not rotating. 24hr modulation by Earth rotation	Sun	Al – Pt	$(-0.3 \pm 0.9)\text{x}\mathbf{10^{-12}}$
E. Fischbach et al.: "Reanalysis of the Eötvös Experiment" PRL 1986				
Eöt-Wash, PRD **1994**	<u>Rotating</u> torsion balance. ≈ 1hr modulation	Earth	Be – Cu	$(-1.9 \pm 2.5)\text{x}\mathbf{10^{-12}}$
			Be – Al	$(-0.2 \pm 2.8)\text{x}10^{-12}$
Eöt-Wash, PRL 1999	<u>Rotating</u> torsion balance. 1hr to 36' modulation	Sun	Earthlike/ Moonlike	$\approx10^{-12}$ (SEP $1.3\text{x}10^{-3}$)
Eöt-Wash, PRL **2008**	<u>Rotating</u> torsion balance. 20' modulation	Earth	Be – Ti	$(0.3 \pm 1.8)\text{x}\mathbf{10^{-13}}$

Limitations to EP testing by LLR/SLR

Laser raging to the Moon has tested that the Earth and Moon fall the same in the field of the Sun to 10^{-13} *(Williams et al., CQG 2012)*

Improvement of laser ranging to 1 mm with (APOLLO project) will be anyway limited to:

$$\eta_{min-LLR} \simeq 3\frac{\Delta a_{meas}}{d_{\oplus\odot}} \simeq 3\frac{10^{-3}}{1.5 \cdot 10^{-11}} \simeq 2 \cdot 10^{-14}$$

The limitation would be even stronger for laser ranging to LAGEOS-like satellites:

$$\eta_{min-lageos} \simeq 3\frac{\Delta a_{lageos}}{a_{lageos}} \simeq 3\frac{10^{-2}}{1.2 \cdot 10^{7}} \simeq 2.4 \cdot 10^{-9}$$

For WEP/UFF tests relative displacement measurements are required, not absolute distance measurements...this is the weakness...)

Nobili et al., GRG 2008

What can space (low Earth orbit) provide which cannot be attained on ground??

The advantages of space for testing WEP/UFF

- Signal (from Earth) only slightly smaller than in Galileo dropping tests on ground ($\simeq 8\,\mathrm{m/s^2}$): $\simeq 500$ times stronger than in ground balances with Earth as source and $\simeq 1400$ with Sun as source. Note: does not apply to mass-dropping tests

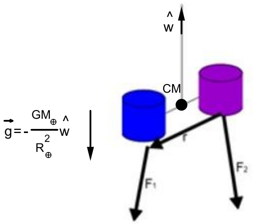
- Absence of weight: on ground the balance is suspended against $1\,g$, in space against $a_{iner-drag} \simeq 10^{-8}\,g$ (the largest acceleration on TMs is the inertial acceleration in response to air drag of the s/c – with GG numbers) $\Rightarrow$ suspending 100 kg mass in GG is like suspending 1 mg on ground! $\Rightarrow$ low stiffness, low natural frequency, high sensitivity..

- "lab" (the spacecraft) isolated in space: local disturbances (from terrain tilts, nearby masses...) much reduced provided that a dedicated and well designed s/c is used..

- If s/c attitude is kept fixed in space (actively) violation signal is at the orbital frequency ($100'$ period). s/c rotation would up-convert it to higher frequency. GG is stabilized by 1-axis rotation at 1 Hz provided once for all at mission start, angular momentum conservation, no motor, no bearings, whole "lab" co-rotating. "Passive" rotation as in Dicke experiment...

Why not flying a torsion balance?

A torsion balance in space



Perfect common mode rejection needs 1g and is lost in weightlessness conditions

In space the largest common mode effect is the inertial acceleration resulting from residual air drag (and solar radiation pressure) acting on s/c:

$$a_{iner-drag} \simeq 10^{-8}\, g \simeq 10^{7}\, \Delta a_{EP} \quad (\eta_{GG} = 10^{-17})$$

Even if partially compensated by drag free control, common mode rejection is needed...

GG: a “balance” and its spacecraft
for testing WEP to 10^{-17} in the field of the Earth

The reasons behind every choice..

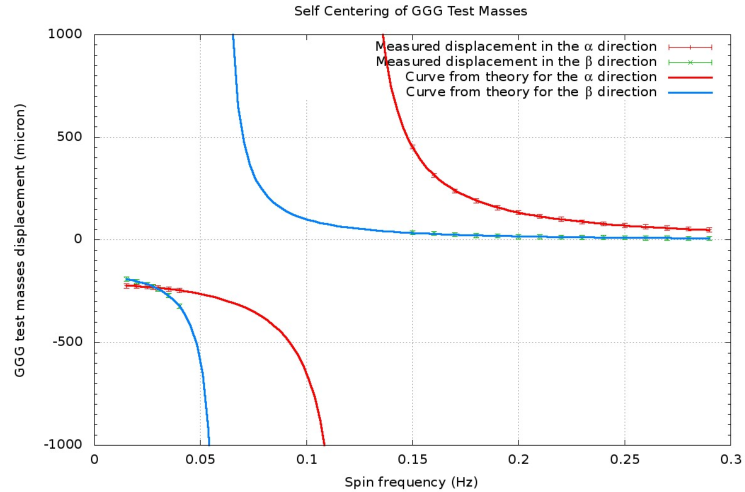
- TMs are cylinders; they should be weakly coupled to form a balance very sensitive to differential accelerations (low natural coupling frequency) with possibility to reduce common mode effects as much as possible
- TMs should be concentric to reduce classical tidal (differential) effects $\Rightarrow$ concentric co-axial cylinders
- Each TM orbiting the Earth is a 2-body problem, with 2DOF (orbital plane) $\Rightarrow$ the balance should be sensitive in 2D too $\Rightarrow$ the plane perpendicular to the symmetry axis of the cylinders is the sensitive plane and lies, nominally, in the plane of the orbit $\Rightarrow$ violation signal is a vector pointing to the CM of the Earth as the balance orbits around it (constant size if orbit circular) - it is at the orbital frequency
- Rotation around the symmetry axis of the cylinders will up-convert the signal to the rotation frequency. If the s/c has the same cylindrical symmetry, stabilizing it by 1-axis rotation around it will provide, after initial spin-up, "passive" rotation of the whole system. Note: since entire "lab" rotates, local mass anomalies give DC effects $\Rightarrow$ no terrific requirements on mass test manufacture $\Rightarrow$ ample choice of materials, also H rich like polyethylene can be considered...
- Since the test needs low coupling frequency and high spin rate, this is by definition a rotor in supercritical regime. Theory & long record of such rotors tell us that while it is highly unstable in 1D, in 2D it provides self centering (by physics). There is a known weak instability (whirl motion) at known frequency (natural, away from signal frequency) which does not interfere with the measurement

How physics allows rapid rotation in 2D

The centers of mass of the tests bodies cannot be perfectly concentric. The offset vector $\vec{\varepsilon}$ (fixed with the rotating masses) is not zero but in 2D it is reduced by the factor $\omega^2_{diff}/\omega^2_{spin}$. The solution (in the non rotating frame) is:

$$\vec{r}(t) \simeq -\varepsilon \left(\frac{\omega^2_{diff}}{\omega^2_{spin} - \omega^2_{diff}} \right) \begin{pmatrix} \cos(\omega_{spin} t + \varphi) \\ \sin(\omega_{spin} t + \varphi) \end{pmatrix} \simeq -\varepsilon \left(\frac{\omega^2_{diff}}{\omega^2_{spin}} \right) \begin{pmatrix} \cos(\omega_{spin} t + \varphi) \\ \sin(\omega_{spin} t + \varphi) \end{pmatrix}$$

Proof masses are centered on one another by physics.

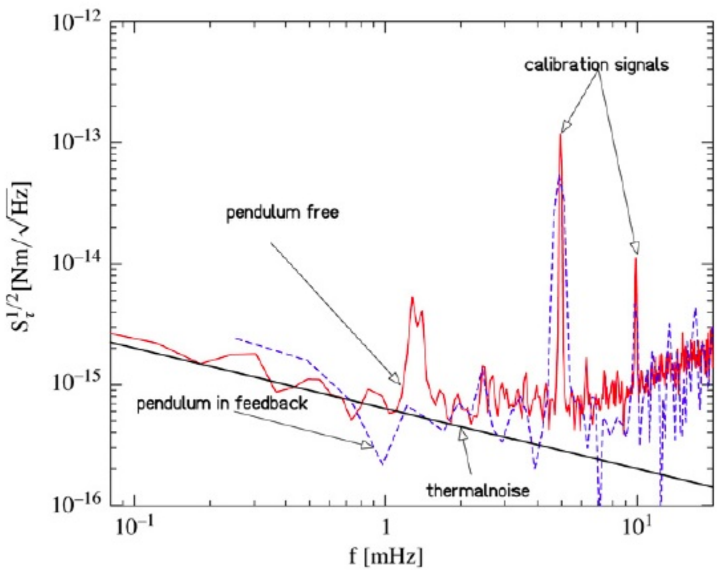


Experimental data from the GGG accelerometer agree with the theoretical curves in both directions $\alpha\,,\beta$ of the rotating plane:

$$r_{\alpha,\beta}(\nu_{spin}) = \varepsilon_{\alpha,\beta} \cdot \frac{\nu^2_{\alpha,\beta}}{\nu^2_{\alpha,\beta} - \nu^2_{spin}}$$

Frequency dependence of thermal noise from internal damping

E.G. Adelberger et al. / Progress in Particle and Nuclear Physics 62 (2009) 102–134



- Thermal noise due to internal damping usually dominant. Known to decrease with frequency (*Saulson PRD, 1990*):

$$\gamma_{id}(\omega) \simeq \frac{k\phi(\omega)}{\omega} = \frac{\mu\omega_n^2\phi(\omega)}{\omega}$$

  Better up-convert signal to higher frequency

- Demonstrated by Adelberger by rotating the balance and up-converting the signal to the rotation frequency, ***just below the resonance frequency***. Above resonance, effects are attenuated like in any 1D oscillator, and read-out noise dominates

Thermal noise from internal damping in GG

- No such attenuation occurs in 2D oscillators when the signal is up-converted by rotation above resonance

(*Pegna et al. PRL, 2011*; demonstrated experimentally in GG prototype *Nobili et al., CQG, 2012*).

- In GG rotation up-converts the signal from the orbital frequency to 1 Hz where thermal noise from internal damping is reduced by a very large factor:

$$\frac{<|\hat{F}_{th-id}(\omega_{orb})|^2>}{<|\hat{F}_{th-id}(\omega_{spin})|^2>} \gtrsim \frac{\omega_{spin}}{\omega_{orb}} \simeq 6000$$

down to (at $T \simeq 300\,K$ with $\Phi \simeq 1/20000$, $\omega_n \simeq 2\pi/540\,\mathrm{rad\,s^{-1}}$):

$$<|\hat{F}_{th-id}(\omega_{spin})|^2> \simeq 4k_B T\gamma_{id}(\omega_{spin}) \simeq 8.9\cdot 10^{-29}\,\mathrm{N^2/Hz}$$

which turns out to be lower than thermal noise from residual gas damping

GG integration time to reach 10^{-17}

$$< |\hat{F}_{th}(\omega_{spin})|^2 >_{tot} =$$
$$< |\hat{F}_{th-gas}|^2 > + < |\hat{F}_{th-id}(\omega_{spin})|^2 > + < |\hat{F}_{th-J}|^2 > \simeq$$
$$3.5 \cdot 10^{-28}\,\mathrm{N}^2/\mathrm{Hz}$$

- Gas damping noise estimated with reference to Cavalleri et al., PRL 2009 and a 2 cm gap as in GG baseline with laser gauge read-out.
- Johnson noise and Eddy currents damping estimated assuming gradient of the Earth's magnetic field as large as the field itself and with a 150 reduction by μ-metal shield

With $SNR = 2$ and a WEP target to 10^{-17} (test bodies 10 kg each; $F_{signal} \simeq 4 \cdot 10^{-16}$ N) the required integration time is:

$$t_{int} = SNR^2 \cdot \frac{< |\hat{F}_{th}(\omega_{spin})|^2 >_{tot}}{F_{signal})^2} = 4 \cdot \frac{3.5 \cdot 10^{-28}}{(4 \cdot 10^{-16})^2} \simeq 2.4\,\mathrm{h}$$

A full 10^{-17} measurement will be done in 1 d (8 t_{int} cycles, almost 15 orbits)

Nobili et al., PRD to appear

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μSCOPE integration time to reach 10^{-15}

μSCOPE to fly in 2016, possibly 2015

Thermal noise is dominated by internal damping in the gold wire connecting each test mass to its enclosure and is estimated by μSCOPE scientists to be *(Touboul Space Sci. Rev., 2009; Touboul et al. CQG, 2012)*:

$$a_{th-\mu scope} \simeq 1.4 \cdot 10^{-12}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$$

For a WEP test to 10^{-15} and $SNR = 2$:

$$a_{WEP-\mu scope} \simeq 8 \cdot 10^{-15}\,\mathrm{ms}^{-2} \quad \mathit{and} \quad t_{int-\mu scope} = 4 \cdot \frac{(1.4 \cdot 10^{-12})^2}{(8 \cdot 10^{-15})^2} \simeq 1.4\,\mathrm{d}$$

which allows a reliable measurement in several days and leaves room for checks and/or improvements in 9-month mission.
Aiming at 100 times better would require a 10^4 times longer integration time!
Would cryogenics be the answer????

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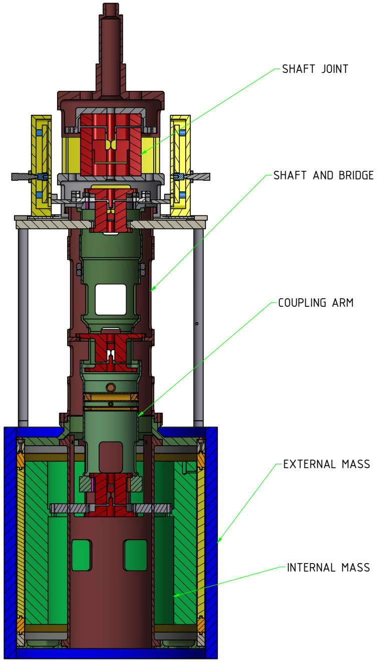
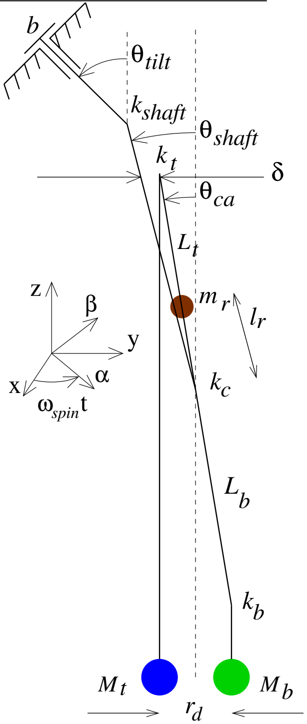
GG on Ground (GGG)

Possible because the GG sensor has 2 DOF: use spin/symmetry axis to suspend it, sensitive in the horizonatl plane of lab (same number of DOF as in space), full scale, rotation in supercritical regime...

... remember: **it is the prototype of a sensor designed and optimized for space. At $1\,g$ torsion balances are better (much higher sensitivity..)**

The GGG prototype

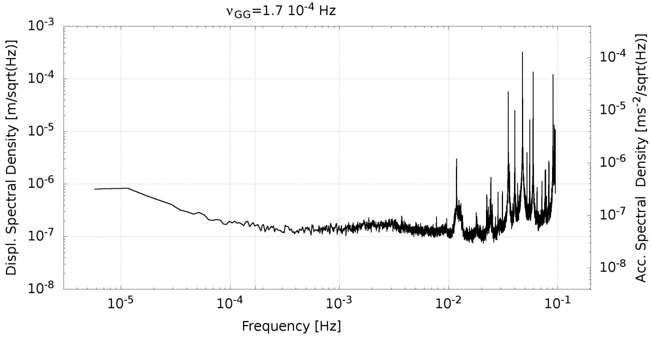


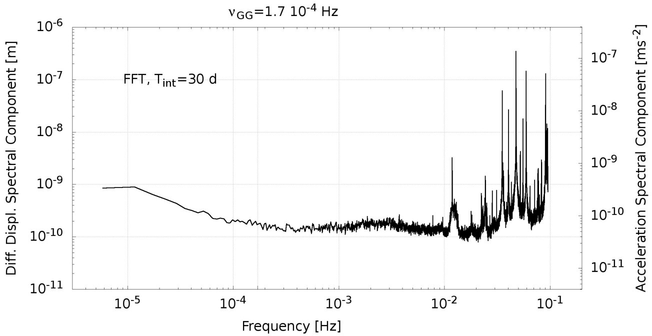


GG in space needs no motor no bearings, has no "terrain" tilts, has weaker coupling and higher sensitivity by 3 orders of magnitude; the driving signal from Earth is 500 times stronger ...yet the key features are the same as in GGG

Monolithic rotating 2D joint provides attenuation of low frequency terrain microseismicity (much better than active control in closed loop on conventional tiltmeter...)

GGG: where does it stand?





Nobili et al., CQG 2012

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

  $\eta_{GG_{\oplus} target @ 1.7\cdot10^{-4}\text{Hz}} = 10^{-17}$

  $\frac{\eta_{GGG_{\oplus} prototype @ 1.7\cdot10^{-4}\text{Hz}}}{\eta_{GG_{\oplus} target @ 1.7\cdot10^{-4}\text{Hz}}} = 8.9\cdot10^{5}$

  $\frac{sensitivity@zero-g}{sensitivity@one-g} = (540\,\text{s}/10\,\text{s})^2 = 2.9\cdot10^{3} \quad \Rightarrow$

  factor that can be gained by GGG $= \frac{8.9\cdot10^5}{2.9\cdot10^3} = 307 \quad \Rightarrow$

  i) reduce rotation and tilt noise (not present in space)

  ii) replace capacitance readout with laser gauge (JPL design, as in space)

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

  Sensitivity to differential accelerations @ low frequencies:

  i) $6\cdot10^4$ *times* **worse** *than torsion balances (they cannot fly)*
  Braginsky & Panov, JEPT 1972 (Univ. Moscow)
  Baessler et al., PRL 1999 (UW Seattle, USA)

  ii) $2.9\cdot10^3$ *times* **better** *than* ^{85}Rb, ^{87}Rb test
  Fray et al., PRL 2004 (Max Planck, DE)

  iii) 202 *times* **better** *than* Cs, SiO_2 test
  Peters et al., Nature 1999 (Stanford, USA)

  iv) 124 *times* **better** *than* ^{87}Rb, SiO_2 test
  Merlet et al., Metrologia 2010 (LNE-SYRTE, Paris, FR)

  v) 20 *times* **better** *than* Al, Cu test
  Carusotto, Polacco et al., PRL 1992 (CERN)

You are welcome to visit the GG website
http://eotvos.dm.unipi.it