Gravitation Measurements on Earth and in Space

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Tests of the Equivalence Principle

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- -Proposed balloon test

Scientific relevance of the Equivalence Principle

The total mass-energy of a body can be expressed as the sum of many terms corresponding to the energy of all the conceivable interactions and components (as fraction of the total):

-rest mass ($\cong 1$)
-nuclear binding energy ($\cong 8\cdot 10^{-3}$)
-mass difference between neutron and proton ($\cong 8\cdot 10^{-4}$ (A-Z)/A)
-electrostatic energy of repulsion in the nuclei ($\cong 6\cdot 10^{-4} Z^2 A^{-4/3}$)
-mass of electrons ($\cong 5\cdot 10^{-4}$ Z)
-antiparticles ($\cong 10^{-7}$)
-weak interactions responsible for β decay ($\cong 10^{-11}$)

The Eötvös parameter η, which quantifies the violation of equivalence for two bodies of composition *A* and *B*, inertial mass m_i and gravitational mass m_g, can be generalized into

$$\eta_k = \frac{2[(m_g/m_i)_{Ak} - (m_g/m_i)_{B_k}]}{[(m_g/m_i)_{Ak} + (m_g/m_i)_{B_k}]}$$

Each $\eta_k \neq 0$ would define a violation of Equivalence between the inertial and gravitational mass-energy of the k-th type. If the Equivalence Principle holds, all these separate *Equivalence Principles* must hold, corresponding to a very peculiar coupling of each field to gravity (true only for the gravitational interaction!!!).

Nearly all attempts to extend the present framework of physics predict the existence of new interactions which are composition dependent and therefore violate the Equivalence Principle. EP tests are by far the most sensitive low energy probes of such new physics:

fractional differential acceleration between bodies of different composition
↓ falling in the gravitational field of a source mass

$\Delta a/a$ $\propto$ post-Newtonian deviations from General Relativity (e.g. measured by γ^*)
↑

↓ vector models
proportionality factor: $10^{-5} \div 10^{-3}$
↑ scalar models

$\gamma^* = \gamma - 1$ γ Eddington parameter

$\gamma^* < 10^{-3}$ by post Newtonian or pulsar tests

$\Delta a/a < 10^{-12} \div 10^{-13}$ by EP tests $\Rightarrow$ $\gamma^* < 10^{-7} \div 10^{-9}$ or $10^{-8} \div 10^{-10}$

The superior probing power of Equivalence Principle tests is beyond question !!!!

Experiment principle and expected signal (I)

Any EP experiment needs 2 test bodies (of different composition) “falling” (freely or suspended) in the field of a source mass (e.g. Earth), plus a read out system to detect the effects of a (non classical...) differential acceleration between them (expected signal always pointing to the source mass)

All non gravitational effects (e.g. due to air pressure, radiation pressure, electric forces, magnetic forces), must produce differential effects smaller than expected signal
All inertial forces (except the one being compared with the gravitational force of the source mass to check EP) deriving from the reference system not being inertial must produce differential effects small than signal (e.g. inertial forces resulting from air drag)

Ground tests with Earth as the source mass:

(adimensional) Eötvös parameter ↓ ↓ driving acceleration signal (9.8 m/s^2)

- mass dropping (free falling bodies: $a_{EP} = \eta \cdot GM_\bullet / R_\bullet^{\ 2}$)
  Release bodies simultaneously; record difference in time of fall

- pendula:
  release 2 pendula (same length, different composition of suspended bodies) from maximum elongation and monitor how accurately they keep in step (Note: no clock needed ....)

- torsion balance:
  only one suspension wire suspends 2 test bodies at the ends of a rigid bar; differential forces twist wire (expected signal maximum if beam balance in the East-West direction)

$$a_{EP} = \eta \cdot \omega_\bullet^{\ 2} R_\bullet \ \cos\vartheta \sin\vartheta \cong \eta \cdot 0.017 \ m/s^2 \quad maximum, \ \vartheta=45°$$

latitude of laboratory ↑

Acceleration signal in the North-South direction

The centrifugal force due to the diurnal rotation of the Earth on a suspended body (proportional to its inertial mass) lies in its meridian plane and is perpendicular to the spin axis of the Earth; its component in the horizontal plane (balanced by Earth gravity horizontal component at equilibrium) is in the North-South direction and pushes the suspended body towards South;
if EP violated ⇒ suspended bodies of different composition are pushed differently towards South; if they are arranged on a torsion balance with the beam in the East-West direction the balance is twisted

Torsion balance is sensitive only to differential effects (ideally.....)

If balance stationary and expected signal in a fixed direction ⇒ no zero check
(orientation of beam balance must be changed, or bodies must be swapped to check !!!!)

Experiment principle and expected signal (II)

The price to pay when using suspended test bodies (instead of free falling) is a weaker driving signal (by a factor $\cong 600$)

Torsion balance stationary, source mass fixed $\Rightarrow$ no signal modulation (no zero check)
Torsion balance stationary, source mass moving $\Rightarrow$ signal follows source mass, e.g. it varies periodically (in intensity and/or direction) if source mass motion is periodic (w.r.t balance); check provided
Torsion balance spinning (spin rate set by experimentalist), source mass rotating (w.r.t it) $\Rightarrow$ signal must show both frequencies; signal check provided

<u>Ground tests with Sun as the source mass</u>

Sun as source mass for test bodies suspended on a (stationary) torsion balance on the surface of the Earth
$\Downarrow$
fastest frequency in signal comes from diurnal (apparent) motion of the Sun (due to Earth's daily rotation around its axis).
If balance beam in the East-West direction, signal must be zero at sunrise and sunset, maximum/minimum at noon/midnight (depending on which test body's composition would be stronger attracted by the Sun, should EP violation occur .....)

$$m_i^A \vec{a}^A = -m_g^A \cdot \frac{GM_{sun}}{{R_A}^3} \vec{R}_A + m_i^A \cdot (\vec{\omega}_\oplus \times (\vec{\omega}_\oplus \times \vec{R}_{ES}))$$

$\vec{R}_{ES}$ Earth to Sun vector

$\vec{\omega}_\oplus$ Earth rotation angular velocity vector

$$m_i^B \vec{a}^B = -m_g^B \cdot \frac{GM_{sun}}{{R_B}^3} \vec{R}_B + m_i^B \cdot (\vec{\omega}_\oplus \times (\vec{\omega}_\oplus \times \vec{R}_{ES}))$$

$$\vec{R}_A \cong \vec{R}_B = \vec{R}$$

$$m_i^A \vec{a}^A = -m_g^A \cdot \frac{GM_{sun}}{R^3} \vec{R} + m_i^A \cdot \frac{GM_{sun}}{R_{ES}^3} \vec{R}_{ES}$$

$$m_i^B \vec{a}^B = -m_g^B \cdot \frac{GM_{sun}}{R^3} \vec{R} + m_i^B \cdot \frac{GM_{sun}}{R_{ES}^3} \vec{R}_{ES}$$

Inertial force to be compared with gravitational one of EP check is the centrifugal force due to orbital rotation of the Earth around the Sun (annual motion), no longer the centrifugal force due to Earth rotation around its axis

Experiment principle and expected signal (III)

If we define

$$m_g^A = m_i^A \cdot \left(1 + \frac{\eta}{2}\right)$$

$$m_g^B = m_i^B \cdot \left(1 - \frac{\eta}{2}\right)$$

$$m_i^A \vec{a}^A = -GM_{sun} m_i^A \cdot \left(\frac{\vec{R}}{R^3} + \frac{\eta}{2}\frac{\vec{R}}{R^3} - \frac{\vec{R}_{ES}}{R_{ES}^3}\right)$$

$$m_i^B \vec{a}^B = -GM_{sun} m_i^B \cdot \left(\frac{\vec{R}}{R^3} - \frac{\eta}{2}\frac{\vec{R}}{R^3} - \frac{\vec{R}_{ES}}{R_{ES}^3}\right)$$

then

$$\vec{a}_{EP}^{sun} = \vec{a}^B - \vec{a}^A = \eta \cdot \frac{GM_{sun}\vec{R}}{R^3} \cong \eta \cdot 0.006\ m/s^2$$

$$\vec{R}_{sun} = R_{ES}(\cos\delta\cos H, \cos\delta\sin H, \sin\delta)$$

position vector of Sun in geocentric frame

δ, H declination and hour angle of Sun

$$\vec{R}_{lab} = (R_\oplus \cos\vartheta,\ 0,\ \sin\vartheta)$$

position vector of lab in geocentric frame

$R_\oplus$ Earth radius, ϑ latitude of lab $\vec{R} = \vec{R}_{sun} - \vec{R}_{lab}$

$$\vec{R} = (R_x \sin\vartheta - R_z\cos\vartheta, R_y, R_z\sin\vartheta + R_x\cos\vartheta)$$

x, y horizontal plane x, z meridian plane (x NS , y EW)

$$\vec{a}_{EP,NS}^{sun} = \eta \cdot G\frac{M_{sun}}{R^3}\cdot(R_x\sin\vartheta - R_z\cos\vartheta) \qquad \vec{a}_{EP,EW}^{sun} = \eta \cdot G\frac{M_{sun}}{R^3}\cdot R_y$$

Dependence on Sun's daily motion obviously there; range of effect is now Earth-Sun distance (1 AU), no longer Earth radius, as in tests using Earth as source; price to pay is a smaller driving signal (by about a factor 3, depending on latitude of laboratory)

Brief history of past ground experiments (I)

Aristotle's statement that heavier bodies should fall faster than lighter ones was questioned in the *6th* century by Philoponus:

"if two bodies are released by the same altitude one can observe that the ratio of the times of fall of the bodies does not depend on the ratio of their weights, and the difference of the times is very small".

In 1553 Benedetti reconsidered the issue, stating that the velocity of fall does not depend on the weights of the falling bodies.

Galileo showed the internal contradiction of Aristotle's reasoning with a simple argument:

"*If then we take two bodies whose natural speeds are different, it is clear that on uniting the two, the more rapid one will partly be retarded by the slower, and the slower will be somewhat hastened by the swifter....Hence the heavier body (made by the two tied together) moves with less speed than the lighter* (the former swifter one)*; an effect which is contrary to your* (by Aristotle) *supposition"*

Galileo was aware of the need to provide experimental evidence. By dropping bodies of different composition in media much denser than air Galileo came to the conclusion that all bodies fall equally fast and that any observed difference is due to the different resistance of the medium that different bodies are subject to.

"...veduto, dico questo, cascai in opinione che se si levasse totalmente la resistenza del mezzo, tutte le materie descenderebbero con eguali velocità "
"... having observed this I came to the conclusion that, if one could totally remove the resistance of the medium, all substances would fall at equal speeds "

↑ First clear statement of the Universality of Free Fall (UFF) (composition independent); taken from: "*Discorsi e dimostrazioni matematiche intorno a due nuove scienze attinenti alla meccanica e ai movimenti locali*", published outside Italy (Leiden) in 1638 due to Galileo's prosecution by the Church of Rome. Galileo was 74, blind and under house arrest, but the "Discorsi" are based on much earlier work, mostly on experiments with the inclined plane and the pendulum going back ≅ 40 years to the time when he was a young lecturer at the University of Pisa

Galileo was also aware of the difficulty to provide evidence by dropping masses from a height (from a big height the accumulated effect of air resistance is too large to allow a reliable conclusion; from a small one any difference is too small to appreciate). Most probably Galileo was not able to calculate precisely the effect of air resistance; but he knew that it was much smaller if the velocity of the body was small (in fact, $a_{drag} \propto v^2$). He therefore performed experiments with bodies falling on inclined planes where only a fraction of the gravitational acceleration is relevant, which reduces the falling velocity –hence also the effect of air resistance.

Brief history of past ground experiments (II)

Better still than bodies falling on inclined planes are bodies suspended from a wire and brought to oscillation like a pendulum: if all bodies fall with the same acceleration in the gravitational field of the Earth, bodies suspended from wires of the same length which are released at the same time by the same angle must keep in step regardless of their mass or composition. Besides reducing the velocity –and air resistance– the periodic repetition of the motion allows a better measurement and improves the accuracy of the experiment:

"*....e finalmente ho preso due palle, una di piombo e una di sughero, quella ben più di cento volte più grave di questa, e ciascheduna di loro ho attaccata a due sottili spaghetti eguali, lunghi quattro o cinque braccia, legati ad alto; allontanata poi l'una e l'altra palla dallo stato perpendicolare, gli ho dato l'andare nell'istesso momento, ed esse, scendendo per le circonferenze de' cerchi descritti da gli spaghi eguali, lor semidiametri, passate oltre al perpendicolo, son poi per le medesime strade ritornate indietro e reiterando ben cento volte per lor medesime le andate e le tornate, hanno sensatamente mostrato, come la grave va talmente sotto il tempo della leggiera, che né in ben cento vibrazioni, né in mille, anticipa il tempo d'un minuto secondo, ma camminano con passo egualissimo*"

↑
from Galileo's "Discorsi", 1638;
but also reported in a letter from Galileo to Guidobaldo dal Monte dated 1602;
tests repeated, just as described by Galileo, in 1993 (Fuligni and Iafolla) to show that an accuracy of *1* part in 10^3 (e.g. corresponding to an error of *0.1%* in the length of the suspension) was achievable with no special care.

Pendulum experiments have provided the most accurate tests of the Equivalence Principle (Bessel, 1827; to $\cong 2 \cdot 10^{-5}$) till the torsion balance of Loránd Eötvös at the end of last century.
Newton often reported as the first ever to perform accurate pendulum tests of the Equivalence Experiment (he reports an accuracy of 10^{-3}).
Remember: no clock needed in pendulum tests of EP (pendulum clock invented by Christian Huygens in 1657, after Galileo's death)

More important by far is Newton's conclusion from his pendulum experiments:

" 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... " (Principia, opening paragraph).

↑ first statement on the Equivalence between inertial and gravitational mass (from which the UFF follows and can be subjected to experimental testing (1687)

Brief history of past ground experiments (III)

Einstein, 1907: "…hypothesis of complete equivalence" between a gravitational field and an accelerated reverence frame (in a freely falling system all masses fall equally fast ⇒ gravitational acceleration has no local dynamical effect), also known as Weak Equivalence Principle (WEP). Then generalized by Einstein (EEP) to become the founding pillar of his theory of General Relativity:

in an electromagnetically shielded laboratory, freely falling and non rotating, the laws of physics –including their numerical content– are independent of the location of the laboratory. In such a laboratory all particles (small enough to neglect tidal effects and free of non gravitational forces) move with no acceleration. (i.e., according to general relativity the effects of gravity are equivalent to the effects of living in a curved space-time; true for all metric theories of gravity)

Eötvös , 1888 – 1905/1908 (most detailed paper published in 1922, after he died in 1919)

Eötvös built a sensitive torsion balance for gravimetric measurements and decided to use it to test the equivalence between gravitational and inertial mass (very subtle idea that a violation of equivalence should show up as a rotation of the balance)

He could improve the best pendulum tests of the EP by about 4 orders of magnitude (to about 1 part in 10^8, later improved by his students by about another order of magnitude)

Probably motivated by the huge capabilities of the instrument he had built (reached 1/60000 arcsec). He started before Einstein's work ; Einstein was probably not even aware of his results

THE BEST INSTRUMENT FOR EP TESTING TODATE; IN THIS FORM IT LACKS SIGNAL ZERO CHECK AND FREQUENCY MODULATION……..

The torsion balance used by Loránd Eötvös to test the Equivalence Principle

Brief history of past ground experiments (IV)

1964, Robert Dickey: first to use the torsion balance with the Sun as a source rather than the Earth

⇓
from a DC to a *24-h* signal

EP test reported to about *1 part in* 10^{11} : 2-3 orders of magnitude improvement over previous torsion balance experiments which used the Earth as source (despite the weaker driving signal ...)
Roll, Krotkov & Dicke, 1964

$$\eta\,(Al, Au)=(1.3 \pm 1.0)\cdot 10^{-11}$$

Similar experiment in principle (torsion balance tested for twist in the field of the Sun, 24-h frequency provided by Earth's rotation): Braginsky and Panov, 1972
(experiment carried out in basement of Physics Department in Moscow; special care in manufacturing suspension wire and in the distribution of test bodies, to make balance less sensitive to multipole moments)

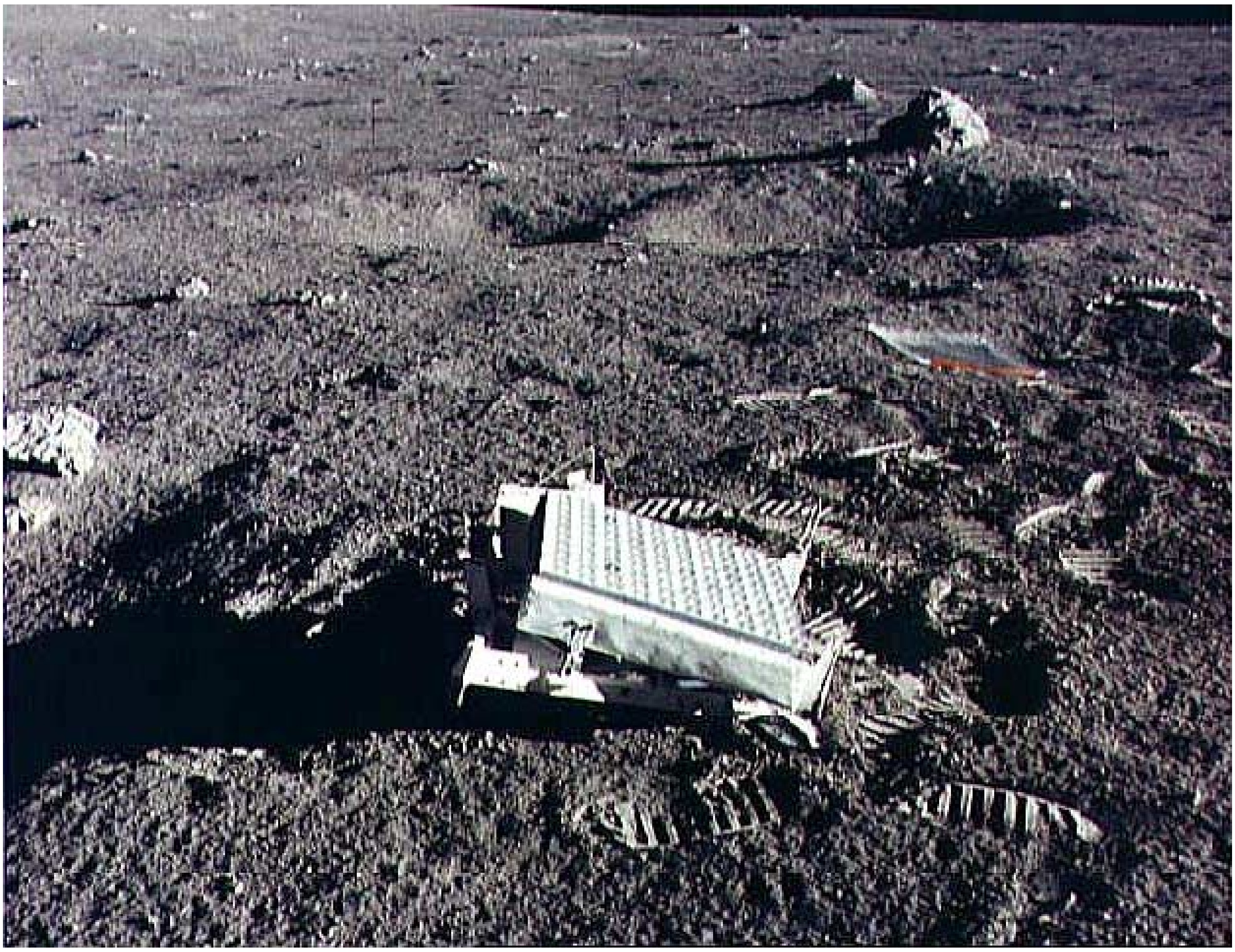
No EP violation reported to:

$0.9\cdot 10^{-12}$ *(95% confidence Al, Pt test bodies)*

Equivalence Principle tests by Lunar Laser Ranging (I)

21 July, 1969: during the first manned lunar mission Apollo 11 the first retroreflector array was placed on the Moon enabling highly accurate measurements of the Earth-Moon separation by means of laser ranging (measurement of the round trip travel time)
Further arrays were placed on the Moon by the Apollo 14, Apollo 15, Lunakhod 1 and Lunakhod 2 (allowing favorable geometry)

Ranging accuracies on the order of *1 cm* (for short laser pulse lengths with high power)



The retroreflector array of Apollo 14 on the lunar surface

Lunar laser ranges (and microwave ranges) to planetary orbiting s/c and landers, have greatly contributed to tests of gravitational theories in the Solar System: Moon and planets are ideal test bodies because the ratio of nongravitational to gravitational forces is very small (solar radiation pressure on the Moon only $4 \cdot 10^{-13}$ of Earth's gravitational attraction)

Equivalence Principle tests by Lunar Laser Ranging (II)

Gravitational self energy negligible (compared to rest mass) for lab-size bodies, not for Earth and Moon, which are large enough to have a significant fraction of their mass coming from gravitational energy.

$$f \equiv -\frac{3}{5}\frac{GM^3}{R}/(Mc^2) \propto \pi G\rho \cdot R^2/c^2$$

$$f_{Earth} \cong -4.6 \cdot 10^{-10}$$

$$f_{Moon} \cong -1.9 \cdot 10^{-11}$$

If gravitational self energy does not contribute equally to gravitational and inertial mass, with the Moon orbiting the Earth and both falling in the field of the Sun, a violation of the Equivalence Principle would cause the orbit of the Moon around the Earth-Moon center of mass to be polarized in the direction of the Sun with a typical size of $\cong$ *13 m* (signature is the *29.5 day* synodic period of the Moon w.r.t. the Earth)

(“Nordtvedt” effect, 1968)

Assuming no violation depending on composition, LLR provide EP tests to a few parts in 10^{13} (Dickey et al., 1994; Williams et al., 1996)

But Earth and Moon do have different composition; compositions of Earth’s core and mantle are different (iron core, silicate mantle), composition of Moon similar to that of the Earth’s mantle

⇓

for unambiguous interpretation of LLR data, laboratory EP test experiments should be carried out with test bodies having Earth core-like and Moon-like composition falling in the field of the Sun. Done by Baessler et al., 1999 (rotating torsion balance), who report no violation to about a part in 10^{13}

Note: LLR tests of the EP are based on highly complex physical models of many perturbing effects on the orbit of the Moon (i.e. tides) whose signature can be the same as that of an EP violation, and which involve many parameters to be adjusted. EP experiments with test bodies of lab size can always provide a zero check: no sensitivity can be claimed better than the one which is obtained using test bodies of the same composition.

Recent and ongoing laboratory experiments

Rotating torsion balance experiments

Best results obtained with systematic tests by the Eöt-Wash group (University of Washington, Seattle).
Torsion balance rotating on a turntable provides $\cong$ *1 hr* period modulation of signal (source is the Earth, signal in the North-South direction of horizontal plane); small test cylinders *(10 gr)*, room temperature, effects of local mass anomalies coupling differently to higher multiple moments of test bodies measured and reduced by careful distribution of nearby masses); active compensation of tilt effects

Adelberger et al., 1990	*Be/Al, Be/Cu*	*about* 10^{-11}	Earth (1 R●)
Su et al., 1994	*Be/Al, Be/Cu*	*about* 10^{-12}	Earth (1 R●)
Baessler et al., 1999	*Earthlike, Moon like about* 10^{-13}		Sun (1 AU)
Smith et al., 2000	*Cu, Pb*	$\Delta a/a \cong 10^{-9}$	3 ton, rotating ^{238}U (short range 10-1000 km)

Galileo type (mass dropping) experiments

Carusotto et al., 1992 (Cern, Pisa): single disk made of two half disks of different composition (*Al, Cu* $\cong$ *350 gr* each) in *4.2 m* free fall

$$\Delta g/g = 7.2 \cdot 10^{-10} \quad \textit{sensitivity}$$

Ongoing experiments

-Eöt-Wash group, rotating torsion balance, room temperature, small test masses
-Indian group (Cowsik et al): not rotating torsion balance, ring made of two halves of different composition, large mass *(1.4 kg)*, underground, remote, very low noise site, room temperature
-Group at Irvine, California (Newman et al.): cryogenic torsion pendulum, gain expected in reduced thermal noise, reduced temperature sensitivity, improved temperature control, improved fibre characteristics
-Group at university of Washington (Boynton et al.): room temperature torsion pendulum, new observable suggested
-GGG (Pisa-Firenze, Italy): large mass *(10 kg)* fast spinning, coaxial rotors; experiment designed to serve as prototype for an EP test in space

Advantages of EP experiment in low Earth orbit

For test bodies orbiting the Earth at low altitude driving signal in the field of the Earth is about 3 orders of magnitude stronger:

$$a_{EP} = \eta \cdot \frac{GM_{\oplus}}{(R_{\oplus} + h)^2} \cong \eta \cdot 8.4 \quad m/s^2 \qquad (h \cong 500 \ km)$$

↑ driving acceleration

Effect in space:
500 times stronger than it is for suspended bodies on Earth (if Earth is the source mass); *1400 times* stronger (if Sun is the source mass)

ADVANTAGE OF EP EXPERIMENTS IN SPACE BEYOND QUESTION (not so for short range tests, or for testing violation in the field of Sun, galaxy etc...; advantage is there only if motion of test masses is checked for anomalies caused by the Earth mass)

Other advantage: weightlessness. Test bodies can be suspended with extremely weak suspensions (*100 kg* in space like *1 milligram* on Earth !!!!)

However ....

Space laboratory is far away: preliminary tests must be carried out at *1-g*; repeatibility costly unless mission proposed is small... But same is true also for large scale ground based research projects whose results often need another big experiment to check, e.g. CERN high energy physics experiments

Space is far from being empty and quiet: no seismic noise like on the surface of the Earth, but, residual atmospheric pressure, solar radiation pressure, infrared radiation from Earth make charged particles... All these are matters of concern for any space experiment on the Equivalence Principle

Torsion balance not a suitable apparatus at almost *0-g*

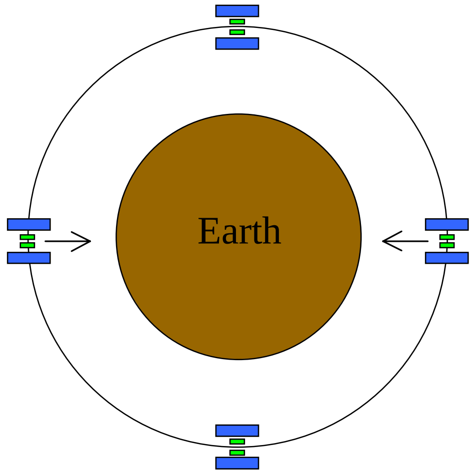
Differential, purely classical effects between the test bodies depending on non uniformity of gravitational and centrifugal forces (tides) suggest the centers of mass of test bodies should "coincide"
⇓
test bodies design accepted by all proposers of EP experiments in space is that of hollow, "concentric" cylinders

Proposed space experiments: STEP ("Satellite Test of the Equivalence Principle") and its variants (I)

Note: First proposed experiment to test the Equivalence principle in low Earth orbit (Chapman and Hanson, 1970) suggest to rotate the test cylinders on an aluminum wheel at about 100 rpm (*1.7 Hz*), so as to modulate the expected signal at high frequency; symmetry/sensitive axis on the plane of wheel; rotation axis perpendicular to plane of wheel (Problem: with only one dimension motion available for the test cylinders, such a system is indeed known to be unstable, Den Hartog, 1934)

STEP concentric test cylinders as they orbit the Earth. Sensitive axis is along the symmetry axis of the cylinders; in the plane perpendicular to it the system is very stiff and essentially no relative motion is allowed

If attitude of spacecraft enclosing the test cylinders (not shown here) is kept fixed w.r.t. inertial space (by careful active control), its orbital motion (with $\cong 6000\ sec$ period) makes a putative EP violation signal to change at the same frequency (regarded as quite a high frequency when it was proposed in the early 70s)



MAIN CHOICE: <u>Cryogenic experiment</u> (superfluid *He*, $\cong 2\ K$)

PROS

- reduced thermal noise
- reduced thermal expansion effects (holds only for mass inside dewar)
- reduced residual pressure (only way to cope with radiometer effect)
- superconductivity
- SQUID read out (potentially higher measurement accuracy)

CONS

- large amount of potentially moving mass close to test bodies
- need for careful ejection of boiled off *He*
- constraint on technology for drag compensation (*He* thrusters: mechanical tuning, less accurate than electric tuning; small specific impulse, hence large amount of propellant)
- reduced mission duration

STEP and its variants (II)

MAIN ISSUES & CONCERNS

Radiometer effect	Major killer for EP experiments with signal along symmetry axis of test cylinders: (state equation for case in which mean free path much larger than vessel size) $a_{re} = \frac{p}{2\rho} \cdot \frac{1}{T} \cdot \frac{dT}{dz}$ ρ density of test body Effect obviously differential Unless pressure is strongly reduced, effect exceeds by far the expected signal Cryogenic experiment reduces pressure STEP requirement for temperature gradient between faces of test body: not larger than $10^{-3}\ K$
Electric charging	Objects in space get charged, and effect is huge compared to tiny gravitational signal expected. If test bodies are not physically coupled and suspended via conducting suspensions, charge needs to be measured and bodies must be actively discharged. A *130 kg* tungsten shield was included in the STEP design during Phase A study within ESA, or else a radiation sensor was proposed to discard contaminated data (STEP ESA/NASA Phase A Study Report, 1993; STEP Phase A Study, ESA, 1996)
He tides	Superfluid *He* in not perfectly full or perfectly empty dewar will move around test cylinders at orbit frequency (due to Earth tidal effect). Effect is differential (Even assuming that the symmetry axes of test cylinders are parallel enough to produce adequate Common Mode Rejection, the test cylinders can be designed so as to have reduced multipole moments, but they cannot be perfect gravitational monopoles because of machine errors). *He* in dewar must be prevented from moving (aerogel proposed)
s/c casing thermal expansion effect	Although the experiment core is kept at very low temperature inside the dewar, its outer parts (e.g. solar panels) will undergo thermal expansion/contraction if exposed to varying temperature. STEP s/c is kept fixed w.r.t inertial space while orbiting the Earth, hence each part of the s/c will change from facing outer space (cold) to facing Earth (warm); the resulting thermal contraction/expansion will cause s/c mass displacement at exactly the orbit frequency, and in the Earth direction. The resulting acceleration has the same signature as the expected signal and is several orders of magnitude bigger. If the test cylinders do not have sufficiently small quadrupole moments, it will coupled differently to them and give an effect indistinguishable from expected signal ($\Rightarrow$ test cylinders residual quadrupole moments must be known from direct measurements to at least *1 part in* 10^4.

STEP and its variants (III)

MAIN ISSUES & CONCERNS

signal at s/c orbit frequency	Signal modulation at frequency higher that the orbital one desirable, to avoid perturbing effects which follow the s/c motion around Earth (e.g. charged particle effects from South Atlantic Anomaly as the satellite passes over it once per orbit; eclipse effects; thrusters firing for drag compensation ....). STEP s/c will be set into slow rotation mode (≅ *1000 sec* period) to give higher modulation frequency to signal; rotation can only be very slow because STEP was not designed to spin
drag compensation	Residual drag effect much larger than expected signal unavoidable in all EP experiments in space; it must be either compensated (s/c designed for drag active control), or rejected (test bodies must be insensitive to common mode forces to some extent), or both (difficulty of task shared between s/c and EP test apparatus). Thrusters should be proportional and finely tunable (for more accurate control and smaller perturbations at firing), and have high specific impulse (to require less propellant (any movable mass is potentially dangerous for sensitivity of experiment). STEP can only use *He* thrusters, because needs to get rid of boil off He used to maintain the experiment at very low temperature; and *He* thrusters are not the best choice (≅ 250 liters of He mass to carry for about *6 months* mission duration and mechanical tuning).
mission duration	STEP mission duration limited by amount of *He* required to ensure cryogenic experiment; data accumulation over longer time would help improve the measurement sensitivity.

STEP Target accuracy:

10^{-17} according to Phase A Studies in Europe (STEP Phase A Study Report: ESA/NASA 1993, ESA 1996); 10^{-18} according to current analysis in the US

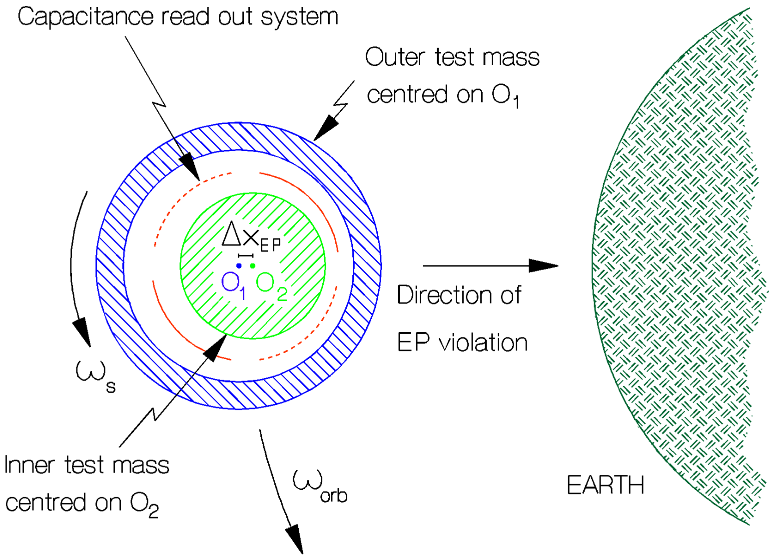
STEP variants in France

GEOSTEP: *same accelerometers as STEP, French s/c, cryogenic but not as low temperature as STEP, 10^{-16} accuracy expected (1996)*
μSCOPE: *room temperature, spinning (slowly) s/c, French accelerometers with capacitance read out (same principle as STEP test cylinders) 10^{-15} accuracy expected, accelerometers tested only to 10^{-9} $ms^{-2}/\sqrt{Hz}$ (Willemenot and Touboul, 2000).*
(Radiometer effect at room temperature?…)

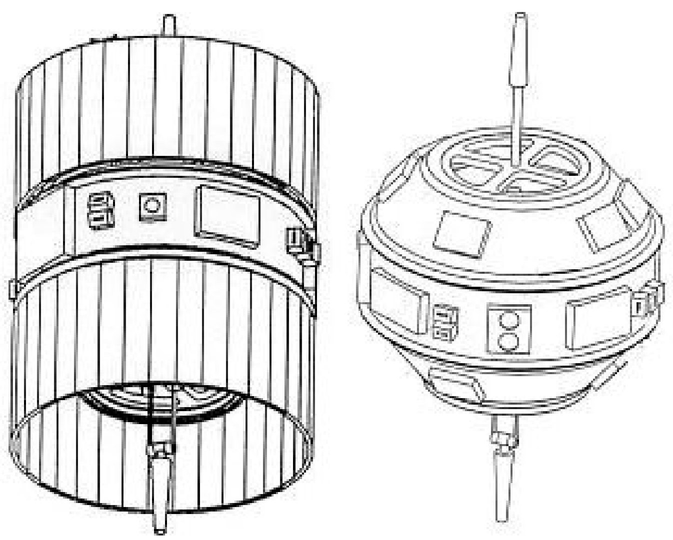
Proposed space experiments: GG ("Galileo Galilei") (I)

Concentric, coaxial test cylinders (10 kg each) with capacitance bridge in between; sensitive to differential effects in the plane perpendicular to symmetry axis

Capacitance sensors, test cylinders (and whole s/c) spin around symmetry axis at 2 Hz (s/c stabilized by passive rotation around axis of maximum moment of inertia)
Rotation of capacitance read out clearly modulates the signal at spin frequency. Frequency modulation much higher than ever achieved) helps reduce low frequency "1/f" electronic and mechanical noise



EP violation signal on the GG test bodies modulated at the spin frequency of the system (2 Hz)

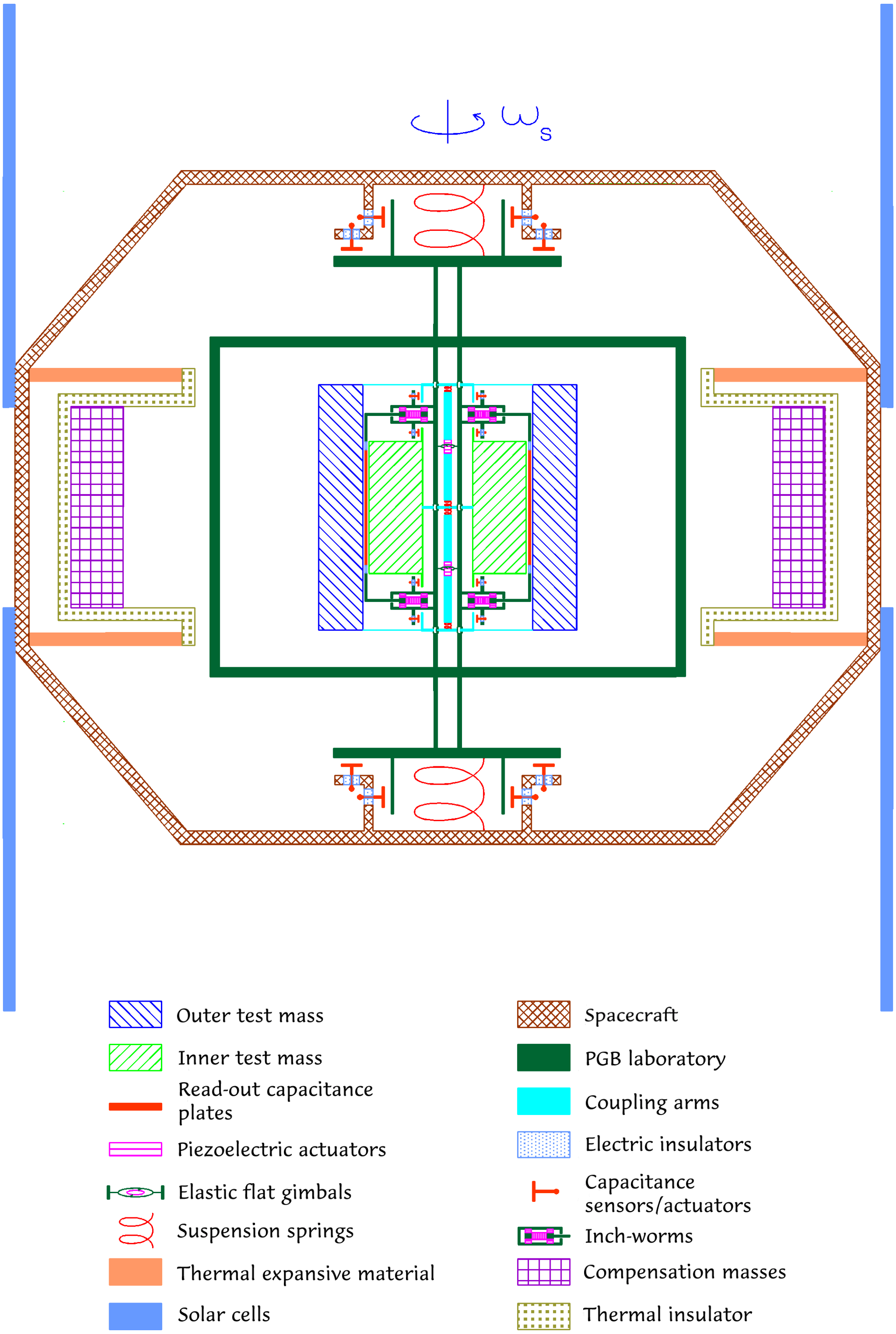


The GG s/c: 1 m wide, 1.3 m high, 250 kg mass

Orbits the Earth at 520 km altitude along an almost equatorial, almost circular orbit; spin axis almost perpendicular to orbit plane

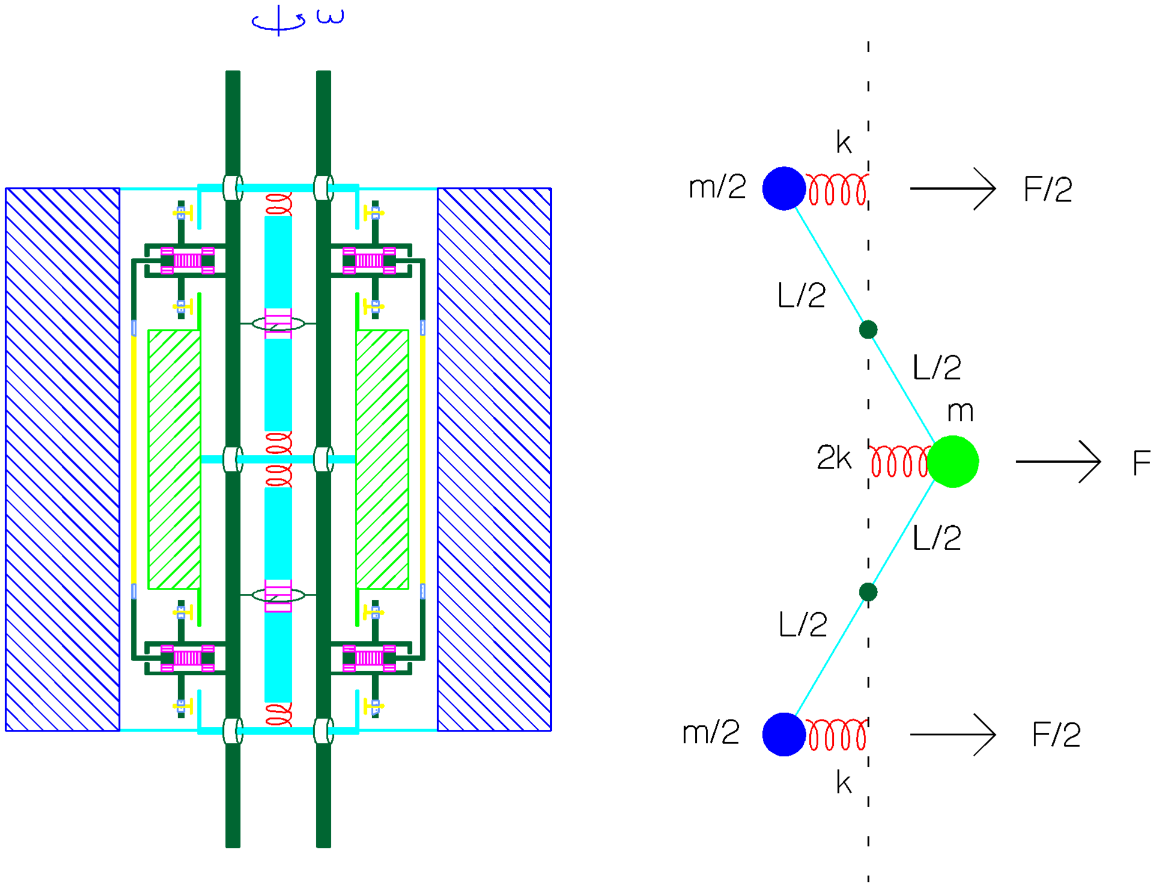
Passive stabilization by spin about symmetry axis; spin axis almost perpendicular to orbit plane. No active attitude control needed

Proposed space experiments: GG (II)



Section of the GG s/c through its spin axis

Proposed space experiments: GG (III)



Section of test cylinders showing that they are coupled like in an ordinary balance (with vertical beam) so that common mode effects can be rejected by adjusting the length of the arms by means of PZT actuators

Capacitance bridge sensors (shown in between test cylinders) will transform extremely small mechanical displacements into electric signals of $\cong$ *1 nV*. They have been realized in the lab reaching a sensitivity, on bench, of *5 pm* in *1 sec* integration time; which is adequate for the space test but is not yet confirmed with full system.

Prototype of the mechanical suspensions (helical springs and flat gimbals) have been manufactured (CuBe, electroerosion in 3D, thermal treatment...) and Q has been measured at the spin frequency (frequency relevant for losses in this sustem); we have obtained Q=19,000

Note that there is no electric signal going through the helical springs; electric connections are through the flat gimbals but with insulation only at the clamping. Fine coating will ensure the whole system to be electrically grounded . This is the core of the experiment and like in all gravitational small experiments it should be as passive as possible

Proposed space experiments: GG (IV)

Experiment is run at room temperature.

Since the expected signal is in the plane perpendicular to the spin/symmetry axis, relevant radiometer effect is zero to first order simply for symmetry reasons (radiometer acceleration has radial symmetry in the plane); deviations from symmetry due to imperfect alignment of axes is proved to be negligible.

Higher thermal noise (as compared to STEP) can be compensated for by more massive test bodies, because it is proportional to $\sqrt{(T/m)}$ (300 k over 10^4 gr in GG yields the same ratio as 3 K over 100 gr, which is the case for STEP)

Fast spin helps reduce thermal effects and gives requirements on thermal stability which can be met by means of passive isolation only

Not having He onboard, choice of drag compensation technology is free (drag effects are reduced partially by compensation, partially by common mode rejection).
We choose FEEP electric thrusters (Field Emission Electric Propulsion): proportional thrusters, fine electric tuning, very high specific impulse. Very small mass of Caesium propellant needed, no concern on its perturbations, no limitation on mission duration (a few tens of gram propellant enough for a few year mission duration)

Sensitivity of capacitance read out at room temperature well adequate; no need for low temperature sensors such as SQUIDs

With whole system spinning any local disturbing source rotates with the sensors and gives DC effect (i.e. local mass anomalies, parasitic capacitances, patch effects...)

Major tidal effects are at twice the orbit frequency (relative displacement fixed –or slowly moving- in the rotating frame)

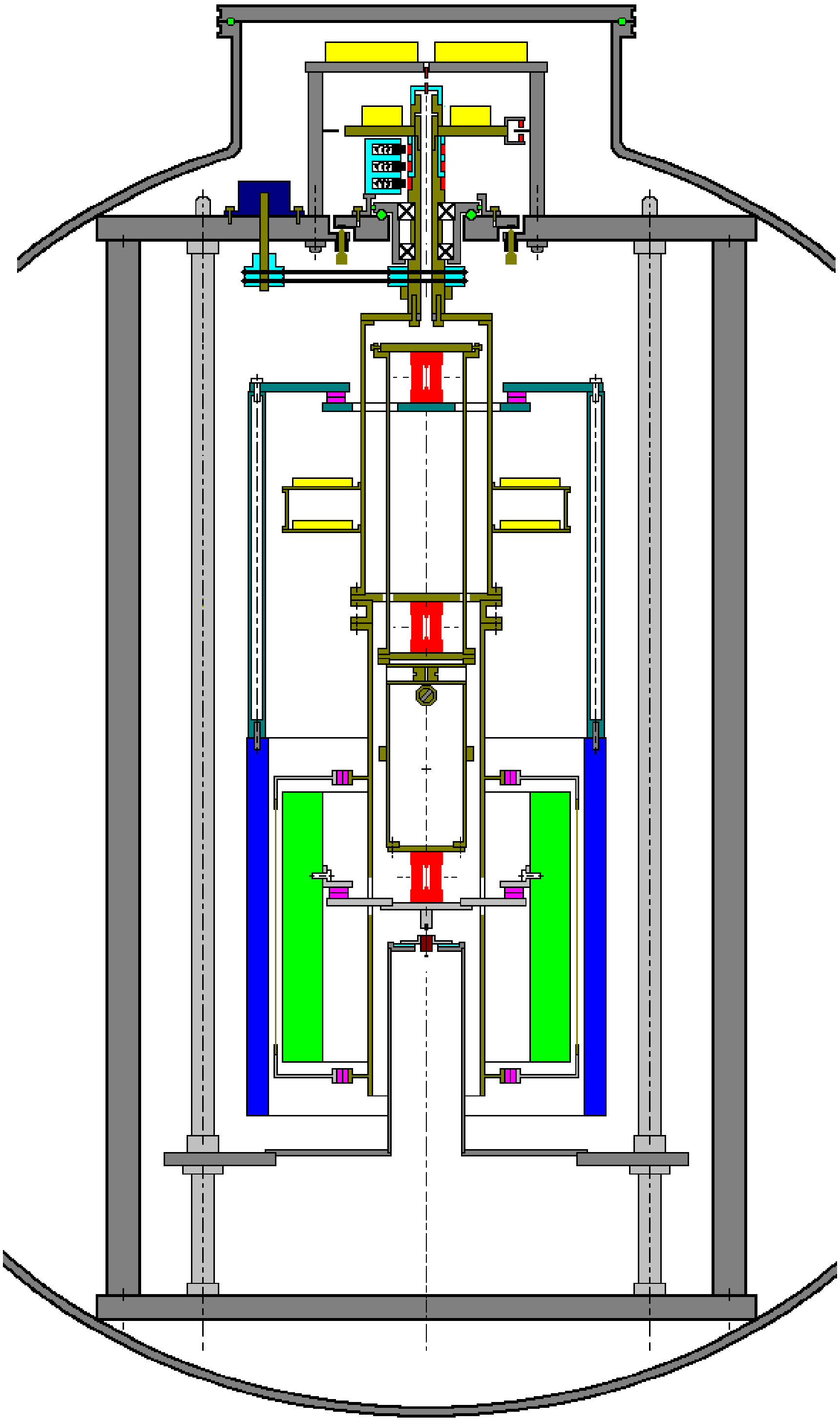
No need for magnetic shielding, requirements can be met (in torsion balance experiments magnetic torque, due to $B_\bullet$ competes directly with expected signal because they measure a torque, which is not the case here)

System can be fully tested on the ground looking for signal in the horizontal plane and using vertical direction to suspend rotors against local gravity

Supercritical rotation ensures good alignment of rotors axes; whirl instabilities are very slow and can be stabilized (simulated numerically and tested on ground)

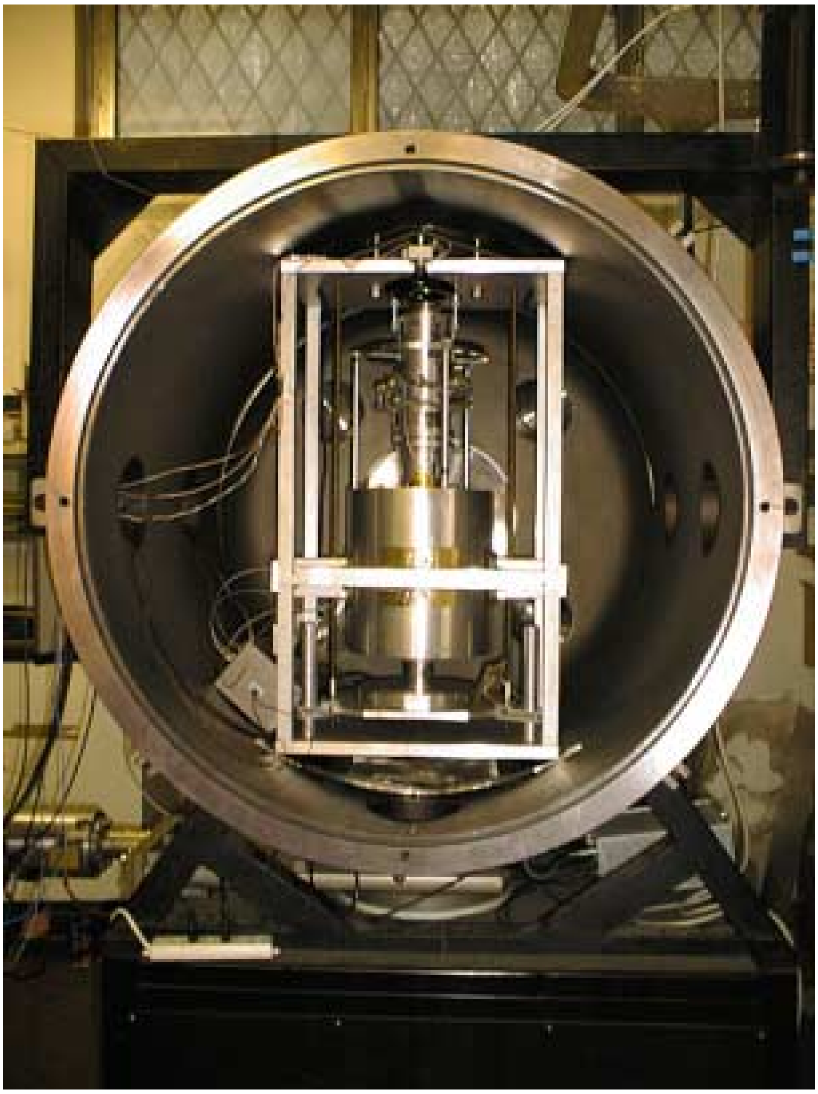
PRE PHASE A and PHASE A studies of GG (ASI 1996, ASI 1998) give an error analysis which is compatible with a target accuracy of 10^{-17} in EP testing

Ground test of proposed space apparatus: the GGG experiment ("GG on the Ground") (I)



Sketch of GGG apparatus mounted inside vacuum chamber (1 m diameter)

The GGG experiment (“GG on the Ground”) (II)

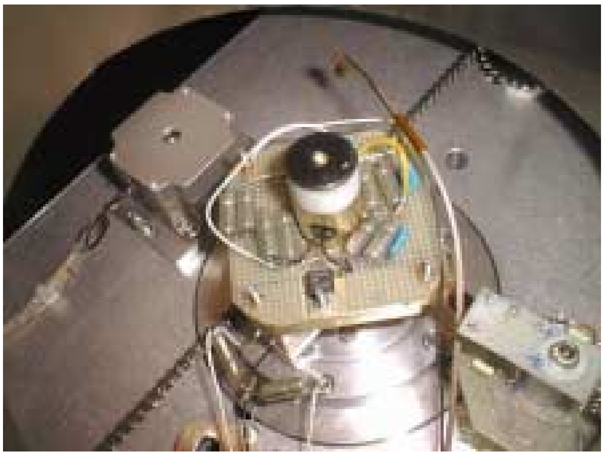


The GGG apparatus inside the vacuum chamber (in the basement of the laboratory)

The laminar suspension of the GGG apparatus (manufatured in CuBe, 3D electro erosion starting from a single piece). Design is such that they can withstand gravity in the vertical direction while allowing weak coupling in the horizontal plane were differential signal is expected

The GGG experiment ("GG on the Ground") (III)

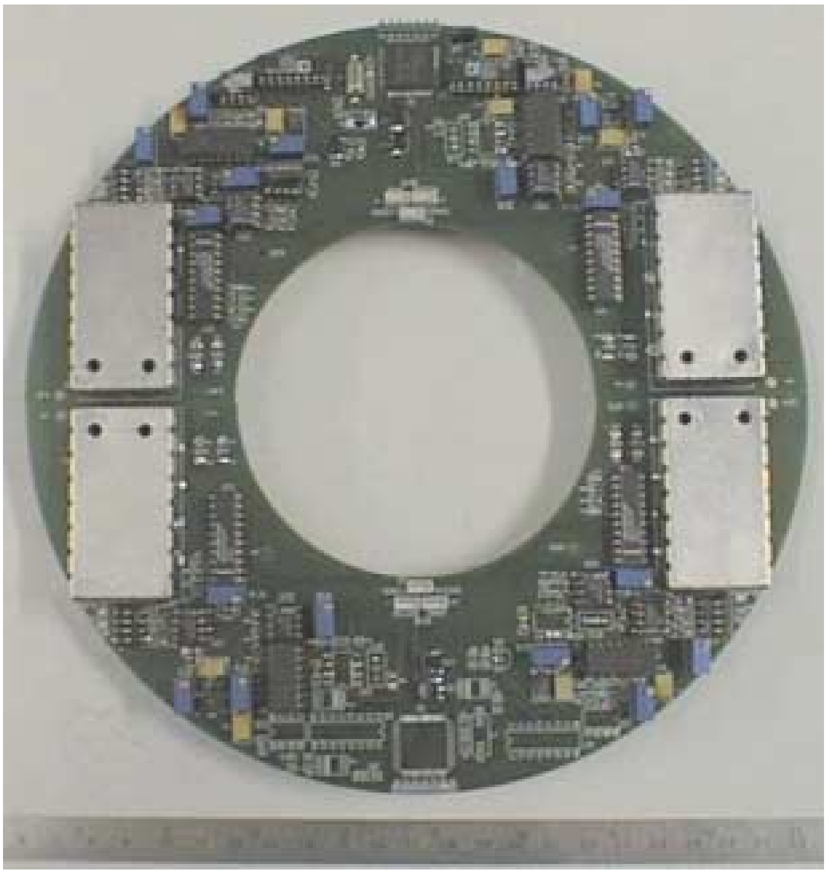
The GGG capacitance plates for measurement of relative displacements. On bench: **5·10^{-12} m in 1 sec** integration time; with full GGG system operational at 6 Hz rotation: **10^{-9} m s^{-2}/√Hz**



Led used for optical transfer of signals from the rotating appartus to the non rotating frame (then transferred outside teh vacuum chamber and acquired by the computer)

The capacitance plates (forming the two bridges of the read-out system) mounted in between the test cylindres (system operational at 6 Hz rotation rate)

The GGG experiment (“GG on the Ground”) (IV)

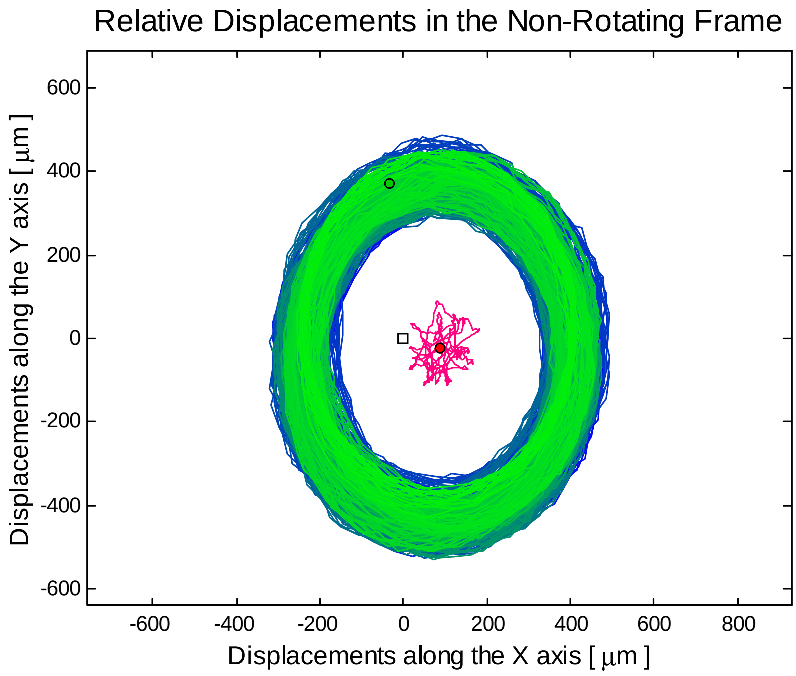


The electronic s of the read-out bridges (doubled for redundancy and symmetry)

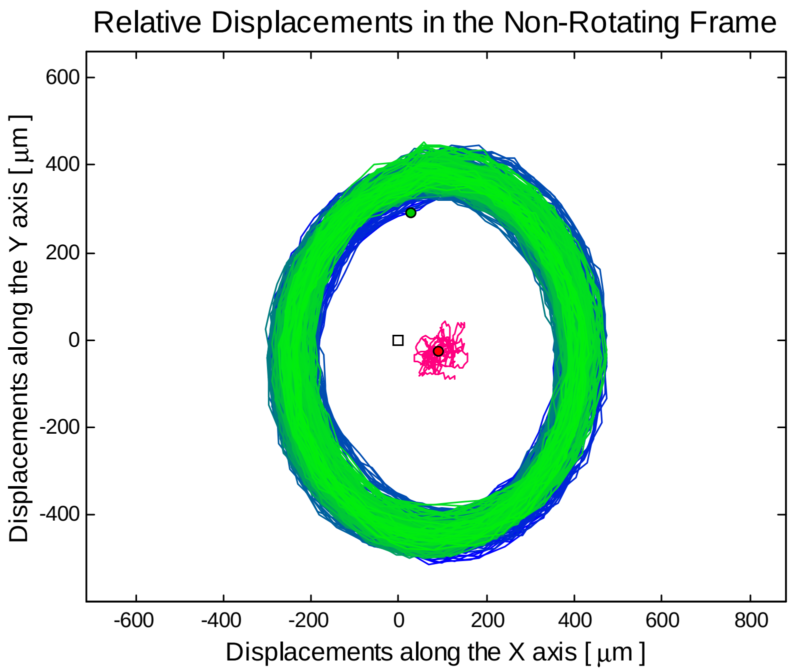
Electronics for optical transfer (20 signals per turn, with information on phase)

The GGG experiment ("GG on the Ground") (V)

February 25, run at 6 Hz, data set No. 7

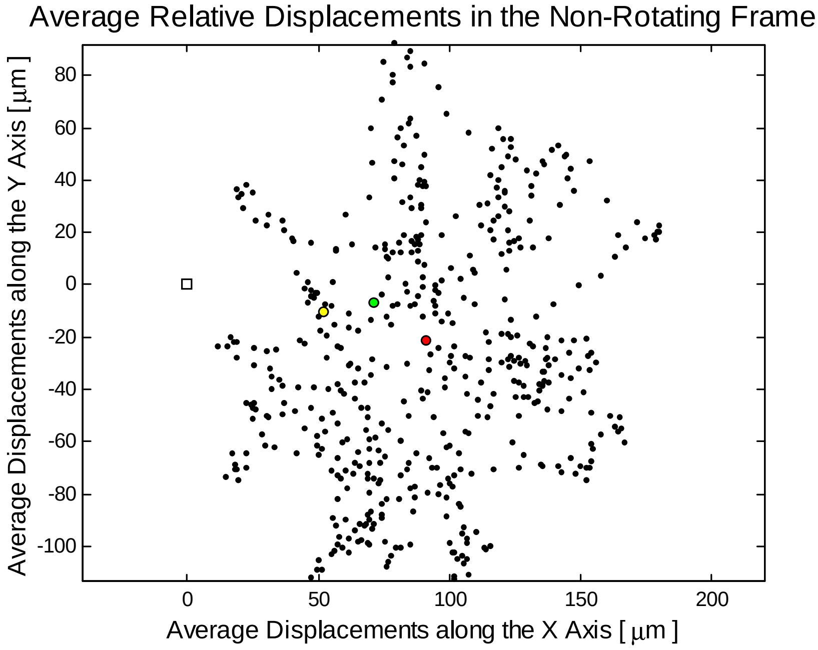


February 25, run at 6 Hz, data set No. 8

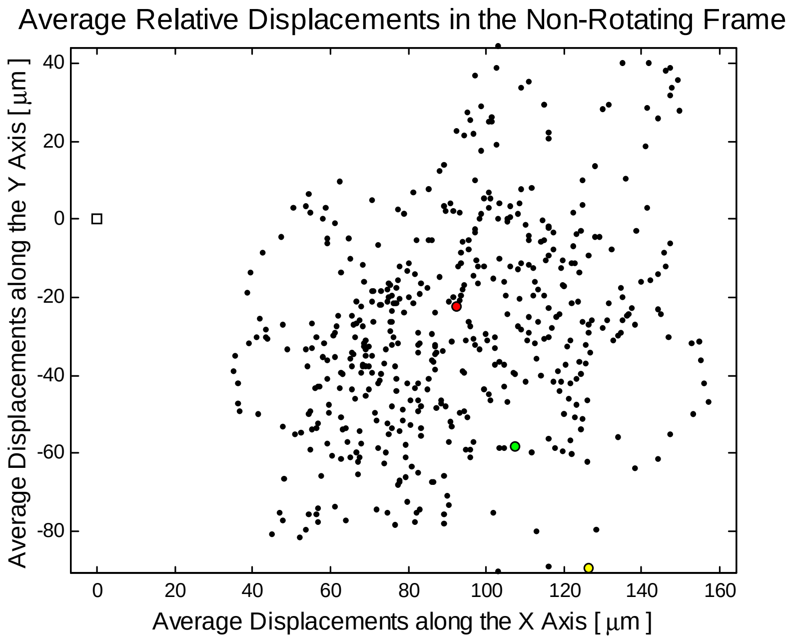


The GGG experiment ("GG on the Ground") (VI)

February 25, run at 6 Hz, data set No. 7



February 25, run at 6 Hz, data set No. 8

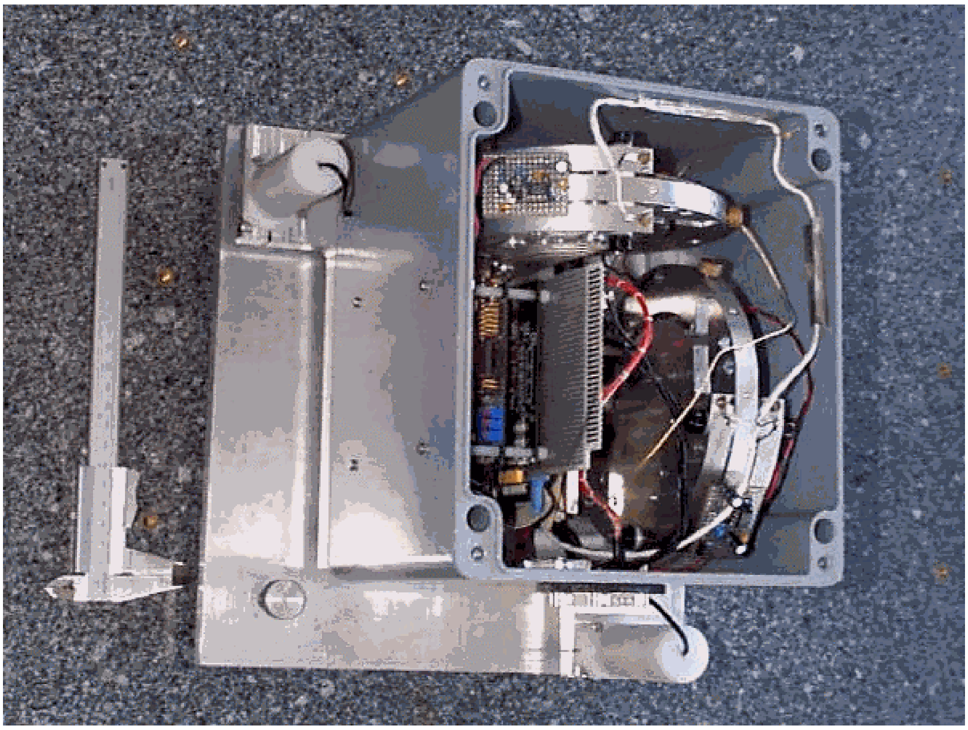


Proposed balloon test

A free fall experiment has been proposed for testing the Equivalence Principle inside a vacuum capsule to be released from a balloon at an altitude of 40 km, allowing a free fall time of 30 sec.

The gravity detector to be used is a differential version (zero baseline) of the ISA-Italian Spring Accelerometer, built at IFSI- CNR and tested in the Gran Sasso Laboratory by measuring Luni-Solar tides (torsional spring suspensions of test masses, capacitive pick ups). The sensitivity achieved, limited by seismic noise, is 10^{-9} m/s^2/√Hz

Signal modulation is achieved by spinning the detector to 1 Hz before release of the instrument inside the capsule.



3-Axis ISA accelerometer

Error analysis consistent with EP test to 10^{-15} (Iafolla et al., 1998)