Testing the Equivalence Principle

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Newton’s view

In the gravitational field of a source body (Earth):

$$m_i\vec{g} = -\frac{GM_{\oplus}m_g}{r^3}\vec{r}$$

1687 “PRINCIPIA” opening paragraph:

“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... ”

Equivalence of inertial to gravitational mass

⬇

All bodies fall with the same acceleration regardless of their mass or composition

Universality of Free Fall (UFF)

Galileo’s test of the Universality of Free Fall

Galileo: “e finalmente ho preso due palle, una di piombo ed 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 passo della leggiera, che né in ben cento vibrazioni, né in mille, anticipa il tempo d'un minimo momento, ma camminano con passo egualissimo. Scorgesi anche l'operazione del mezzo, il quale, arrecando qualche impedimento al moto, assai più diminuisce le vibrazioni del sughero che quelle del piombo, ma non però che le renda più o meno frequenti; anzi quando gli archi passati dal sughero non fusser più che di cinque o sei gradi, e quei del piombo di cinquanta o sessanta, son eglin passati sotto i medesimi tempi”.

[Galileo; Le Opere, Vol. VIII p. 128]

(Work done in Pisa ≈1600-1602, published nei “Discorsi” Leiden 1638)

Galileo’s test of the Universality of Free Fall

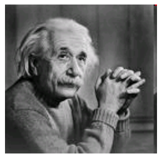
English translation from Galileo’s “Discorsi”: “Dialogues concerning two new sciences”

Accordingly I took two balls, one of lead and one of cork, the former more than a hundred times heavier than the latter, and suspended them by means of two equal fine threads, each four or five cubits long. Pulling each ball aside from the perpendicular, I let them go at the same instant, and they, falling along the circumferences of circles having these equal strings for semi-diameters, passed beyond the perpendicular and returned along the same path. This free vibration [per lor medesime le andate e le tornate] repeated a hundred times showed clearly that the heavy body maintains so

[129]

nearly the period of the light body that neither in a hundred swings nor even in a thousand will the former anticipate the latter by as much as a single moment [minimo momento], so perfectly do they keep step. We can also observe the effect of the medium which it offers to motion, diminishes the vibration of the cork more than that of the lead, but without altering the frequency of either; even when the arc traversed by the cork did not exceed five or six degrees while that of the lead was fifty or sixty, the swings were performed in equal times.

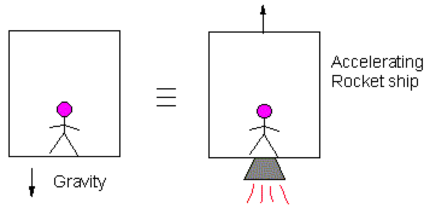
Einstein’s view (I)



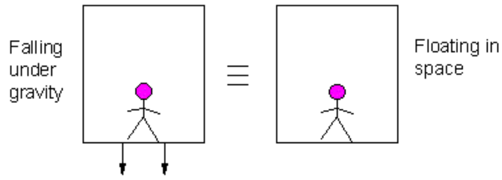
1907: “hypothesis of complete physical equivalence” between a gravitational field and an accelerated frame

Einstein, A.: Über das Relativitätsprinzip und die aus demselben gezogene Folgerungen.
Jahrbuch der Radioaktivitaet und Elektronik, 1907

An observer inside Einstein elevator close to the Earth will not be able to tell –before hitting the ground– whether he is falling with the local gravitational acceleration or else he is moving with an acceleration g in empty space, far away from all masses



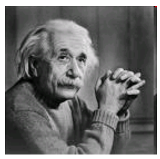
In a freely falling system all masses fall equally fast, hence gravitational acceleration has no local dynamical effects. Any test mass located inside Einstein’s elevator –falling with the local acceleration of gravity g near the surface of the Earth– and zero initial velocity with respect to it, remains motionless for the time of fall.



This is the Weak Equivalence Principle (WEP) (holds only locally)

…also implies UFF

Einstein’s view (II)



1916: Einstein Equivalence Principle (EEP) and the formulation of GR:

A. Einstein: Die grundlage der allgemeinen Relativitätstheorie, Annalen der Physik, 1916

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

C.M. Will, Living Rev. Rel. 2006 http://relativity.livingreviews.org/Articles/lrr-2006-3/

EEP –which assumes the WEP– ensures the fact that in GR the effects of gravity are replaced by a curved 4-dimensional space-time.

Einstein has moved from Newton’s concept of one global reference frame with gravitational forces and the UFF (which is a consequence of WEP), to many free falling local frames without gravitational forces (also a consequence of WEP)

Probing power of GR tests

GR is based on Einstein Equivalence Principle, which assumes the Weak Equivalence Principle

Tests of the WEP are tests of the foundations of GR, not of its predictions, hence have a stronger probing power (quantified…)

Damour CQG 1996; Damour, Piazza & Veneziano PRD 2002

Direct experimental consequence is the UFF. The physical quantity to measure is:

$$\eta \equiv \frac{\Delta a}{a} \equiv \frac{\text{differential acceleration between free falling test masses}}{\text{free fall acceleration of test masses}}$$

$$\eta = 0 \Rightarrow \text{UFF holds; no violation}$$

On the Earth and in its vicinity the strongest source field is that of Earth itself

The Standard Model and General Relativity

General Relativity (GR) and the **Standard Model** (SM) of particle physics form our current view of the physical world. GR governs physics in the macroscopic and cosmic scales; SM governs the physics of the microcosm.

Both very successful in their own fields, but so far could not be reconciled to form a single unified theory

SM: particle fields are defined on a flat Minkowski space-time ..

GR: postulates a curved space-time which evolves with the motion of mass-energy. In addition, quantum mechanics becomes inconsistent with GR near singularities.…

Attempts at reconciling these theories indicate that the pure tensor gravity of GR needs modification or augmentation. New physics is needed, involving new interactions which are typically composition dependent (i.e. would violate the Equivalence Principle on which GR is based).

“Did Einstein have the last word on gravity?”

“Committee on the Physics of the Universe” appointed by the National Research Council of the US National Academies.

The results of the panel’s work published in the book: **”Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century”,** (National Academies press, 2003).

3rd of the eleven questions: **“Did Einstein Have the Last Word on Gravity?”**:

“Black holes are ubiquitous in the universe. The effects of strong gravity in the early universe have observable consequences. Einstein’s theory should work as well in these situations as it does in the solar system. **A complete theory of gravity should incorporate quantum effects—Einstein’s theory of gravity does not—or explain why they are not relevant.”**

“Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century” National Academies press, 2003

“Dark Energy Task Force”

Dark Energy Task Force (**DETF**) established in the US by the Astronomy and Astrophysics Advisory Committee and the High Energy Physics Advisory Panel to advise the Department of Energy, NASA and the National Science Foundation on future dark energy research.

From **Dark Energy Task Force** (**DETF**) Report, the Executive Summary reads:

“…One possible explanation for dark energy may be Einstein's famous cosmological constant. Alternatively, dark energy may be an exotic form of matter called quintessence, **or the acceleration of the Universe may even signify the breakdown of Einstein's Theory of General Relativity.** With any of these options, there are significant implications for fundamental physics. “

Report from the Dark Energy Task Force, available online at http://www.nsf.gov/mps/ast/aaac/dark_energy_task_force/report/detf_final_report.pdf, 2006

Predictions of (W) Equivalence Principle violation

Within a classical framework (which does not postulate any new interaction) Fishbach & al consider the contribution to the mass-energy of a nucleus arising from neutrino-antineutrino exchange and using and exact quantum mechanical calculation find EP violations of the order of one part in 10^{17} between different materials, depending on the proportion of neutrons and protons that they contain.

Fischbach et al.: “Higher order weak interactions and the equivalence principle” PRD, 1995

Beyond the standard model, predictions based on string theory and the existence of dilaton lead to the conclusion that, within a new scenario for the dilaton, the equivalence principle might be violated already below about 10^{-12} (in the case of test masses made of Cu, Be or Pt, Ti)

Damour & Polyakov, Nucl. Phys. B 1994; GRG 1994
Damour, Piazza & Veneziano: “Violations of the equivalence principle in a dilaton-runaway scenario” PRD, 2002
“Runaway Dilaton and Equivalence Principle Violations” PRL 2002

Deviation from UFF / EP violation: the signal (I)

Target sensitivity of EP test $\eta \equiv \dfrac{\Delta a_{EP}}{a}$

Test masses (suspended) in the field of the Earth

$$\Delta a^{\oplus}_{EP,NS} = \eta \cdot \omega^2_{\oplus} \cdot R_{\oplus} \cdot \cos\vartheta \cdot \sin\vartheta$$

Test masses in the field of the Sun

$$\Delta a^{\odot}_{EP,NS} = \eta \cdot G \frac{M_{\odot}}{R^3_{\odot}} \cdot (r_y \sin\vartheta - r_z \cos\vartheta) \qquad \Delta a^{\odot}_{EP,EW} = \eta \cdot G \frac{M_{\odot}}{R^3_{\odot}} \cdot r_x$$

$$\vec{r} = \vec{R}_{\odot} - \vec{R}_{lab} = \left(R_{\odot} \cos\delta \sin H,\ R_{\odot} \cos\delta \cos H - R_{\oplus} \cos\vartheta,\ R_{\odot} \sin\delta - R_{\oplus} \sin\vartheta \right)$$

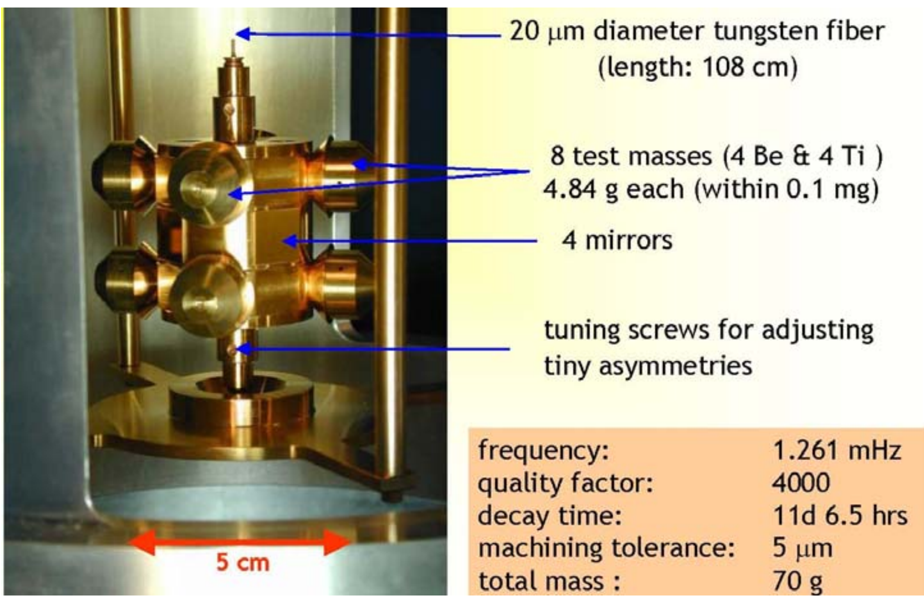
$$\vec{R}_{\odot} = R_{\odot} (\cos\delta \sin H,\ \cos\delta \cos H,\ \sin\delta)$$

Deviation from UFF / EP violation: the signal (II)

Acceleration due to EP violation to level η (m/s^2)		
Type of test	Source mass	
	Earth	Sun
● Lab - Pendulum like	$1.69\cdot10^{-2}\cdot\eta$ (max @ 45° *latitude*)	$6\cdot10^{-3}\cdot\eta$ (max)
Lab - Mass dropping Galileo like	$9.8\cdot\eta$	$6\cdot10^{-3}\cdot\eta$ (max)
Low Earth orbit	$\simeq 8.4\cdot\eta \quad (h\simeq 500\,km)$	$6\cdot10^{-3}\cdot\eta$ (max)

The best lab test (I)

$$\eta^{\oplus}_{Be-Ti} \equiv (0.3\pm1.8)\cdot10^{-13}$$



S. Schlamminger, K.-Y. Choi, T. A. Wagner, J.H. Gundlach, and E. G. Adelberger: "Test of the Equivalence Principle Using a Rotating Torsion Balance". PRL 2008

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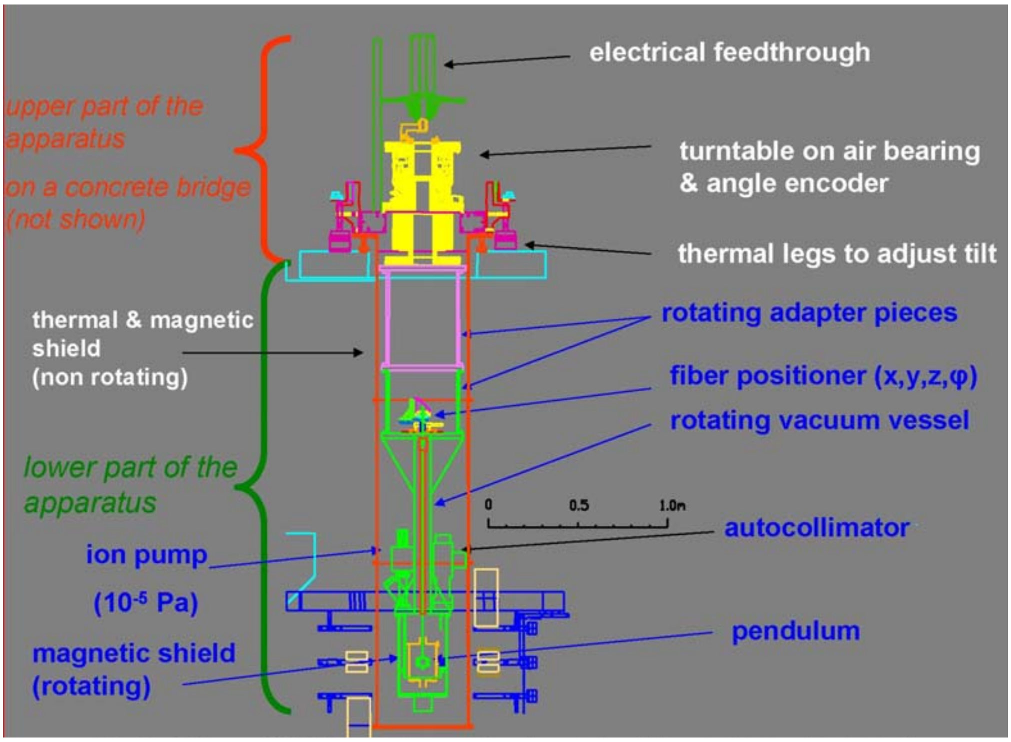


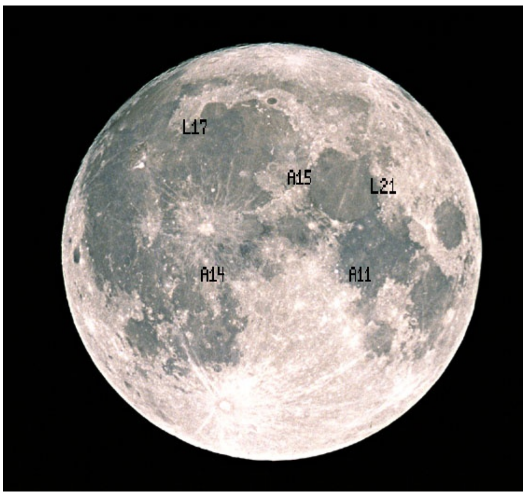
S. Schlamminger, K.-Y. Choi, T. A. Wagner, J.H. Gundlach, and E. G. Adelberger: "Test of the Equivalence Principle Using a Rotating Torsion Balance". PRL 2008

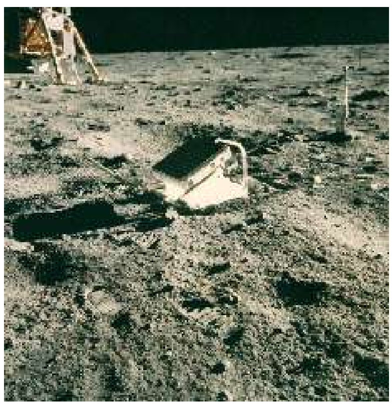
The best LLR test (II)

$$\eta^{\odot}_{EM} = (-1.0 \pm 1.4) \cdot 10^{-13}$$

$$\eta^{\odot}_{SEP\,EM} = (4.4 \pm 4.5) \cdot 10^{-4}$$

LLR only can test the Strong Equivalence Principle (contribution to EP from self energy of falling bodies). To be complemented by composition laboratory tests with test bodies with Earth-like & Moon-like composition





Williams, J.G., Turyshev, S.G., and Boggs, D.H., "Progress in lunar laser ranging tests of relativistic gravity" PRL 2004

State of the art (I)

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	$(1.3\pm1)\times10^{-11}$
Braginsky & Panov JETP 1972	Torsion balance. 8TMs. Not rotating. 24hr modulation by Earth rotation	Sun	Al – Pt	$(-0.3 \pm 0.9)\times10^{-12}$
E. Fischbach et al.: "Reanalysis of the Eötvös Experiment" PRL 1986				
Eöt-Wash, PRD 1994	Rotating torsion balance. ≈ 1hr modulation	Earth	Be – Cu	$(-1.9 \pm 2.5)\times10^{-12}$
			Be – Al	$(-0.2 \pm 2.8)\times10^{-12}$
Eöt-Wash, PRL 1999	Rotating torsion balance. 1hr to 36' modulation	Sun	Earthlike/ Moonlike	$\approx 10^{-12}$ (SEP 1.3×10^{-3})
Eöt-Wash, PRL 2008	Rotating torsion balance. 20' modulation	Earth	Be – Ti	$(0.3 \pm 1.8)\times10^{-13}$

Prospects for improvements (I)

- Rotating torsion balances: $\eta_{Eot-Wash} \simeq 10^{-14}$?!?

- LLR with APOLLO

$$\eta_{\min APOLLO} \simeq 3\frac{\Delta a_{meas}}{d_{\odot}} \simeq 3\frac{10^{-3}\ m}{1.5\cdot10^{11}\ m} \simeq 2\cdot10^{-14}$$

Limitation more stringent for LAGEOS… (testing Yukawa like deviation does not help)

$$\eta_{\min-Lageos} \simeq 3\frac{\Delta a_{Lageos}}{a_{Lageos}} \simeq 3\frac{10^{-2}\ m}{1.23\cdot10^{7}\ m} \simeq 2.4\cdot10^{-9}$$

Nobili et al.: "Limitations to testing the equivalence principle with satellite laser ranging" GRG 2008

Prospects for improvements (II)

- New Galileo like "mass dropping" tests: interferometry of free falling cooled atoms

Dimopoulos, S., Graham, P.W., Hogan, J.M., Kasevich,M.A.: "Testing General Relativity with Atom Interferometry" PRL 2007

Best measurement of free fall gravitational acceleration with cooled atoms so far

$$\frac{\Delta g}{g} \simeq 10^{-9}$$

Peters, A., Chung, K.Y., Chu, S.: "Measurement of gravitational acceleration by dropping atoms", Nature 1999

.. concern about composition: proposed test of equivalence between atoms ^{85}Rb and ^{87}Rb … differing by only 2 neutrons!!! makes the case for violation weak

- ISA like differential accelerometer dropped inside a capsule in a balloon flight. Aim to $\eta \simeq 10^{-14} \div 10^{-15}$

Iafolla, V., Lorenzini, E.C., Milyukov, V., Nozzoli, S.: "Methodology and instrumentation for testing the weak equivalence principle in atmospheric free fall" Rev. Sci. Instrum. 1998.

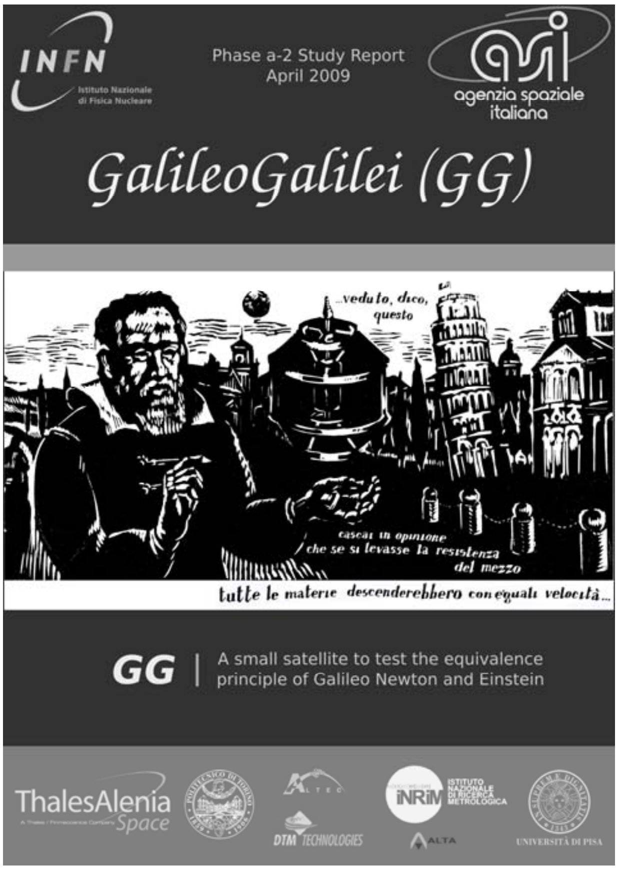
.. move the lab to low Earth orbit!

- Signal stronger by about 10^3 (for free..)
- Weightlessness: weak coupling of test masses easy (low coupling frequency)

$$sensitivity \propto 1/\omega_{diff}^2$$

- Lab (the s/c) is an isolated system
  - rotation of s/c provides passive attitude stabilization & signal modulation (no motor, no bearings, no noise…)
  - no local terrain tilts …
  - local mass anomalies minimized…
- Use very accurate in situ measurement device as in ground lab (absolute measurements from ground not needed – only relative displacements of test masses matter for testing UFF & EP (can be sensed to subpicometer level…)

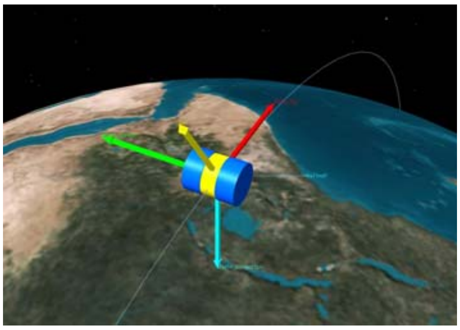
“Galileo Galilei (GG)”



GG undergoing Phase A-2 Study by ASI (Agenzia Spaziale Italiana) Preliminary (April 2009) Report available on the Web:

http://eotvos.dm.unipi.it/PA2

Satellite, orbit and the VEGA launcher



To fly in near circular near equatorial orbit

To be operated from Italian station in Malindi (Kenya)

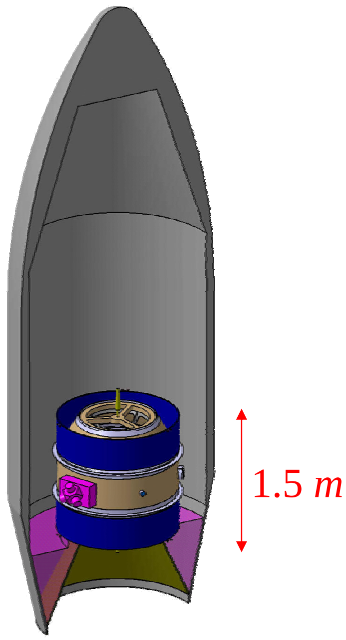
500-600 km altitude

Passive attitude stabilization by 1-axis rotation at 1 Hz

400 kg total mass

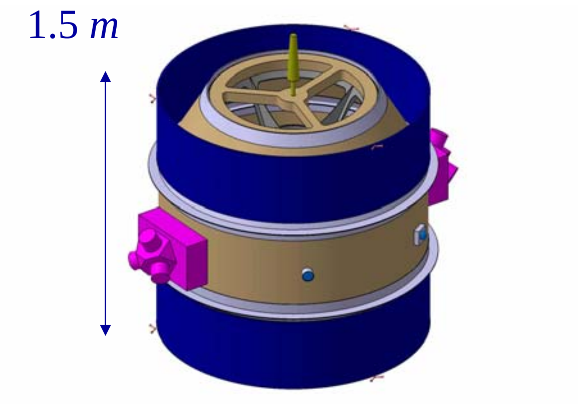
Drag Free Control

2 yr nominal mission duration

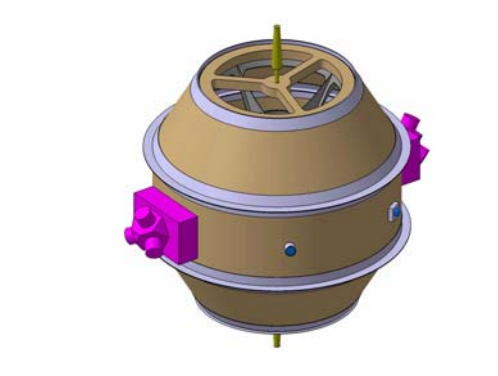


GG satellite in the bay of the VEGA launcher (Kourou launch site)

GG satellite



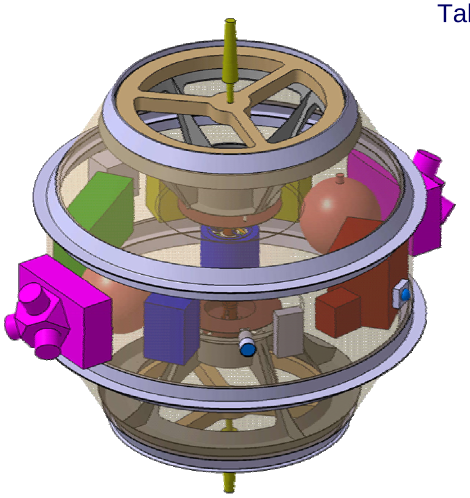
GG satellite with solar panels

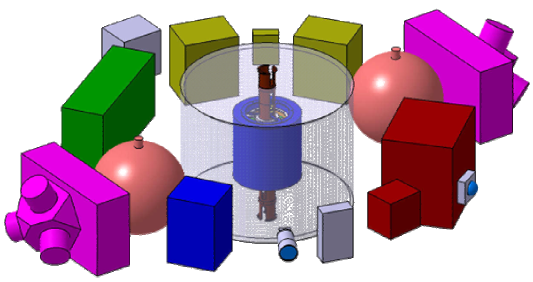


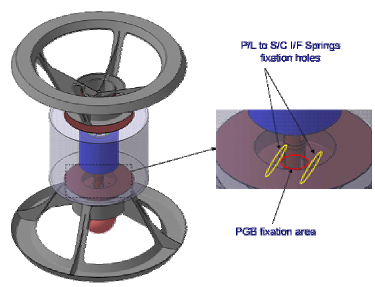
GG “spinning top”

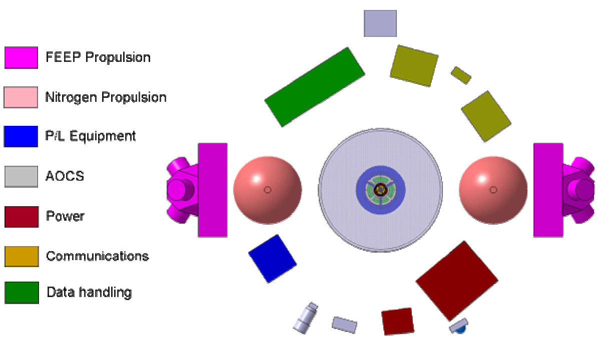
Satellite and payload

Take advantage of launcher capabilities (in terms of mass and room)

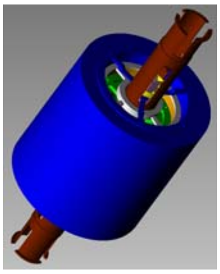
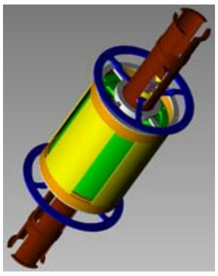
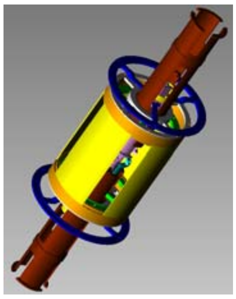
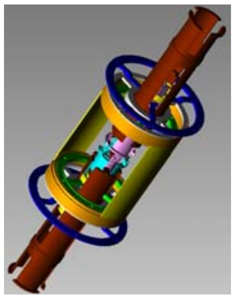


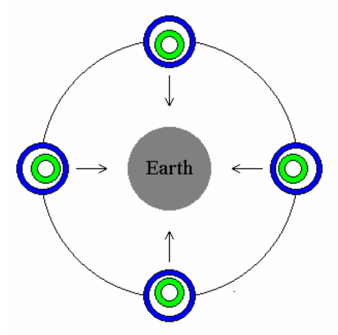


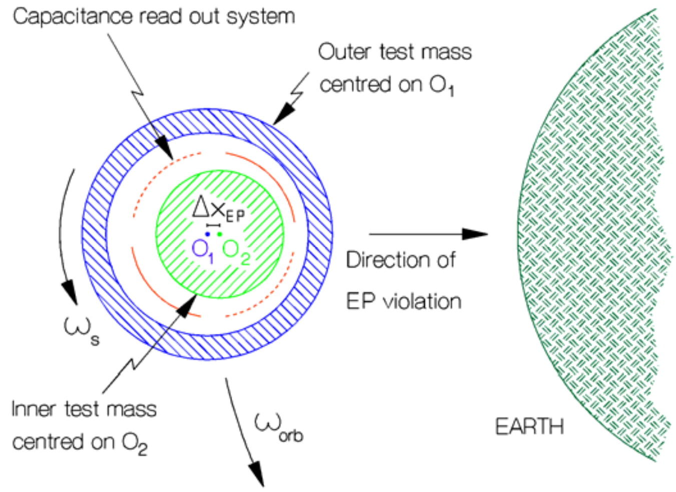




The GG differential accelerometer





Drivers and requirements: some numbers (I)

DRIVER #1: THE SIGNAL

$\eta = 10^{-17}$	**EP test GG mission target expressed in terms of the Eötvös parameter**	
$h = 5.2 \cdot 10^5\ m$ $(a = 6.898 \cdot 10^3\ km)$ $(\nu_{orb} = 1.754 \cdot 10^{-4}\ Hz \quad P_{orb} = 5.7 \cdot 10^3\ s)$	Orbit altitude satellite tracking accuracy no issue	
	$g(h) = 8.38\ ms^{-2}$	driving gravitational acceleration
	$a_{EP} = g(h) \cdot \eta = 8.38 \cdot 10^{-17}\ ms^{-2}$	signal acceleration
$e \simeq 0.01$	orbital eccentricity (standard)	
$I \simeq 5°$	orbital inclination (typical for launch from Kourou)	
$\theta_i \leq 1°$	spin axis to orbit normal angle at start (after spin up)	
$P_{dm} = 540\ s$	Natural period of test masses oscillations in differential mode	
	$\Delta x_{EP} = \frac{a_{EP}}{4\pi^2} \cdot P_{dm}^2 = 0.62 \cdot 10^{-12}\ m$	Signal displacement
$SNR = 2$	Signal to noise ratio	
$T_{int} = 7 \cdot 86400\ s$	Minimum Integration time	

Drivers and requirements: some numbers (II)

DRIVER #2: EXTERNAL NON GRAVITATIONAL FORCES

$(A/M)_{GG} \le 0.05\ m^2 kg^{-1}$	Maximum area to mass ratio of GG satellite
$a_{NG} \le 2 \cdot 10^{-7}\ ms^{-2}$	Maximum external non gravitational acceleration on GG in the sensitive plane
$(a_{NG})_z \le 5 \cdot 10^{-8}\ ms^{-2}$	Maximum external non gravitational acceleration on GG along axis
$\chi_{DFC} \le 1/50000$	Maximum compensation of non grav acc in the sensitive plane
$(\chi_{DFC})_z \le 1/500$	Maximum compensation of non grav acc along axis
$a_{i\_cm} = a_{NG} \cdot \chi_{DFC} \le 4 \cdot 10^{-12}\ ms^{-2}$	maximum common mode non grav acc on test masses in sensitive plane
$(a_{i\_cm})_z = (a_{NG})_z \cdot (\chi_{DFC})_z \le 10^{-10}\ ms^{-2}$	maximum common mode non grav acc on test masses along axis
$P_{cm} = 30\ s$	Natural period of test masses oscillations in common mode
$P_z = 30\ s$	Natural period of test masses oscillations along axis
$\Delta r_{cm} = \frac{a_{i\_cm}}{4\pi^2} \cdot P_{cm}^2 \le 9.1 \cdot 10^{-11}\ m$	maximum common mode displacement of test masses in sensitive plane
$\Delta z_{cm} = \frac{(a_{i\_cm})_z}{4\pi^2} \cdot (P_{cm})_z^2 \le 2.3 \cdot 10^{-9}\ m$	maximum common mode displacement of test masses along axis
$\chi_{CMR} \le 1/100000$	Maximum rejection of common mode effects in the sensitive plane
$(\chi_{CMR})_z \le 1/50$	Maximum rejection of common mode effects along axis
$\chi = \chi_{DFC} \cdot \chi_{CMR} \le 2 \cdot 10^{-10}$	Maximum total reduction of non grav acc in the sensitive plane
$\chi_z = (\chi_{DFC})_z \cdot (\chi_{CMR})_z \le 4 \cdot 10^{-5}$	Maximum total reduction of non gav acc along axis
$a_{dm} = a_{NG} \cdot \chi \le 4 \cdot 10^{-17}\ ms^{-2}$	maximum perturbing differential acceleration on test masses in sensitive plane
$(a_{dm})_z = (a_{NG})_z \cdot \chi_z \le 2 \cdot 10^{-12}\ ms^{-2}$	maximum perturbing differential acceleration on test masses along axis
$\Delta r_{dm} = \frac{a_{dm}}{4\pi^2} \cdot P_{dm}^2 \le 0.3 \cdot 10^{-12}\ m$	maximum differential displacement of test masses due to external non gravitational forces in sensitive plane
$\Delta z_{dm} = \frac{(a_{dm})_z}{4\pi^2} \cdot (P_{dm})_z^2 \le 4.6 \cdot 10^{-11}\ m$	maximum differential displacement of test masses due to external non gravitational forces in sensitive plane
$\chi_{bridge} \le \frac{\Delta x_{gp}}{\Delta r_{cm}} \simeq 6.8 \cdot 10^{-3}$	Maximum fractional mechanical unbalance of capacitance bridges
$d_{bridge} = 2.5 \cdot 10^{-3}\ m$	bridge gap
$\Delta d_{bridge} \le d_{bridge} \cdot \chi_{bridge} \le 1.7 \cdot 10^{-5}\ m$	Maximum mechanical unbalance of capacitance bridges
$P_{PGB} = 360\ s$	Natural oscilaltion period of PGB in the sensitive plane
$(P_{PGB})_z = 30\ s$	Natural oscilaltion period of PGB along axis

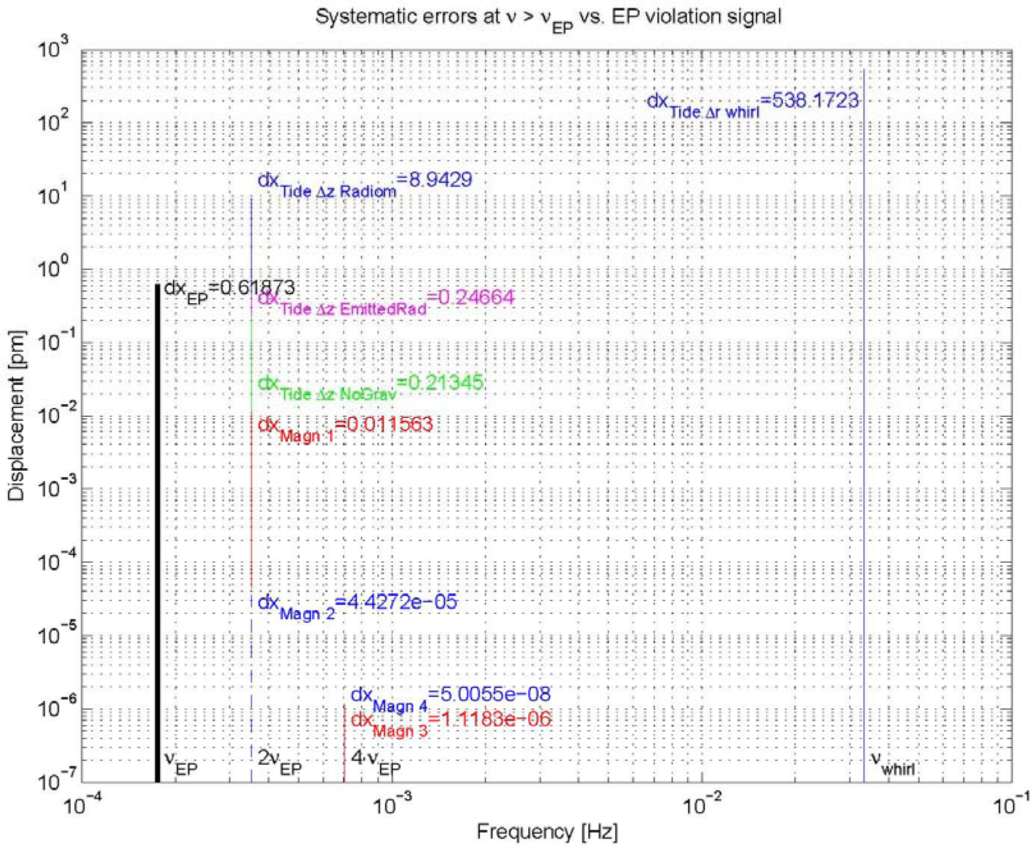
Error budget (I)

How it is built

- Establish requirements
- Implement Drag Free Control
- Run GG Simulator
- Analyze time history of test masses relative displacements
- Single out systematic effects and check their magnitude and signature

Heritage from GOCE!

Error budget (II)



Test masses material choice in GG (I)

Co-rotation makes many disturbing effects DC. Test masse do not need to be manufactured to very high precision. This gives more freedom in the choice of materials so as to maximize possibility of EP violation and significance of test

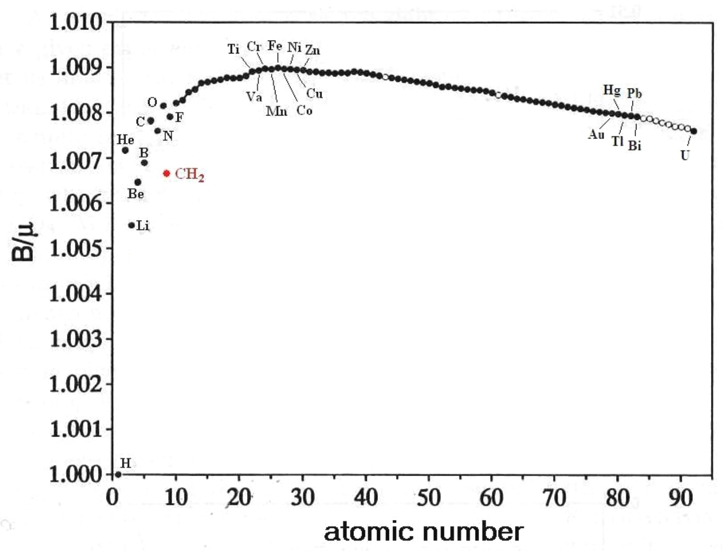
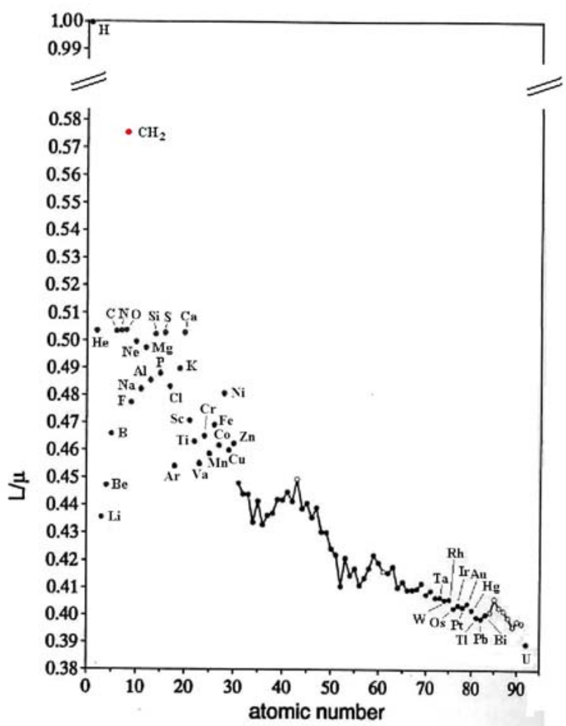
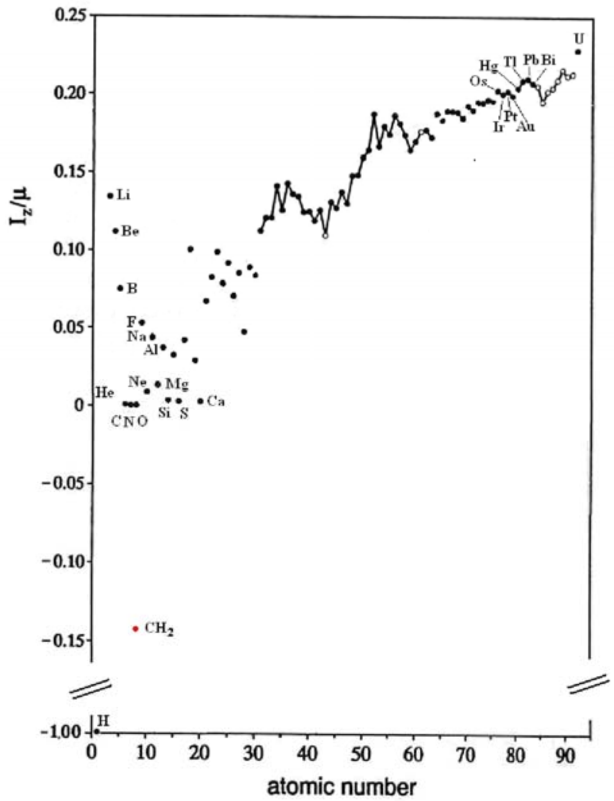


Figure adapted (CH_2 added) from : E. Fischbach, C. L. Talmadge: “The Search for Non-Newtonian Gravity; Springer- Verlag, New York, 1998.

Test masses material choice in GG (II)



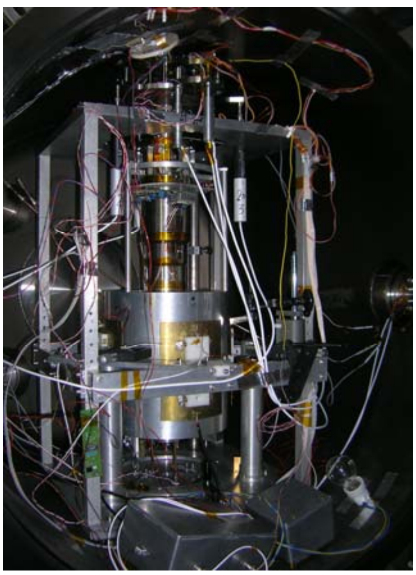


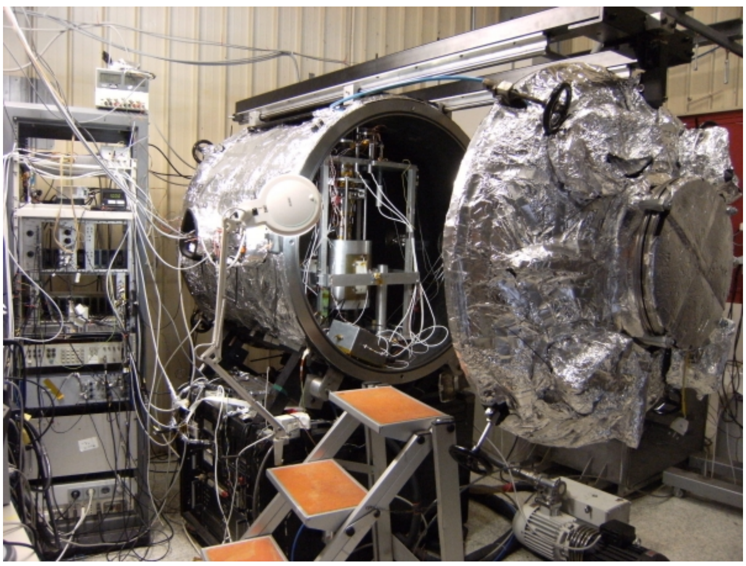
Figures adapted (CH_2 added) from : E. Fischbach, C. L. Talmadge: "The Search for Non-Newtonian Gravity; Springer- Verlag, New York, 1998.

A simulator in the lab: "GG on the Ground (GGG)"

Same number of degrees of freedom; same dynamical properties; position of relative equilibrium of the test masses in the horizontal plane is NOT stabilized by local gravity (as it should be as a test of experiment in space…)

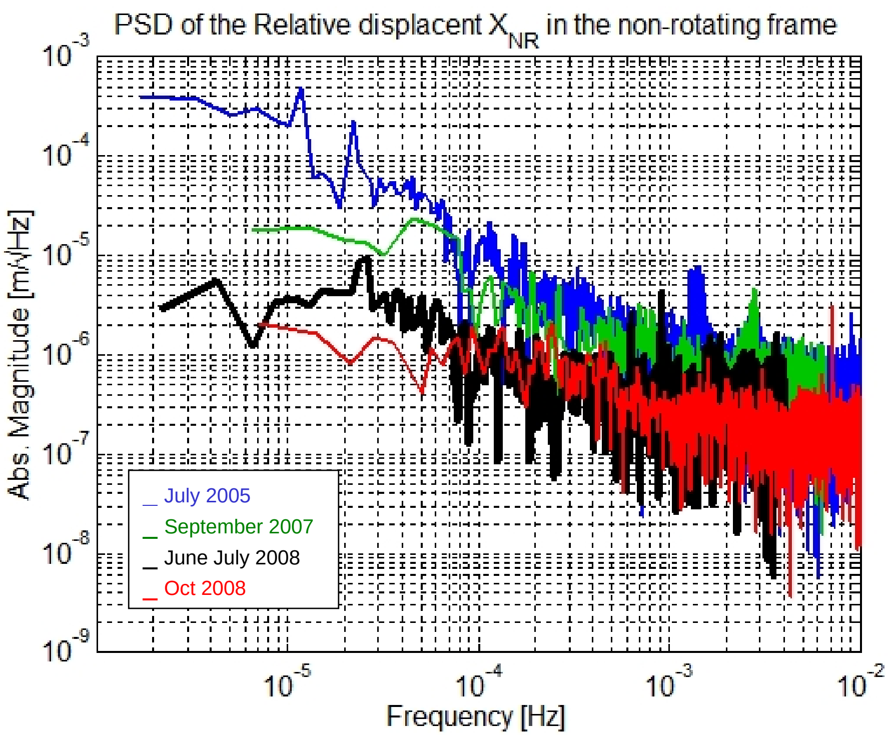
GGG lab at INFN Pisa-San Piero a Grado



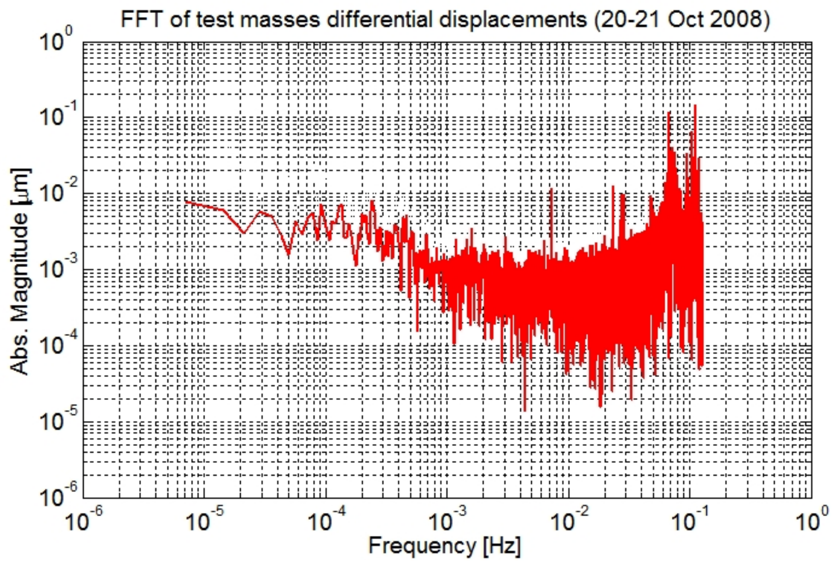


Comandi et al.: Rev. Sci. Instrum. 2006 I; 2006 II

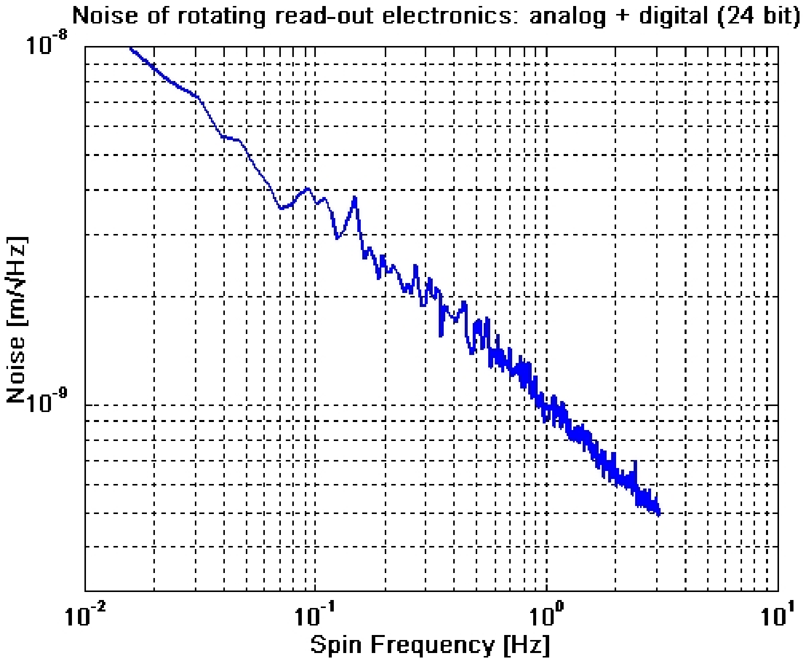
GGG sensitivity (I)



GGG sensitivity (II)

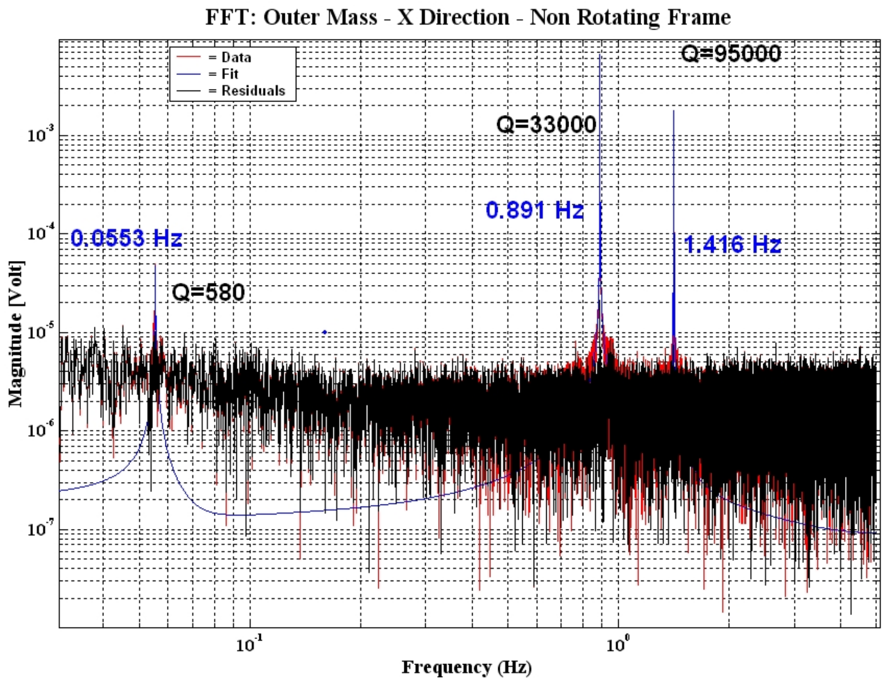


Measured electronic noise

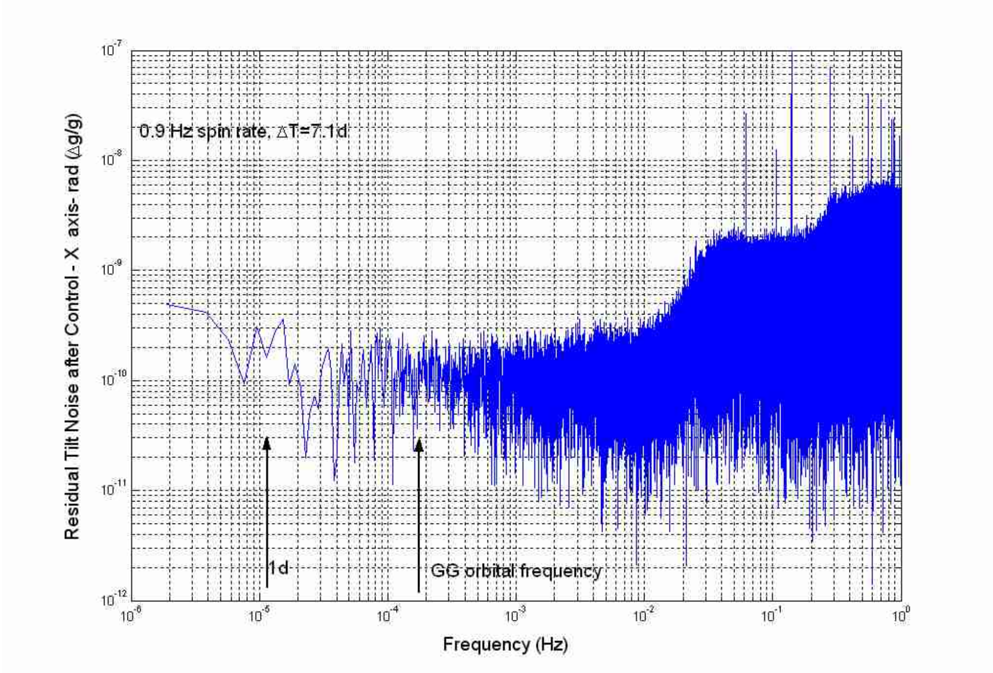


Advantage of high frequency modulation is apparent!

Measured Q



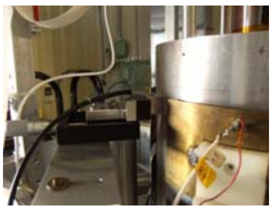
Terrain tilts control loop



Control loop works very well. Problem is temperature dependence of tilt sensor!

Need for thermal stabilization…

Measurement of electric patch effects (I)

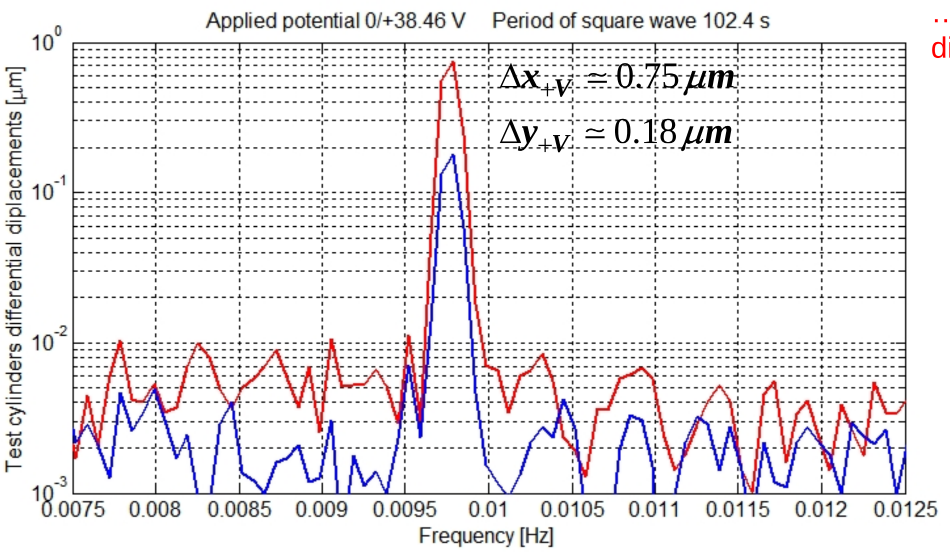


$$F_V = \frac{Q^2}{2\varepsilon_o S}$$

$$Q = VC\ ,\quad C = \frac{\varepsilon_o S}{d}$$

Charge changes sign with applied potential, patch charge does not change sign with applied potential, force (always attractive) is proportional to total charge squared

Note: in GG/GGG patches would rotate with the test masses … not competing directly with signal!



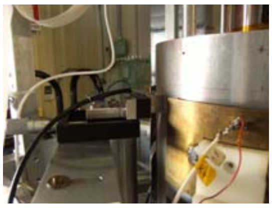
with

$$T_{diff\ x} \simeq 15.3\,s$$

$$T_{diff\ y} \simeq 12.2\,s$$

$$m = 10\,kg$$

Measurement of electric patch effects (II)

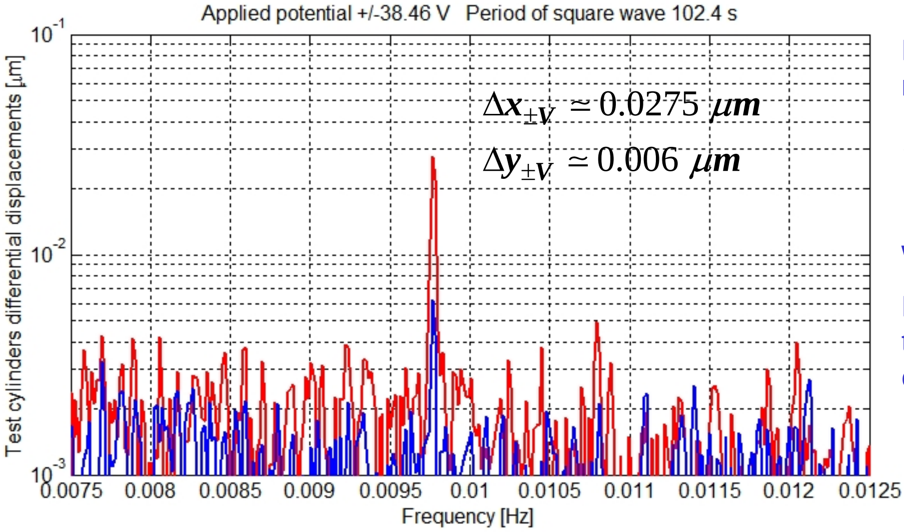


$$F_{\pm V} \equiv F_{patch} = \frac{2Qq}{\varepsilon_o S}$$

q is the charge of patch we want to measure

$$\frac{displacement_{\pm V}}{displacement_{+V}} = 4\frac{q_{patch}}{Q_{+V}} = 4\frac{V_{patch}}{V_{+V}}$$

by measuring the displacements in the two cases we measure V_{patch} …



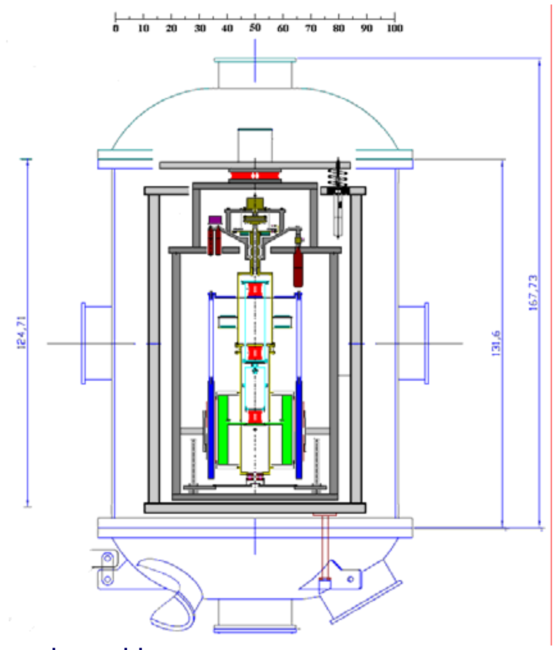
From these measurements:

$$V_{patch} \simeq 0.3V$$

with $S = 4cm^2$

Plate made of Al like test cylinders, no gold coating….

Advanced GGG under construction



Chamber with correct symmetry

Active + passive tilt reduction

Improved accelerometer

GGG Simulator to be built (like GG Simulator) to be compared with measurements …