GGG

Un accelerometro differenziale in rotazione veloce per la verifica del principio di equivalenza

Raffaello Pegna
INFN-Sezione di Pisa, 23 Giugno 2010

GGG: “GG on the Ground”
Laboratory experiment in preparation for the GG (“Galileo Galilei”) experiment in Low Earth Orbit

GG science target:

test the Equivalence Principle (founding pillar of General relativity) to 10^{-17}
(4 orders of magnitude improvement)

Relevance of GG science target to Physics:

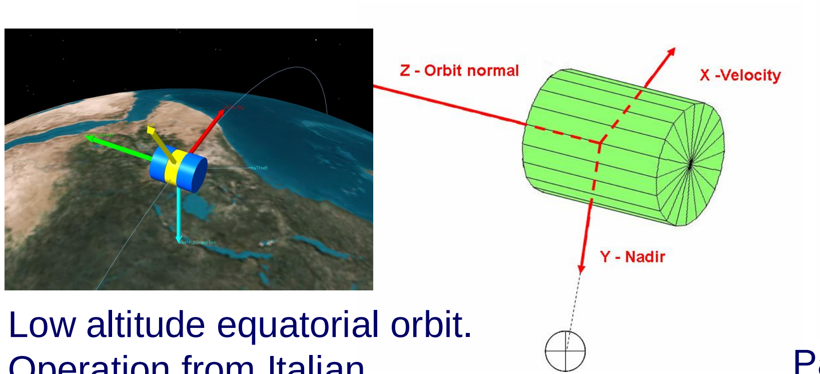
Violation would directly imply the existence of a new physical interaction in Nature (revolutionary…)
Confirmation to such a very high precision will tightly constrain physical theories for decades

Relevance of GG science target to Cosmology:

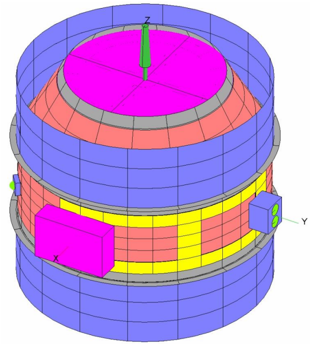
Dark matter and dark energy limit the known mass of the Universe to only 5% of the total!!!
Big problem…
It calls for large scale space missions for in situ measurements (e.g. EUCLID mission under study in ESA and JDEM mission under study in NASA)
& fundamental tests of gravity (EP test in primis – Microscope approved by CNES-France; STEP under study at NASA)

GG Phase A-2 Study

GG Phase A-2 Study funded by ASI completed in 2009 at TAS-I (TO) with support from GG/GGG scientists

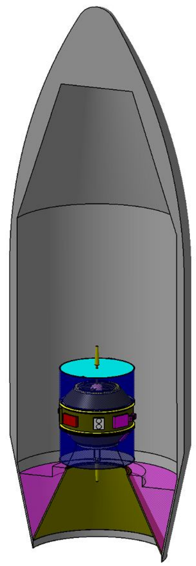


Low altitude equatorial orbit. Operation from Italian station in Malindi (Kenya)



Passive stabilization by 1-axis rotation (cylinder height: 1.5 m)

GG inside Italian Vega launcher (double launch possible; Kourou launch site)



TAS-I Study based on heritage expertise from GOCE (flying successfully…) for Drag Free Control and 3D GG experiment simulator + relevant input data from GGG lab experiment

Results of GG Phase A-2 Study (full documentation delivered to ASI):

- **Error budget consistent with science target**
- **Mission feasible in 3 years from start of Phase B at total cost of 69.560 M€** (to include all mission costs except launch with VEGA)

JPL proposal to ASI

June 10, 2010:
Jacob van Zyl, Head of Astronomy & Physics Directorate of JPL (Jet Propulsion Laboratory of Caltech & NASA) writes to ASI proposing a collaboration of JPL on GG. As a source for funding JPL participation in GG van Zyl envisages an opportunity announced by NASA for late this year: NASA Call named SALMON "Stand Alone Mission of Opportunity" – to provide up to 30M$ for participation of American scientists in Non-NASA missions

For JPL scientists to apply to the SALMON Call of NASA in order to fund their participation in GG, <u>GG should enter Phase B Study within ASI</u> …

JPL contribution to GG

JPL has proposed to replace the GG capacitance read-out with a laser interferometry gauge developed by Mike Shao for SIM mission under many years of NASA funding and capable do detect 1 pm displacements in about 1 sec (very high sensitivity + differential)

Informal Workshop

"Galileo Galilei" (GG) and GGG lab prototype: state of the art and new possibilities

Pisa (Italy) 10-12 February 2010

http://eotvos.dm.unipi.it/Workshop2010/index.html

Would such high sensitive (differential) read out allow GG to achieve an EP test to 10^{-18} ?

GG thermal noise revisited

Quoting from the Workshop summary notes:

Since in GG the signal is read at the rotation/modulation frequency of 1Hz, and the displacement thermal noise of the proof masses is inversely proportional to the square of the frequency at which displacement is modulated, **thermal noise in GG is a factor 1 million smaller** than in similar EP experiments where rotation frequencies are inevitably (by design) much smaller (10^{-3} Hz in other satellite experiments as well as in rotating torsion balances)

This explains why thermal noise of the **LIGO and VIRGO** mirrors above a few tens of Hz has values orders of magnitude well below the picometer. **In GG, by up-converting the frequency of an EP violation signal in the field of the Earth from its (low) orbital frequency of 1.7×10^{-4} Hz to the (high) rotation/modulation frequency of 1 Hz (the highest ever in EP experiments) proof mass thermal noise is reduced by orders of magnitude, as the ratio of these frequencies squared. Instead, cooling the experiment to superfluid He temperature would only reduce thermal noise by a factor 10.**

…GG: towards an EP test to 10^{-18}

A very low thermal noise allows the target signal to be detected in a much shorter integration time, results in a very high duty cycle and allows high precision differential measurements by the laser gauge to be fully exploited. We therefore plan to carry out a careful re-analysis of all systematic perturbations in GG so as to possibly aim at testing the EP one order of magnitude better than in the current error budget, i.e. to 10^{-18}. The end-to-end GG simulator built at TAS-I in 2009 during GG Phase A-2 study is the crucial tool that allows this analysis to be performed in a reliable way and in a short time, **at the very beginning of GG Phase B Study should ASI approve it** … (analysis already started..)

Common paper with JPL in preparation:

"Abatement of thermal noise in Equivalence Principle tests using rapidly rotating macroscopic test masses", by Nobili, Pegna, Shao et al. 2010

State of the art in EP testing

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	$(1.3 \pm 1) \times 10^{-11}$
Braginsky & Panov JETP **1972**	Torsion balance. 8TMs. Not rotating. 24hr modulation by Earth rotation	Sun	Al – Pt	$(-0.3 \pm 0.9) \times \mathbf{10^{-12}}$
E. Fischbach et al.: “Reanalysis of the Eötvös Experiment” PRL 1986				
Eöt-Wash, PRD **1994**	Rotating torsion balance. ≈ 1hr modulation	Earth	Be – Cu	$(-1.9 \pm 2.5) \times \mathbf{10^{-12}}$
			Be – Al	$(-0.2 \pm 2.8) \times 10^{-12}$
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	$(0.3 \pm 1.8) \times \mathbf{10^{-13}}$

Worldwide attempts at improving

Differential accelerometer in a capsule from balloon flight (IFSI, SAO) 10^{-14}

Sounding rocket test (SAO-NASA) 10^{-15}

Microscope (satellite test) (CNES with ESA contribution Under constructiuon) 10^{-15}

MWXG (satellite test, cold atoms) (proposal) 10^{-16}

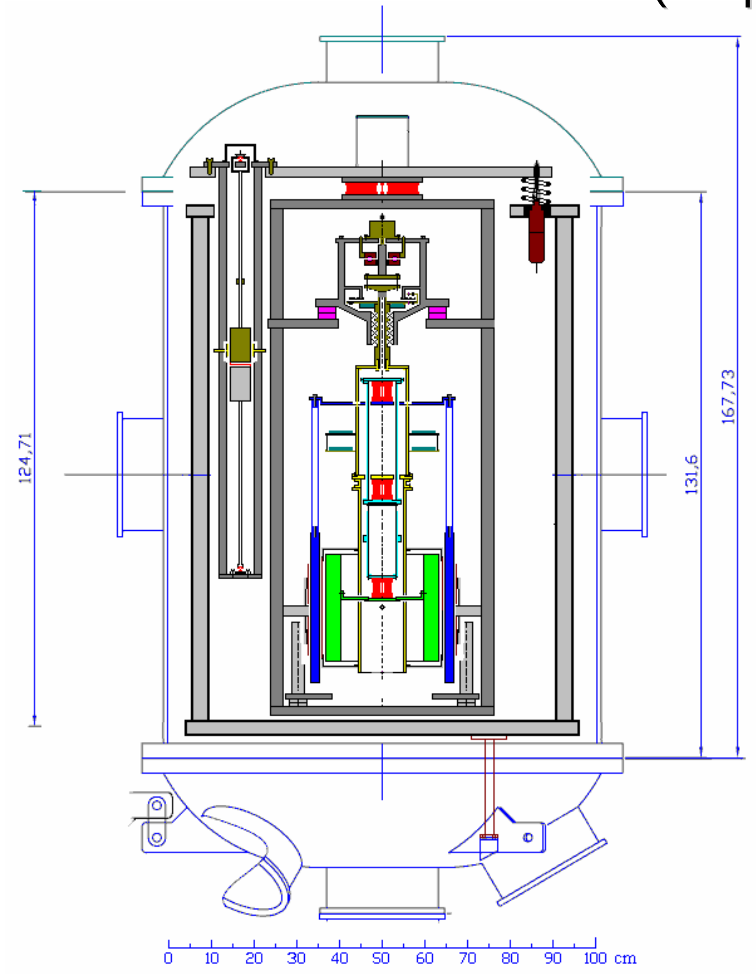
STEP (satellite test, cryogenic) (NASA) 10^{-18}

+ lab tests with torsion balances (and cold atoms trying to catch up..)

+ lunar laser ranging tests with improved laser&telescope (APOLLO)

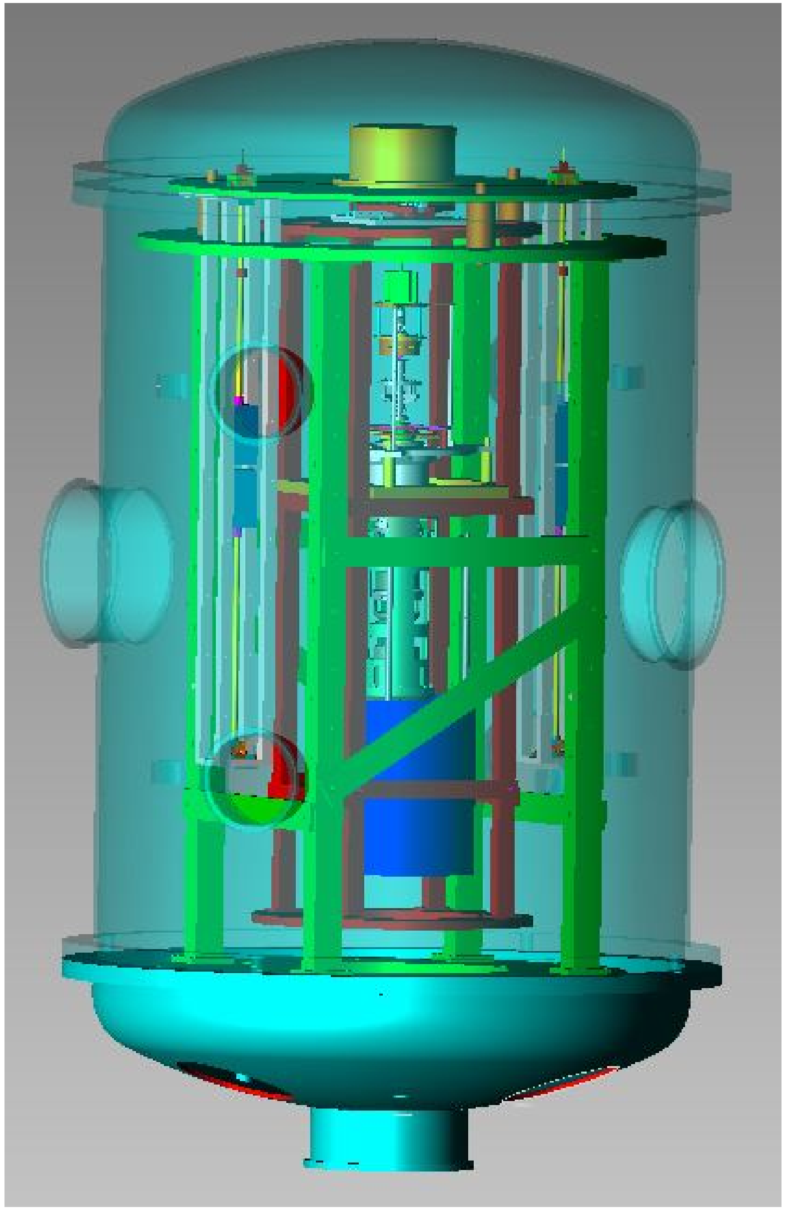
GG highly competitive: target close to STEP, non cryogenic, much less expensive + full scale lab prototype

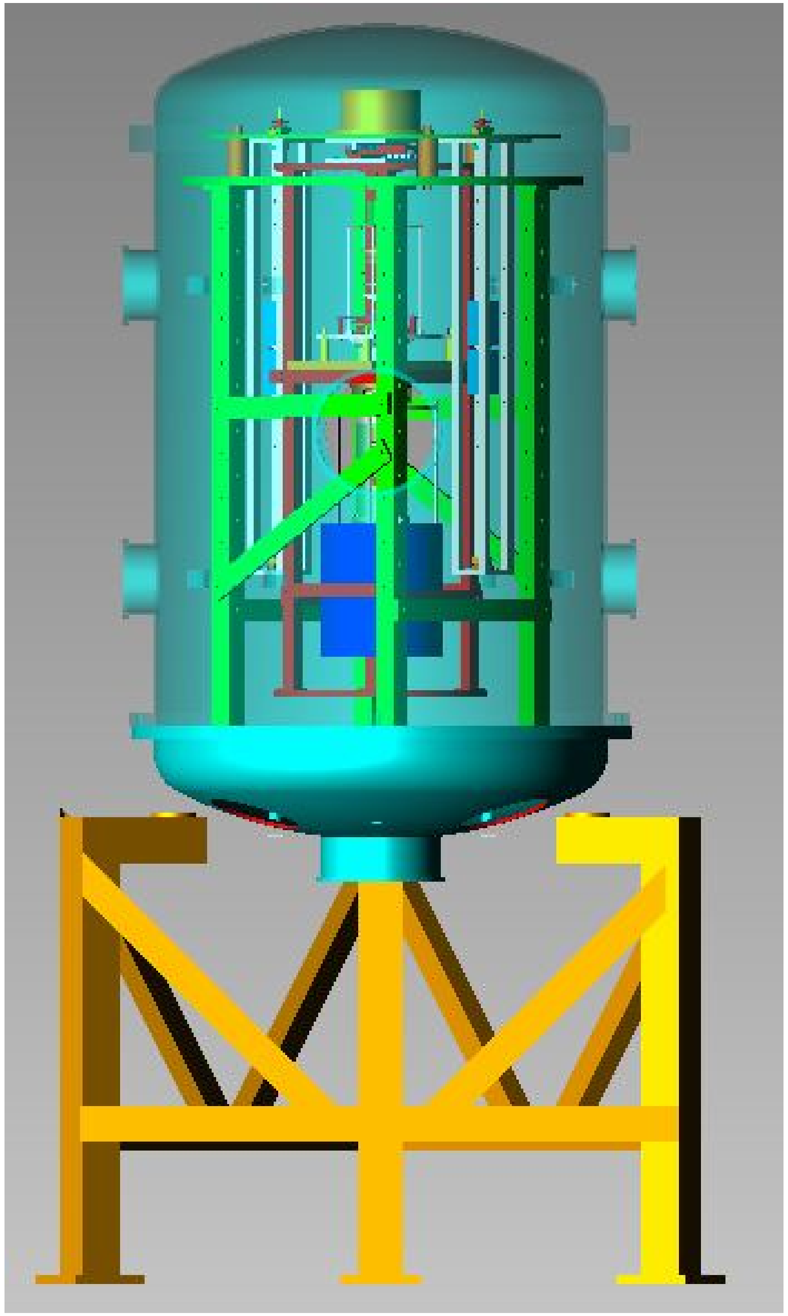
sGGG (suspended GGG) - ASI funds (I)



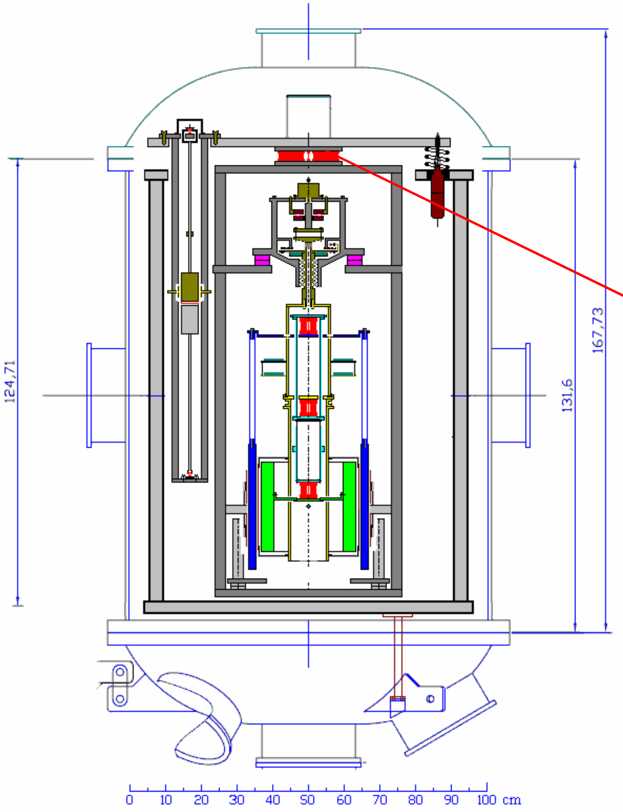
- New chamber has the right symmetry and has been designed to minimize disturbances on GGG experiment
- **sGGG will be suspended inside chamber by cardanic joint** (not rotating) to reduce low frequency terrain tilts passively, in addition to active tilt control now in use (Note: active tilt control is limited by thermal effects on tilt sensor and requires good thermal stabilization to be effective)

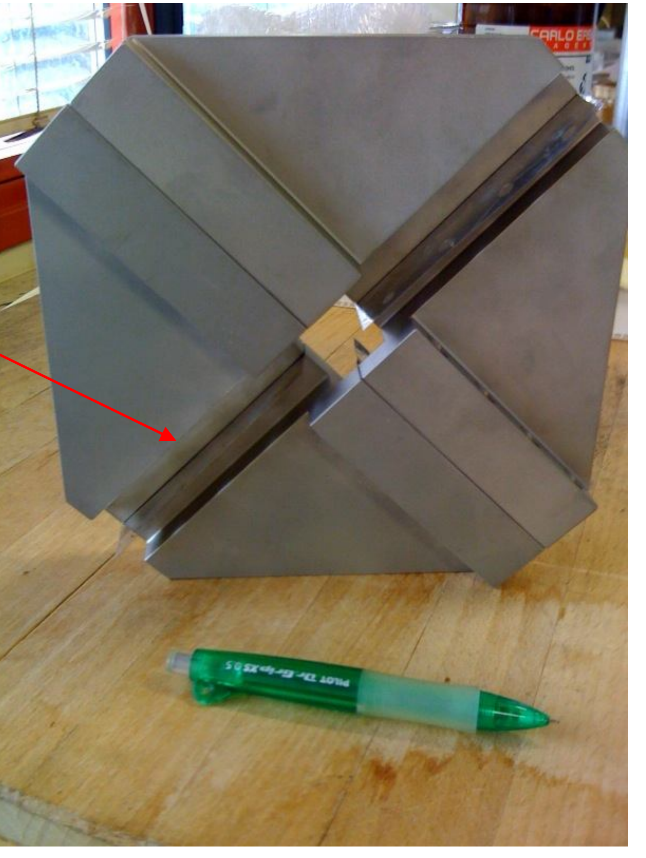
sGGG (suspended GGG) - (II)





Passive attenuation of low frequency terrain tilt noise (I)





Cardanic suspension for low frequency attenuation in the plane (only 2 lamellae of 1 direction visible)

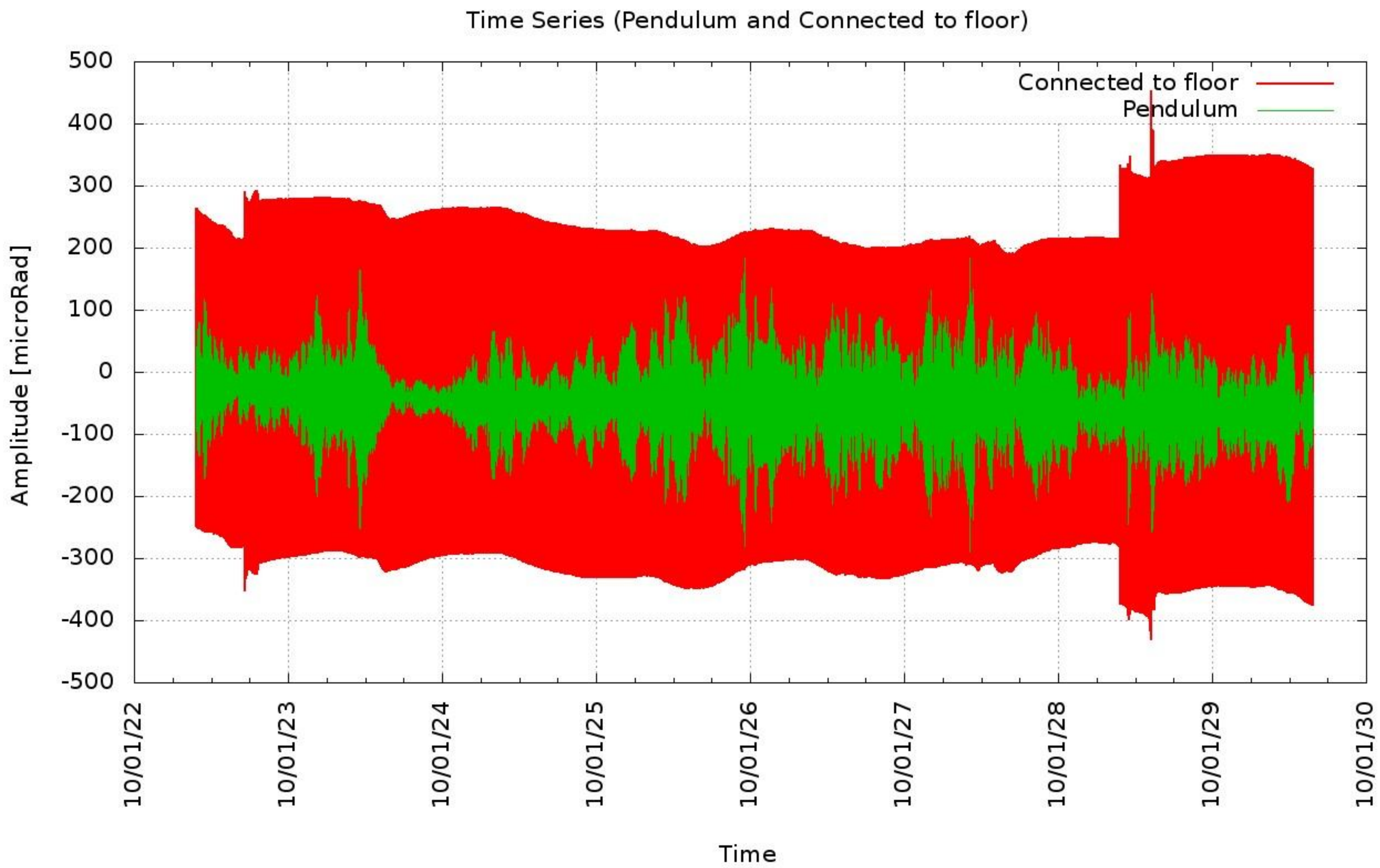
Passive attenuation of low frequency terrain tilt noise (II)

Experimental set up

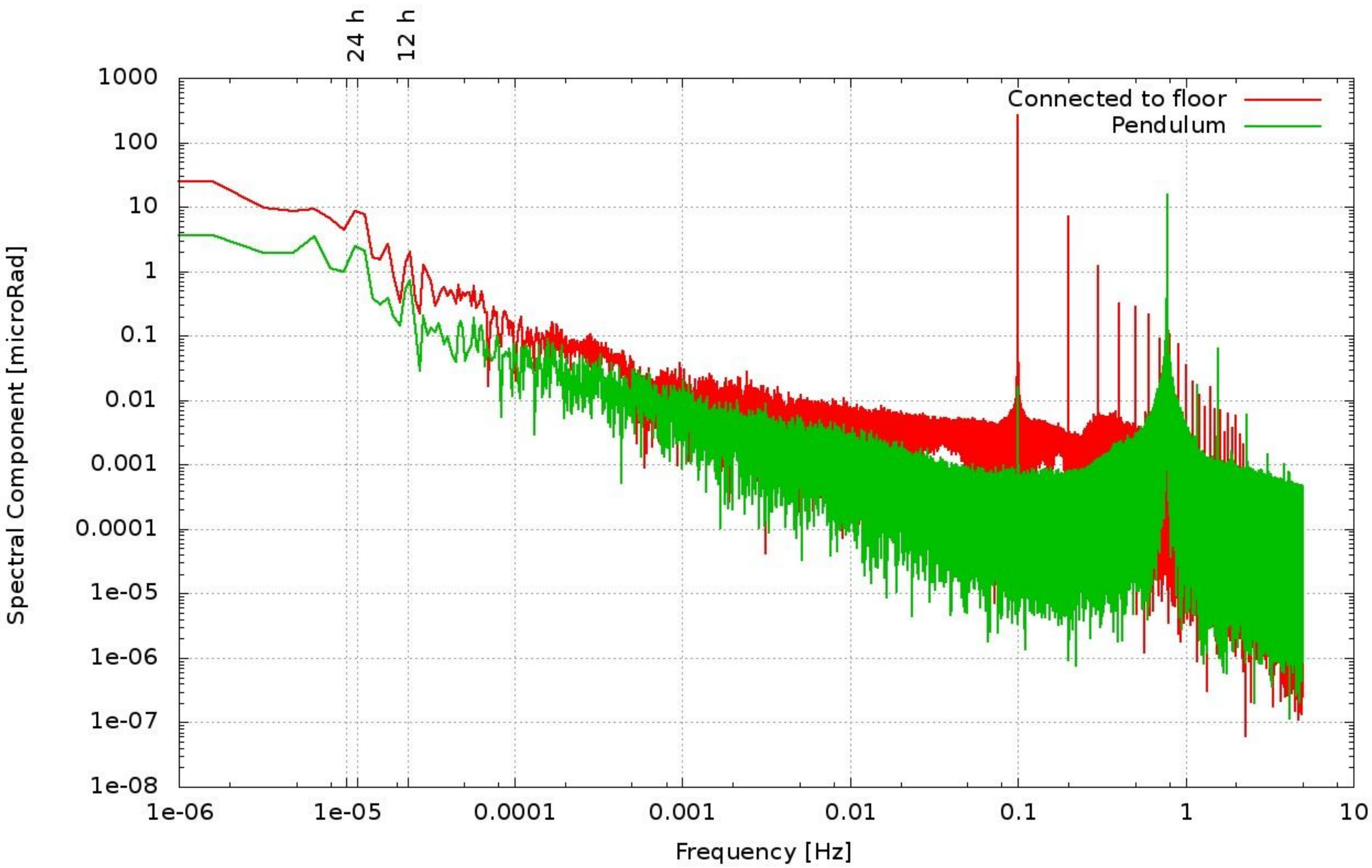
1 lamella of the 2 to be used for tilt attenuation in each direction of the horizontal plane suspends a 64 kg pendulum mass

The bar with the "top" tiltmeter is modulated at a frequency of choice (chosen where noise is low) to measure with another tiltmeter on the pendulum mass how much the modulated signal is attenuated. In air, with large thermal variations and local disturbances this is a good way to establish in a quantitative way the passive attenuation achievable.

Passive attenuation of low frequency terrain tilt noise (III)

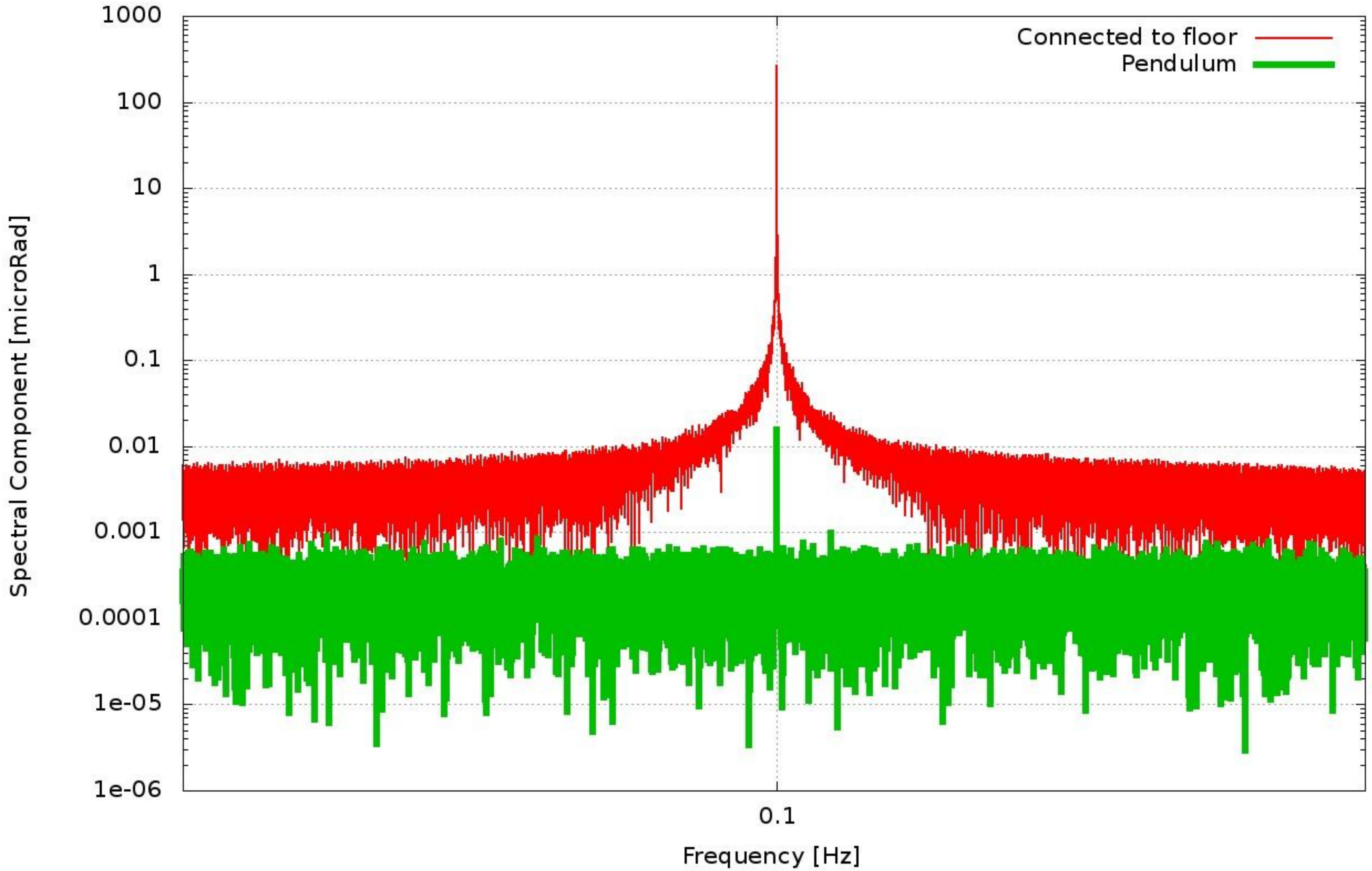


Passive attenuation of low frequency terrain tilt noise (IV)

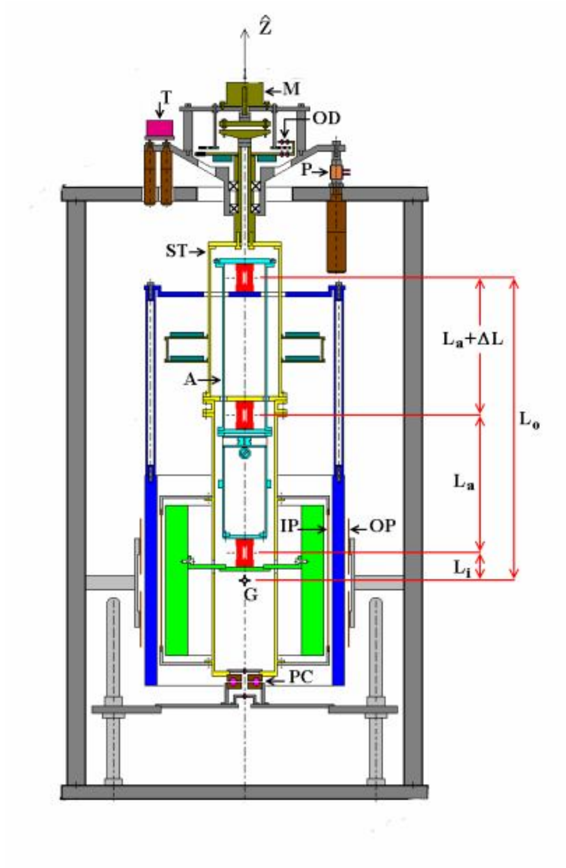


Large diurnal effects are due to the tiltmeter thermal dependence; note that on the pendulum mass the nrad level is achieved, which is the nominal sensitivity of the tiltmeter … BUT IS THIS THE TRUE HORIZONTAL LEVEL ??? Only a more sensitive instrument can tell …

Passive attenuation of low frequency terrain tilt noise (V)

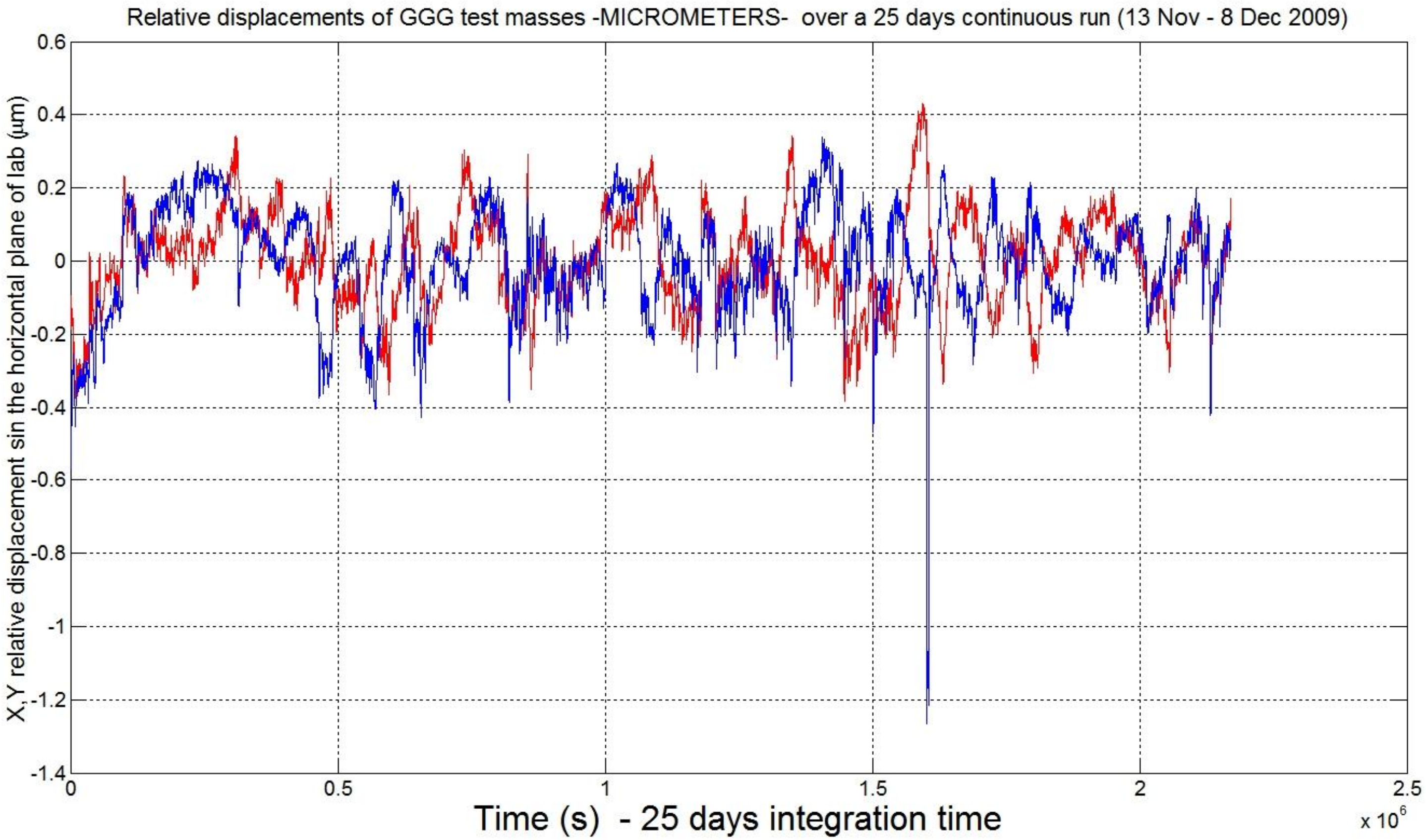


The modulated signal is attenuated by a factor 10000



“Old” GGG in new chamber

25 days continuous run of "old" GGG rotor in new chamber

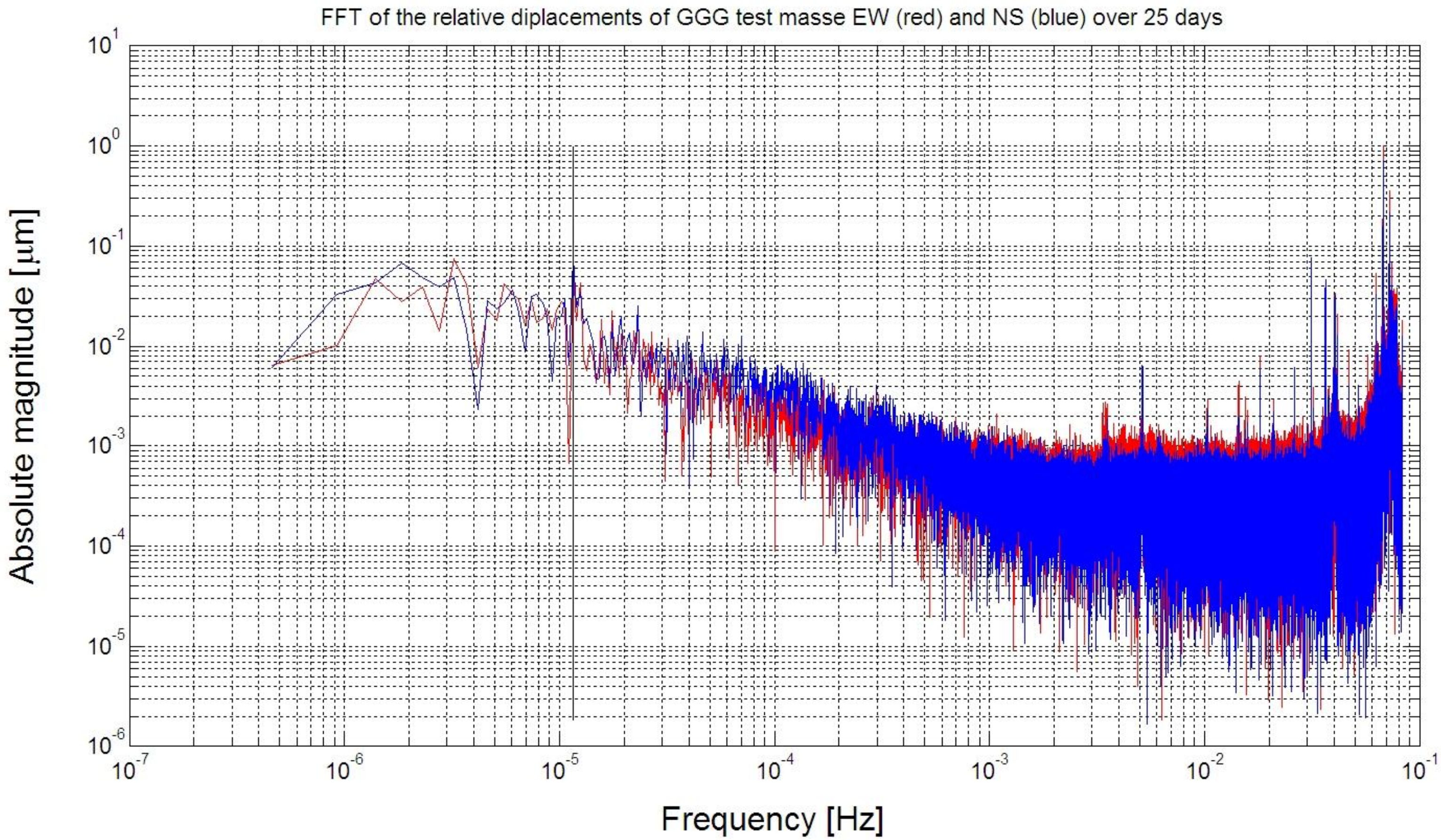


25 days run started 13 Nov 2009 17:13 UTC, 3.6×10^5 spin period, 7.2×10^5 data points: except for a single jump, the rotating test cylinders (10 kg each, 0.167 Hz spin rate) **never move away from each other by more than 0.4 microns** (in the non rotating horizontal plane of the lab – X,Y axes along the lab walls)

With 2D sensitivity of GGG accelerometer it is like having 2 torsion balances oriented along 2 orthogonal directions of the horizontal plane of the lab

Lock in detection relative to the Sun shows that it can reach a sensitivity of about 70 pm

25 days continuous run of old GGG in new chamber (II)



25 days run started 13 Nov 2009 17:13 UTC, 3.6×10^5 spin periods, 7.2×10^5 data points: FFT of the relative displacements of the test GGG cylinders in the EW and NS directions of the horizontal plane of the lab.

An EP violation in the gravitational field of the Sun would appear at 24 hr (black line) but **it should be exactly in phase with the astronomical Sun** during the 25 days of the run **=> sensitivity to EP violation is established by determining the level of noise which is synchronous with the Sun (through "lock in detection", also referred to as "phase sensitive detection" or "synchronous demodulation" – well known…)**

GGG sensitivity to EP violation established by lock-in detection (24 exact rotations of Sun) (I)

- Exploit that both frequency and phase of a putative EP violation signal are exactly known
- Exploit days when lab terrain input noise thermally induced by Sun is smaller:

Best sensitivity:

$$\eta^{\odot}_{GGG} = 2.1 \cdot 10^{-9}$$

obtained from best sensitivity to test masses relative displacements of:

$$\Delta r^{\odot}_{EW} = 35 \text{ picometers}$$

GGG vs GG: The correct comparison in EP testing

GGG in the field of the Sun (ground lab)

$$\eta^{\odot}_{GGG} \equiv \Delta a^{\odot}_{GGG} / a^{\odot}_{GGG}$$

$$a^{\odot}_{GGG} \lesssim 0.006 \text{ ms}^{-2}$$

$$\nu^{\odot}_{EP} = 1.16 \cdot 10^{-5} \text{ Hz}$$

$$\Delta a^{\odot}_{GGG} = (2\pi / T^{GGG}_{diff})^2 \cdot \Delta r^{\odot}_{GGG}$$

$$T^{GGG}_{diff} = 13.5 \text{ s}$$

Hence, the displacement sensitivity

$$\Delta r^{\odot}_{GGG} = 35 \text{ pm}$$

given that

$$a^{\odot}_{GGG} = 0.0036 \text{ ms}^{-2}$$

yields

$$\eta^{\odot}_{GGG} = 2.1 \cdot 10^{-9}$$

GG in the field of the Earth (low Earth orbit)

$$\eta^{\oplus}_{GG} \equiv \Delta a^{\oplus}_{GG} / a^{\oplus}_{GG}$$

$$a^{\oplus}_{GG} = 8 \text{ ms}^{-2} \text{ (630 km orbit)}$$

$$\nu^{\oplus}_{EP} = 1.6 \cdot 10^{-4} \text{ Hz}$$

$$\Delta a^{\oplus}_{GG} = (2\pi / T^{GG}_{diff})^2 \cdot \Delta r^{\oplus}_{GG}$$

$$T^{GG}_{diff} = 500 \text{ s}$$

Hence, by achieving a displacement sensitivity

$$\Delta r^{\oplus}_{GG} = 0.5 \text{ pm}$$

given

$$a^{\oplus}_{GG} = 8 \text{ ms}^{-2}$$

will yield the GG mission target in EP testing

$$\eta^{\oplus}_{GG} = 10^{-17}$$

Due to the stronger acceleration signal [8/0.0036=2200] and weaker coupling of the test masses in absence of weight [(500/13.5)^2=1400], GG can reach its target of testing EP to 10^{-17} with a sensitivity to relative displacements of the test masses of 0.5 pm

GGG results reported demonstrate 35 pm sensitivity: only a factor 70 away from GG required sensitivity!!!

Last 5 years papers

Direct measurement of the effects of electric charge surface patches and of their temporal variations, Pegna, et al, in preparation 2010

Abatement of thermal noise in Equivalence Principle tests using rapidly rotating macroscopic test masses, Nobili, Pegna, Shao et al., in preparation 2010

Equivalence Principle test in space, A.M. Nobili, **Il Nuovo Saggiatore 26, 18-27, 2010**

Testing the Weak Equivalence Principle, A. M. Nobili, G. L. Comandi, R. Pegna, D. Bramanti, S. Doravari, F. Maccarone and D. M. Lucchesi:, **Proceedings of the International Astronomical Union, Cambridge University press 5, S261 pp. 390-401, 2010**

"Galileo Galilei" (GG) A Small Satellite to Test the Equivalence Principle of Galileo, Newton and Einstein, Nobili et al. , **Experimental Astronomy (paper invited for the special issue dedicated to ESA Cosmic Vision proposals**) **23, 689-710, 2009**

Limitations to testing the Equivalence Principle with Satellite Laser Ranging" , Nobili et al., **Gen. Rel. & Grav., 40, 1533-1544, 2008**

Experimental validation of a high accuracy test of the Equivalence Principle with small satellite "Galileo Galilei- GG", Nobili et al. , **Int. J. Mod. Phys. D, 16, 2259-2270, 2007**

Dynamical response of the "GGG" rotor to test the Equivalence Principle: theory, simulation and experiment. Part I: The normal modes , Comandi et al., **Rev. Sc. Instr. 77 034501/1-15 (2006)**

Dynamical response of the "GGG" rotor to test the Equivalence Principle: theory, simulation and experiment Part II: The rejection of common mode forces , Comandi et al**. Rev. Sc. Instr. 77 034502/1-10 (2006)**

GG/GGG Website: http://eotvos.dm.unipi.it

GGG milestones for 2010 (as in “consuntivi 2009” – closed 31 March 2010)

30.06.2010	**Complete set up of sGGG, start commissioning and input file data required by Thales Alenia Space-I for sGGG Simulator**
31.12.2010	**Complete commissioning and provide results assessing sGGG sensitivity**

GGG milestones for 2011

30.06.2011	**Demonstrate long duration run of sGGG**
31.12.2011	**Design how to implement JPL laser interferometry gauge on sGGG. In alternative, design new capacitance bridge electronics with similar sensitivity**

Persone-Pisa

A. Nobili	PA	100%
R. Pegna	Art 23 …..	100%
T.R. Saravanan	PhD Student	100%
G. Mengali	PA	70%
F. Maccarrone	RU	70%
E. Polacco	PO in pensione (associazione senior)	40%
P. Paolicchi	PA	40%
M.L. Chiofalo	PA	40%
Totale ricercatori equivalenti nel 2011 (FTE)		5.6
Numero totale ricercatori 2010		8

Nota: il Dr David Lucchesi, ricercatore di ruolo presso IFSI-INAF, collabora attivamente ed è co-autore di molti lavori. E' stato associato a GGG fino al 2009 ma dal 2010 il rinnovo della sua associazione è stato rifiutato (???)

Persone-Bologna

S. Focardi	PO	70%
P. Baldi	PO	60%
E. Campari	PA	50%
F. Palmonari	PO	40%
P. Tortora	PA	60%
Totale ricercatori equivalenti (FTE)		2.8
Numero totale ricercatori		5

Richieste 2011 (KE)

Missioni interno	Missioni estero	Materiale consumo	Materiale inventariabile	Costruzione apparati	**Totale**
PI 2	5 **<u>Minimo essenziale</u> per collaborazione con JPL al fine di implementare la loro "laser interferometry gauge" sul nostro apparato**	6 Materiale da laboratorio + 8 Manutenzione minimale del laboratorio a San Piero a Grado (essenziale per GGG data la grande altezza del soffitto e la presenza del carroponte)	10 Analizzatore di spettro Agilent 4411B	24 Elettronica a rumore ridotto per ponti rotanti Componenti meccaniche per apparato principale e per tiltmetro a pendolo doppio, Acquisto di un tiltmetro a bolla per verifiche locali, + viti motorizzate PI. Disegni costruttivi aggiornati (comprensivi di proprieta' meccaniche) per l'intero apparato Coating delle masse test	55
BO 2	0	4 Materiale da laboratorio.		4 Componenti per specifici contributi a sGGG	10
Totale					65

Richieste alla Sezione INFN di Pisa 2011: a) Supporto di 1 ingegnere meccanico (Andrea Basti) per 1 mese uomo; b) Supporto di 1 esperto elettronico (Carlo Magazzu') per 1 mese uomo. Collaborazioni già sperimentate con successo