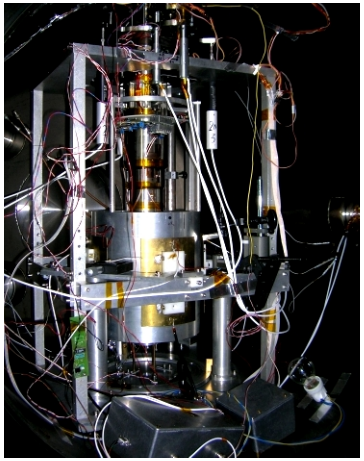

“Galileo Galilei”

GG

to test the Equivalence Principle in Space

Improvements with the laboratory prototype

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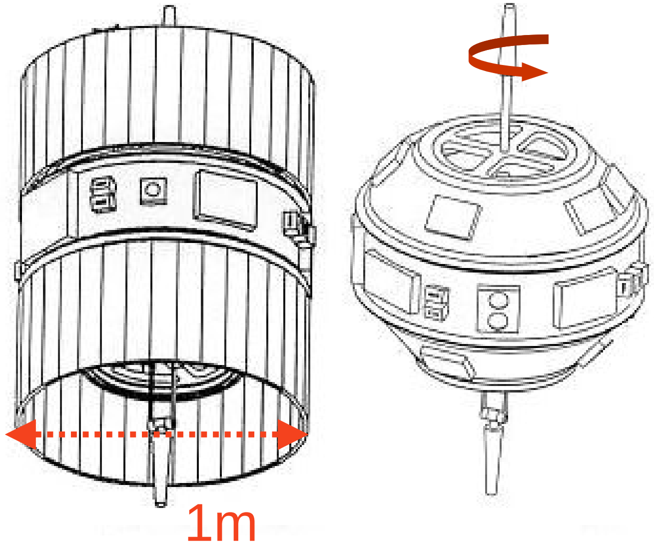
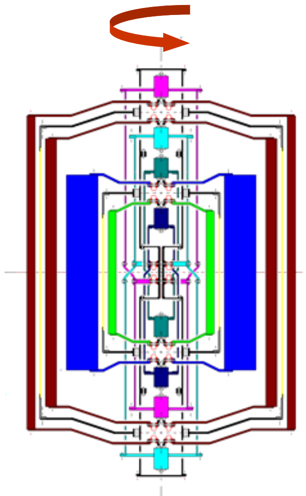
Università di Pisa & INFN

Q2C3, Warrenton Virginia July 2008

GG



Goal: test the UFF (WEP) to 10^{-17}

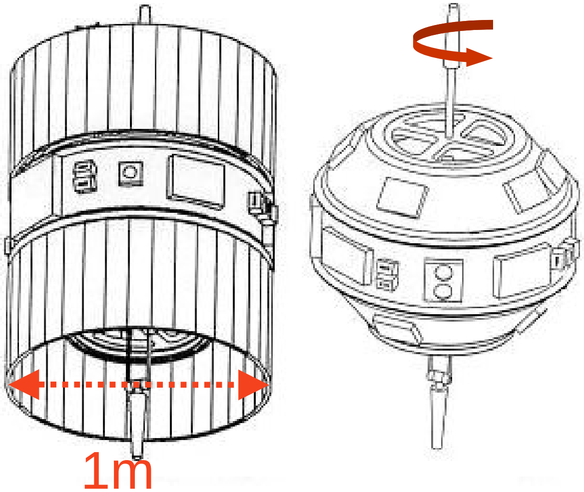


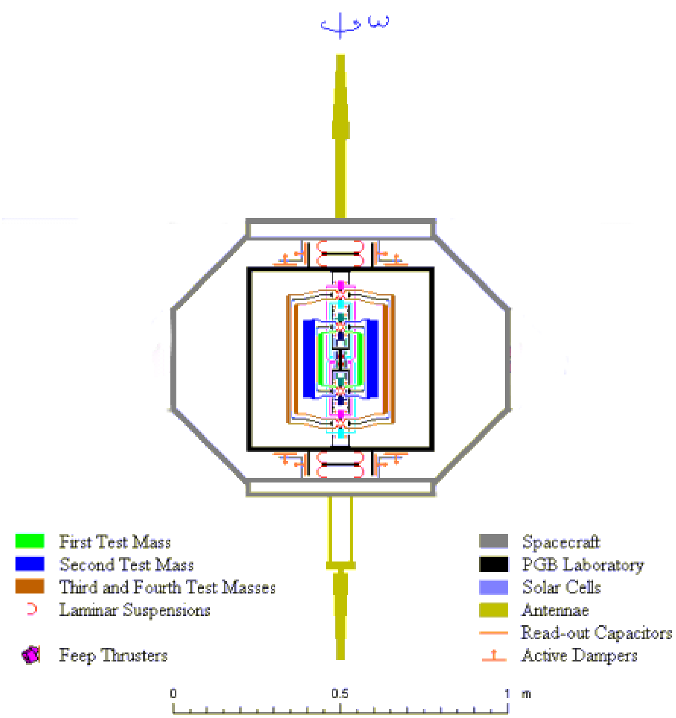
– 250 kg total mass
– circular, equatorial orbit at 520 km
– passive satellite stabilization by symmetryaxis rotation at 2 Hz
– room temperature
– partial along track drag compensation with electric thrusters
– VEGA launch from Kourou
– ground operation from ASI station in Malindi, Kenia

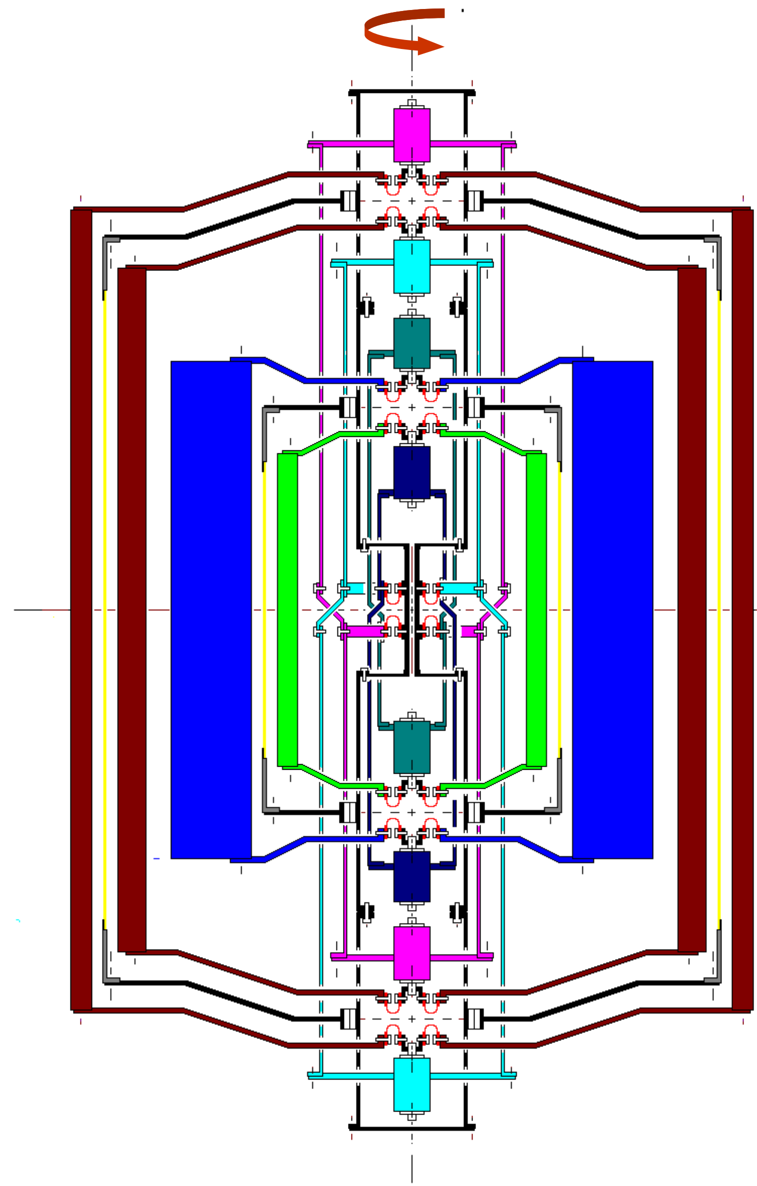
– GG in the National Space Plan of Italian Space Agency **(ASI)**
– GGG (GG on the Ground) prototype funded by **INFN**
– ASI grant for GG industrial study + advanced GGG prototype

50 M€ cost cup
..we try to keep GG below...

GG


1m


ω
First Test Mass
Second Test Mass
Third and Fourth Test Masses
Laminar Suspensions
Feep Thrusters
Spacecraft
PGB Laboratory
Solar Cells
Antennae
Read-out Capacitors
Active Dampers
0
0.5
1 m



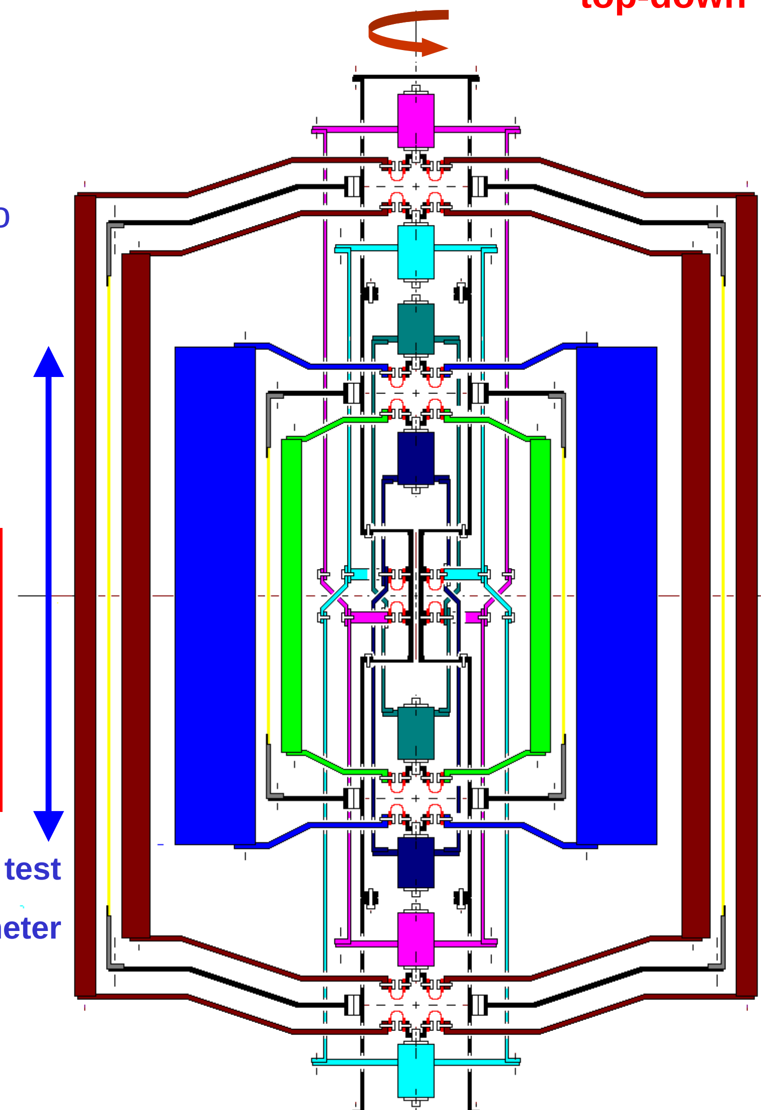
GG differential accelerometers

- Inner differential accelerometer for EP violation test (masses 10 kg each, differentialncapacitance read-out)
- **Outer differential accelerometer for check, same composition masses 10 kg each (differential capacitance read-out)**

…**accelerometers <u>co-centered on CM of sc</u> to improve reliability of check**

- Coupling via very weak meachanical supensions (thanks to absence of weight) ⇒ **<u>passive electric discharging</u>**
- **Rotation around symmetry axis in supercritical regime (≡ spin rate larger than natural frequencies of system)**

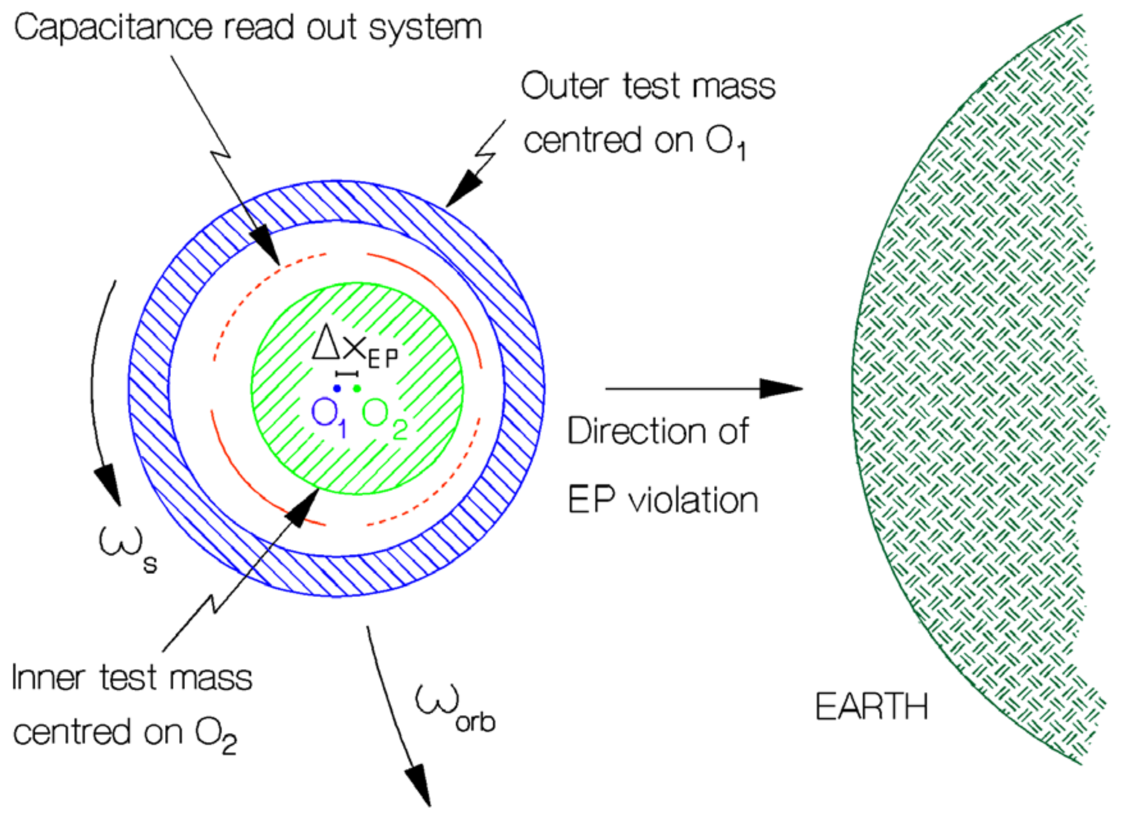
symmetry, both azimuthal and "top-down"



- **in essence, each accelerometer is a (peculiar) beam balance with concentric test masses, <u>with beam along the symmetry/spin axis</u>, sensitive to differential accelerations in the plane perpendicular to axis (stiff along axis)**

23 cm height outer test cylinder of EP accelerometer

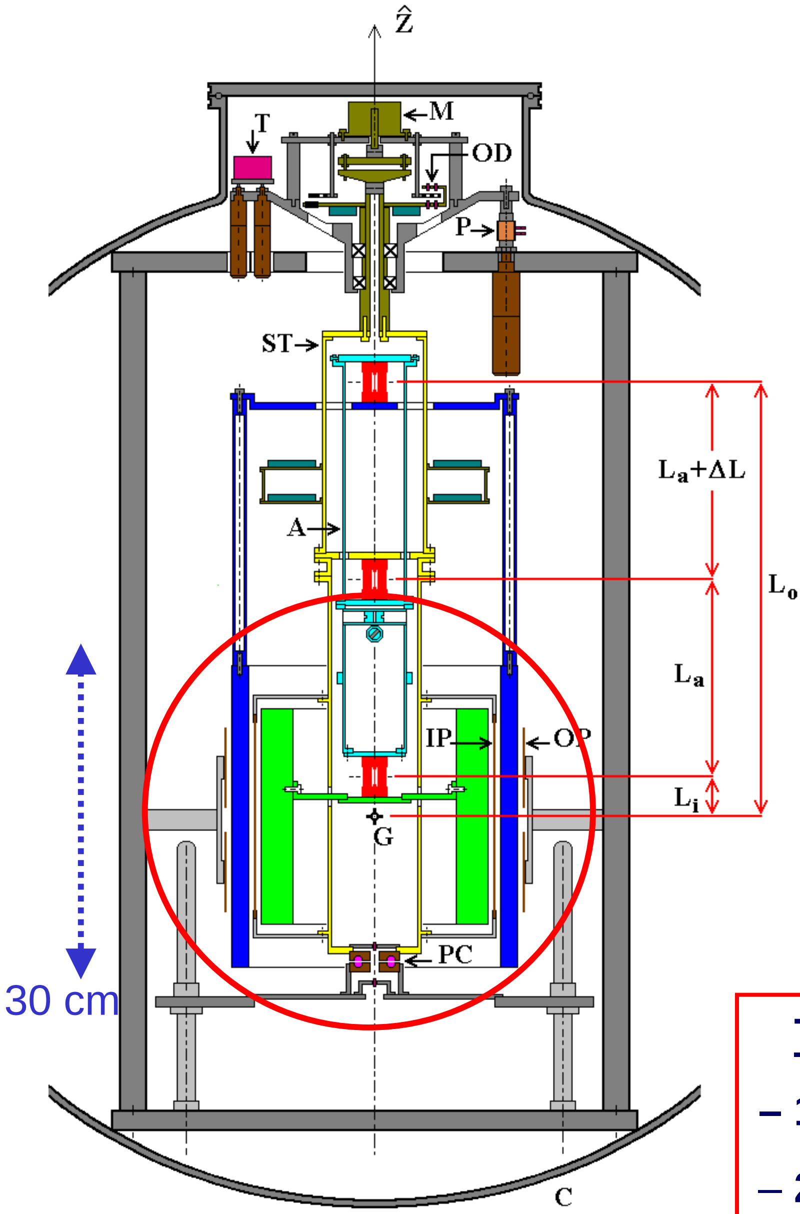
GG: making high frequency signal modulation possible



– test cylinders weakly coupled to form a **2D** differential accelerometer
– rotation (with whole s/c) around **symmetry axis**

EP violation vector not affected by rotation/modulation (no forcing at the rotation frequency) ⇒ rotation frequency can be much much higher than the coupling frequency of test masses (by 3 orders of magnitude in GG) and yet the violation signal is not attenuated!!!

GGG rotating differential accelerometer (I)



- beam balance with vertical beam along direction of local gravity and concentric cylindrical test masses 10 kg each
- 2 DoF sensitivity in horizontal plane
- fast rotation around beam/symmetry axis
- differential capacitance read-out

…like in GG in space,
though not as nicely
symmetric along vertical

- Coupling stiffer than in space ⇒ **lower sensitivity**
  (by factor 1700 now..)
- Rotation requires motor, unlike in space ⇒ **motor/bearings noise**
- System not isolated, unlike in space ⇒

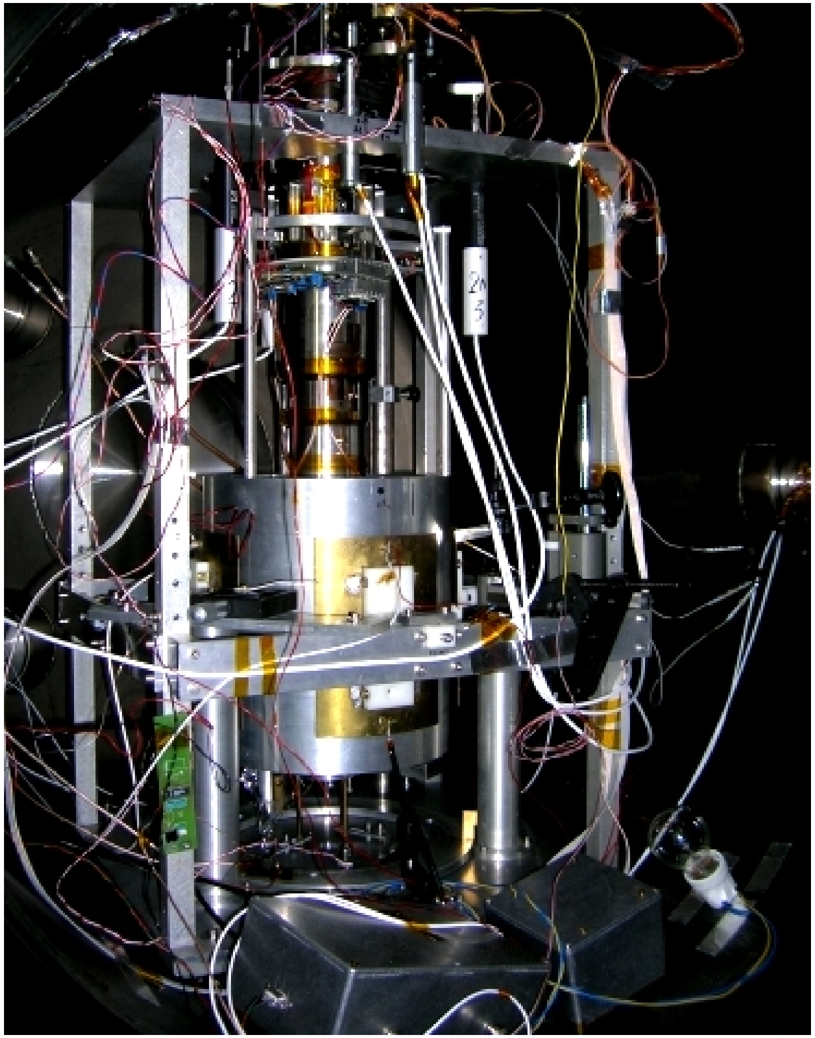
  terrain tilts noise

Target signal: EP violation in the field of the Sun

– **1400 weaker than in GG** (Earth as a source)

– **24 hr period** (1.6 hr=orbital period in GG)

GGG rotating differential accelerometer (II)

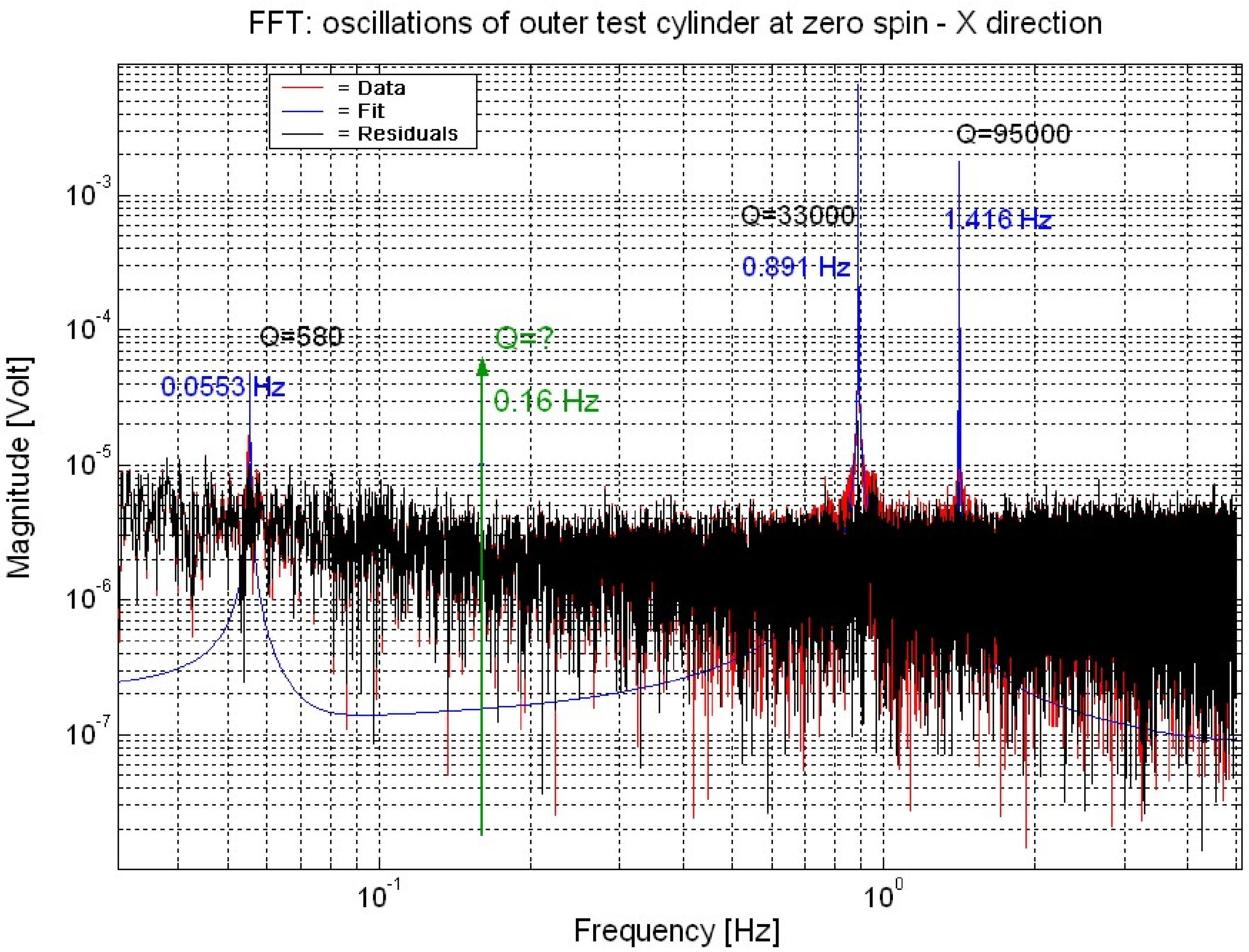


- Contactless power coupler provides 4W required by rotating read out electronics
- Relative displacements of rotating test cylinders read by 2 co-rotating capacitance bridges. 24bit ADC, optical data transmission, data time-tagged by Rb clock; same clock controls stepper motor providing rotation (2000 microsteps per turn)
- Motor along axis, ball bearings, double cardanic joint between motor axis and rotor shaft to transmit rotation (for X,Y as well as ϑ_x ϑ_y freedom – multi-body rotor…)

30 cm (height of outer test cylinder)

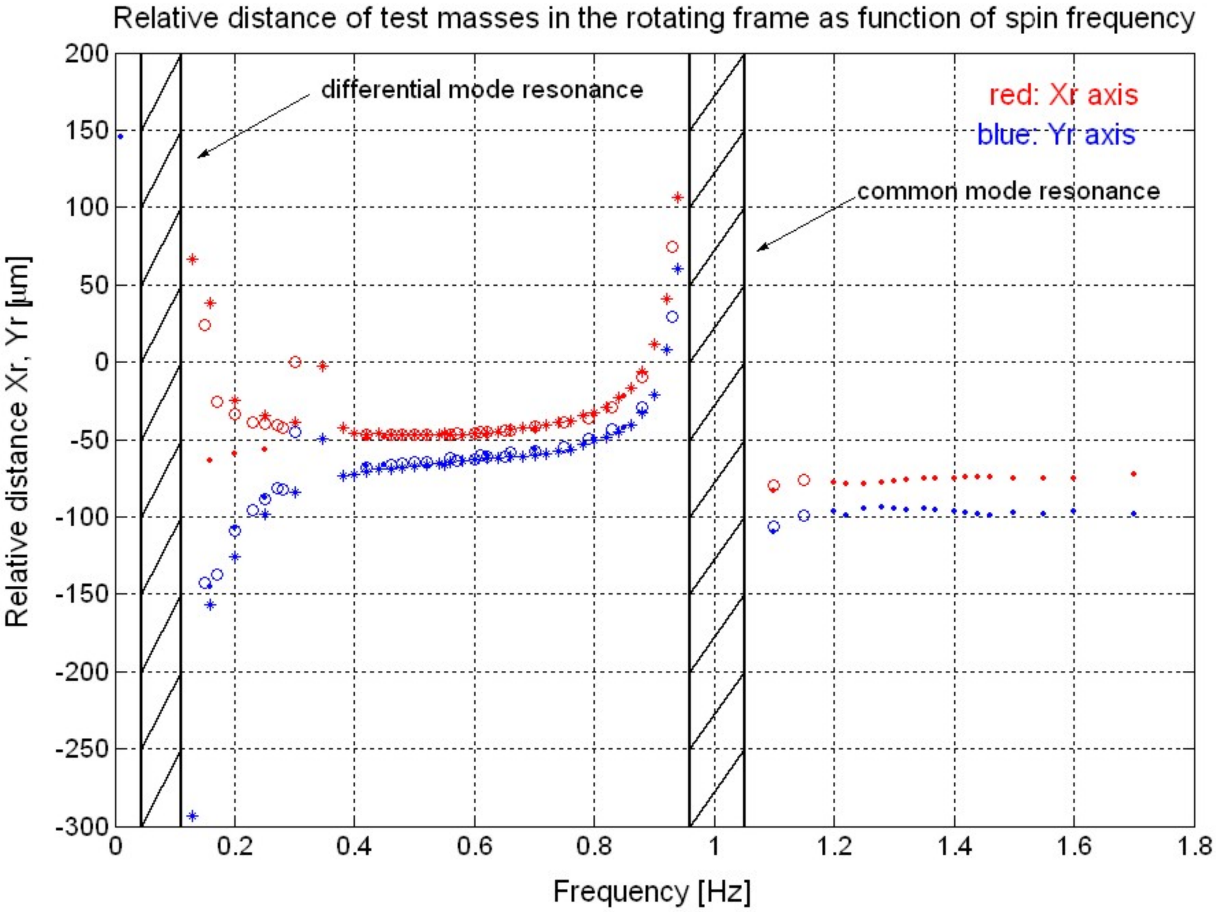
- Whirl control loop (by capacitance sensors/actuators)
- Tilt control loop (tiltsensor; PZT actuators)
- Coarse axis adjustments (at beginning) with PI remote controlled micrometer motors

Established facts: Q

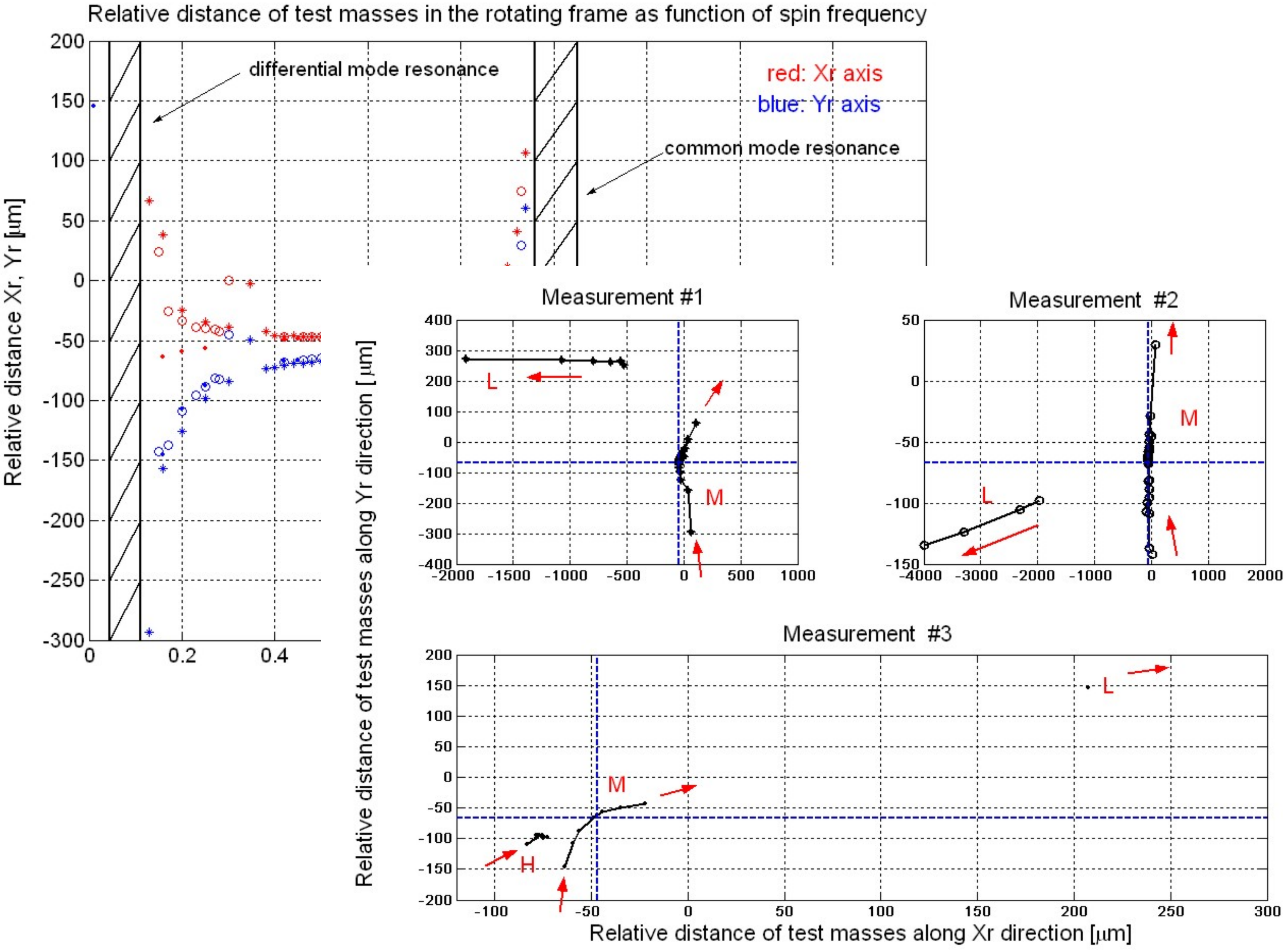


Q measurements at GGG natural frequencies (full system).

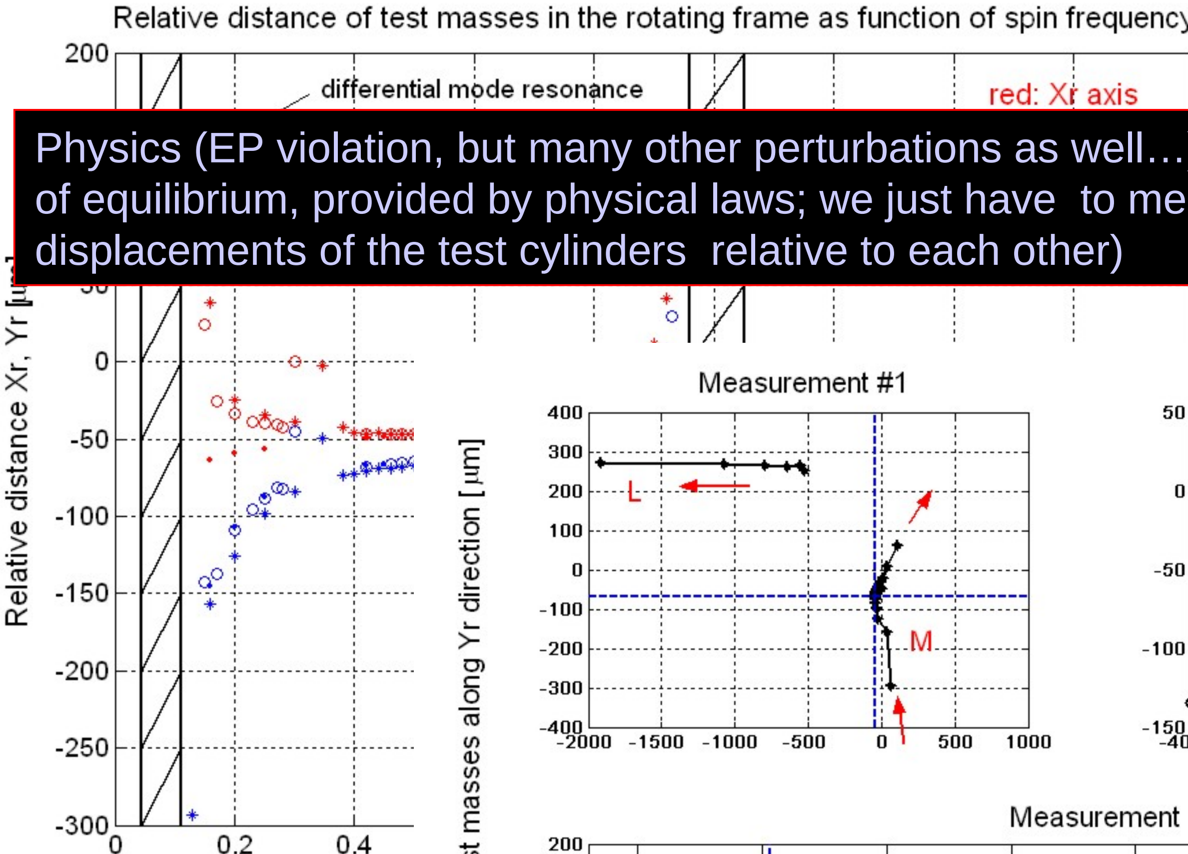
Established facts: equilibrium position of test masses



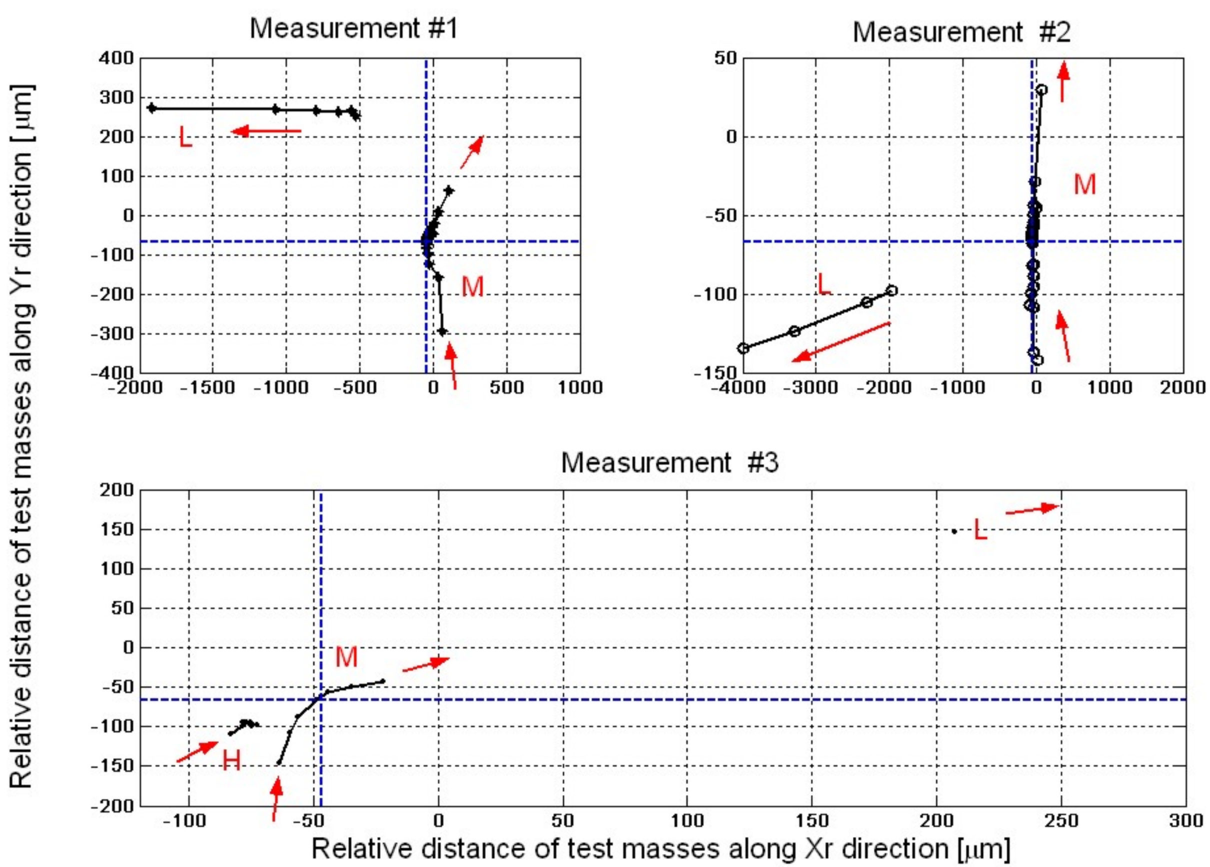
Established facts: equilibrium position of test masses



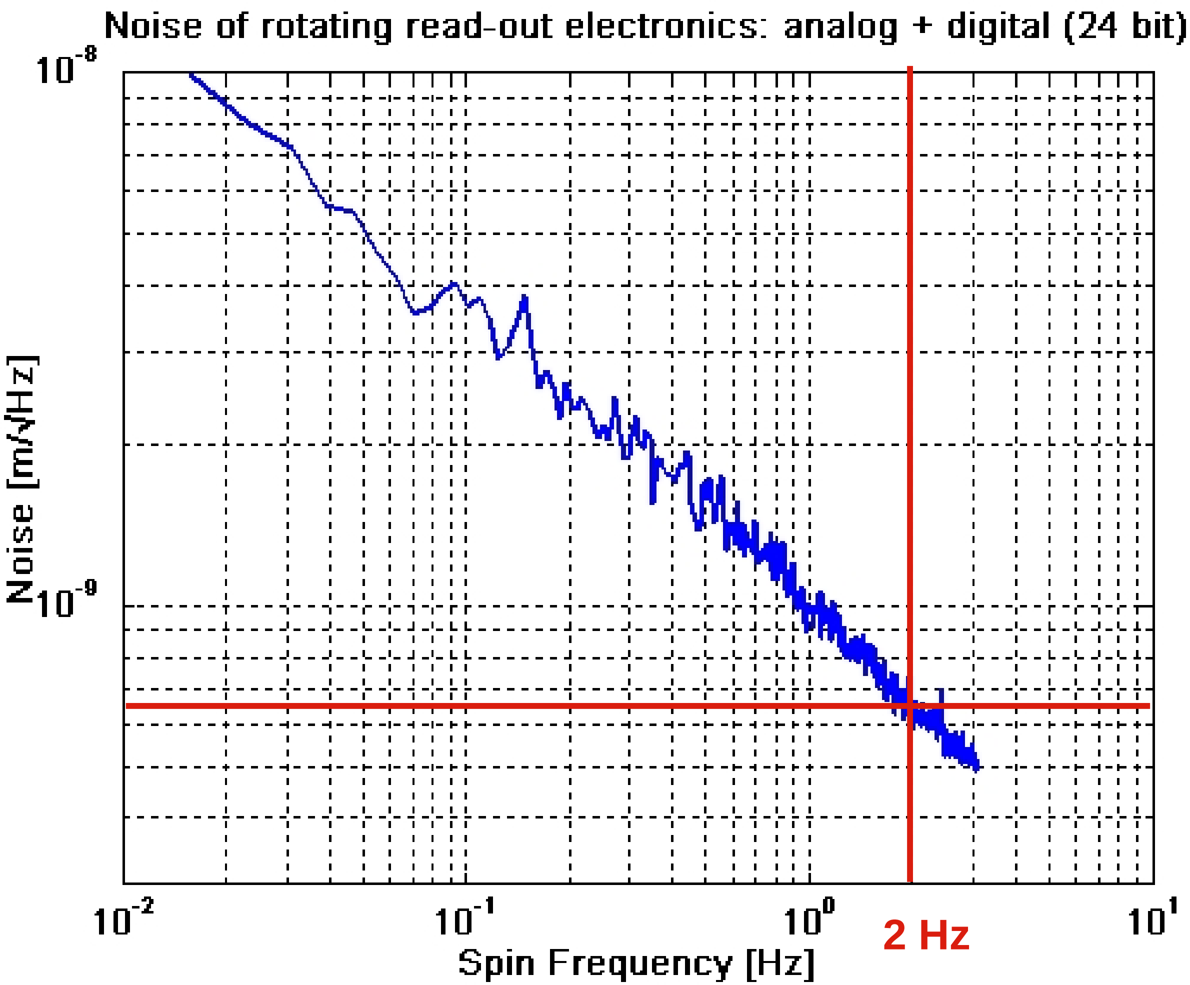
Established facts: equilibrium position of test masses



Physics (EP violation, but many other perturbations as well…) happens around this position of equilibrium, provided by physical laws; we just have to measure! (i.e. measure the displacements of the test cylinders relative to each other)



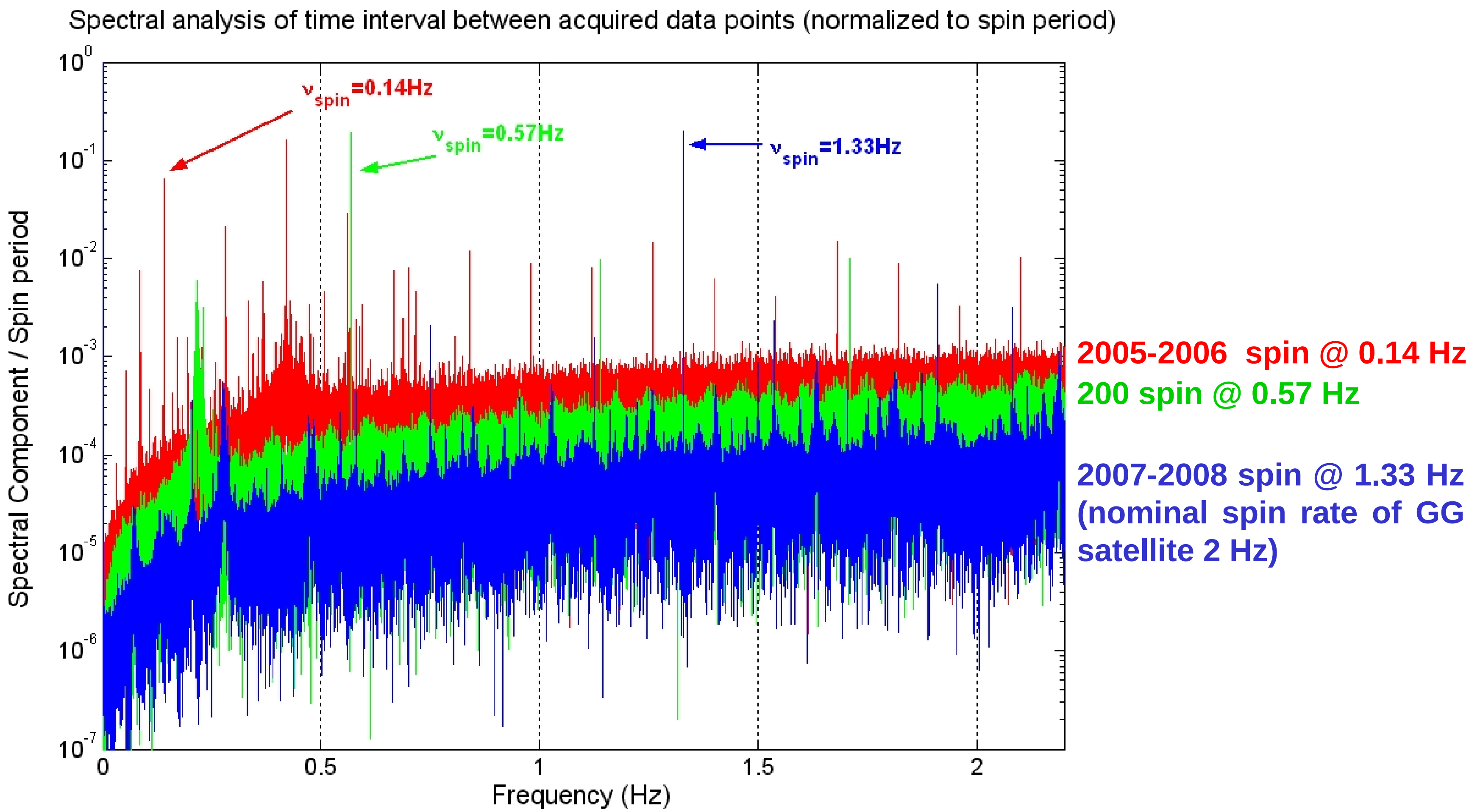
Established facts: noise of read-out electronics as function of spin rate



Relative displacements of rotating test cylinders are read by 2 co-rotating capacitance bridges. The analog output of each bridge is digitized 32 times per turn. Plot shows noise of read-out electronics alone located inside a chamber maintained at 35 $\pm$ 0.1°C. The noise of the digital part (alone) was measured for a few days, sampling at 32 times per spin period, as function of spin frequency **(2 Hz is the nominal spin frequency of GG satellite).** The noise of the analog part was measured with the spectrum analyzer. The curve shows the sum of the two. **The advantage of spin in reducing electronic noise is apparent!!!**

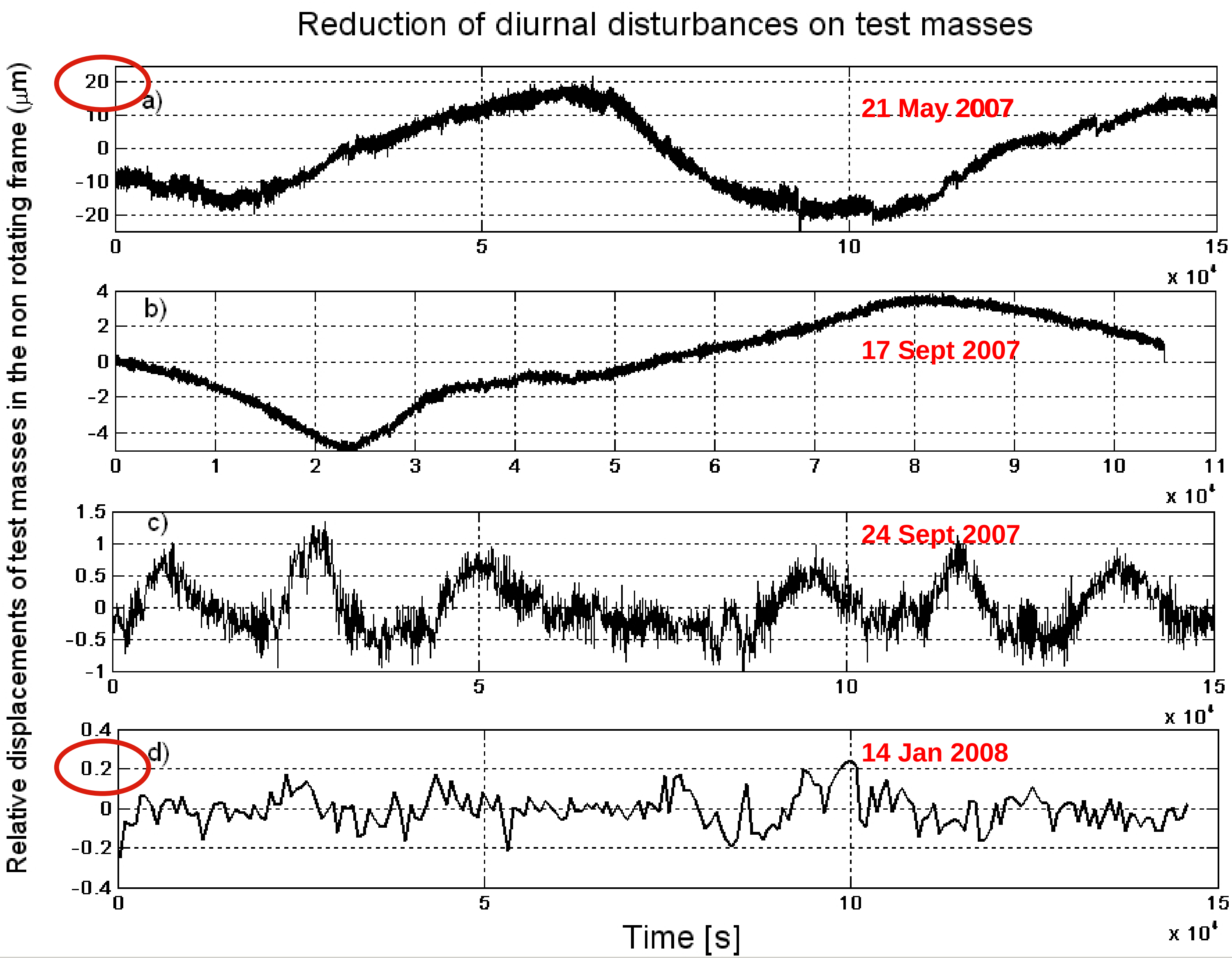
E.g., a slower rotation with 10 minutes period would give a noise level well above the upper limit of this plot!

Established facts: motor noise at various spin rates



Uniformity of rotation of GGG differential accelerometer can be measured from the rotary encoder which controls data acquisition. Figure shows the spectral analysis of the time interval between acquired data points (normalized to spin period). **From red to blue case the rotation speed has increased by a factor 9.5, so the spin energy has increased by almost 2 orders of magnitude, while rotation noise has decreased by about 1 order of magnitude**

Diurnal disturbances on test masses reduced by thermal stability (I)



No thermal control. Motion dominated by diurnal disturbances:

- **terrain tilts (seismic+temperature/pressure induced)**
- **thermal effects on chamber and its base**
- **thermal effects on rotor**

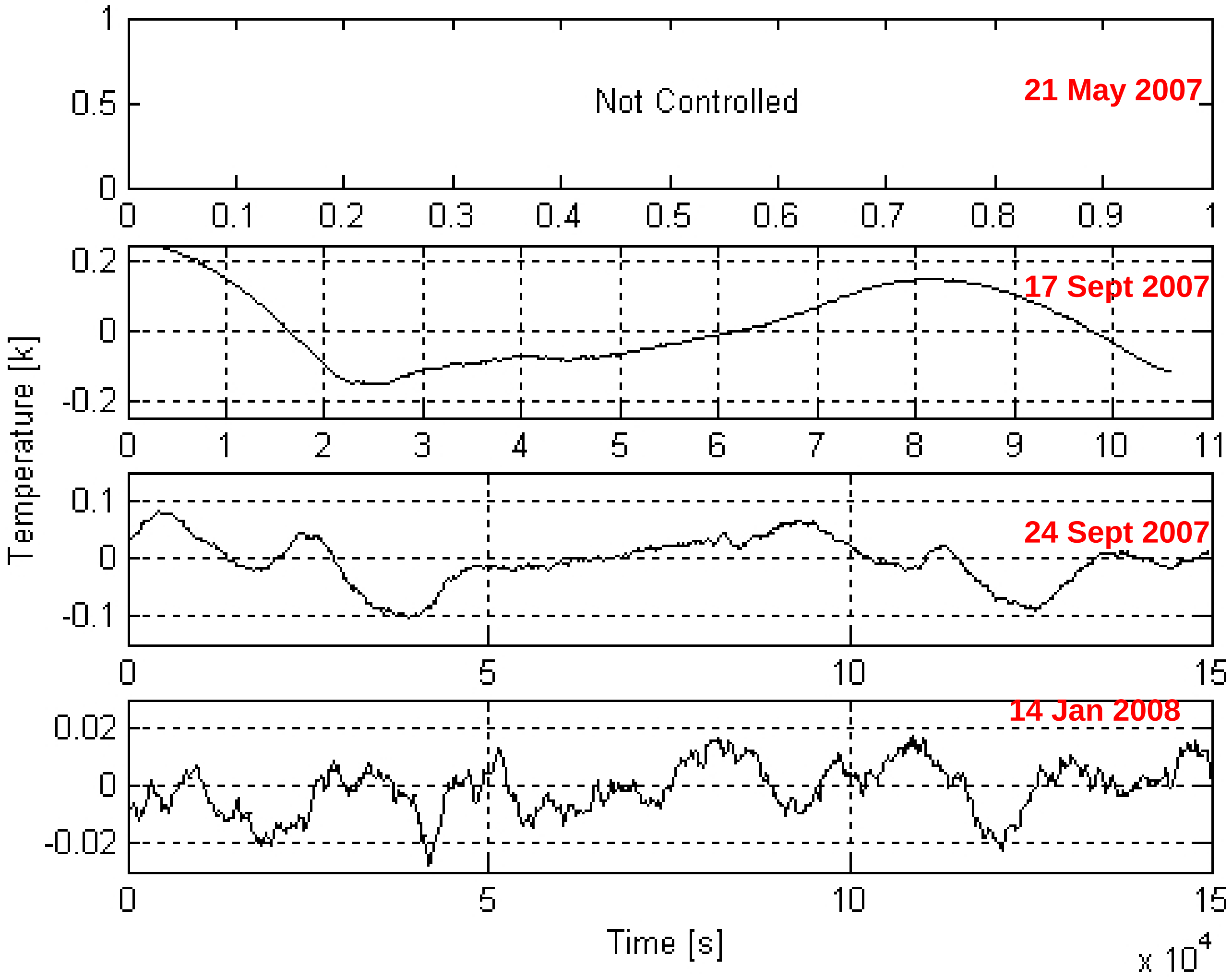
Improvement by factor 100

Diurnal temperature stabilized to 0.02 °C

Diurnal disturbances on test masses reduced by thermal stability (II)

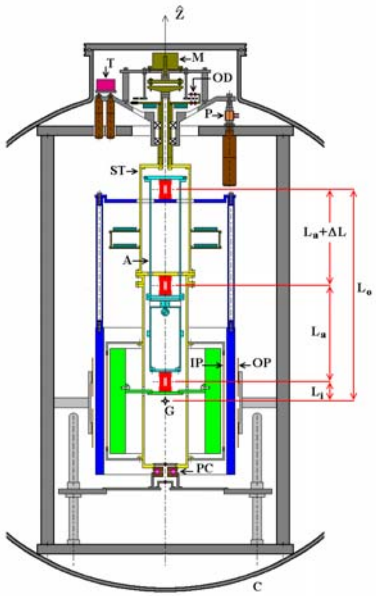
…diurnal motion of test masses clearly correlated to thermal stability inside the vacuum chamber

Improvement in diurnal thermal stability inside vacuum chamber



This result degrades to 0.03 °C, <u>and</u> with a clear daily signature (not presnet here), in summer when thermal input variations on the lab are larger…

Why is diurnal thermal stability so important in GGG?



GGG being a beam balance with a vertical beam, the relative displacements of its test masses in the horizontal plane are influenced by:

- micro-seismic terrain tilts
- terrain tilts caused by diurnal environmental temperature&pressure variations
- temperature induced tilts of the entire vacuum chamber –including the base on which it sits
- temperature induced tilts of the rotor itself inside the chamber (due to non uniform thermal expansion/contraction of the rotor … not sensed by tiltmeter but smaller..)

As long as tilts are actively compensated (tiltmeter sensor + PZT actuators) **and the tiltmeter in the loop is temperature dependent,** thermal variations at the tiltmeter location inside the vacuum chamber result in spurious tilts of the rotor, hence on relative displacements of its test masses. The largest and most dangerous thermal variations are the diurnal ones

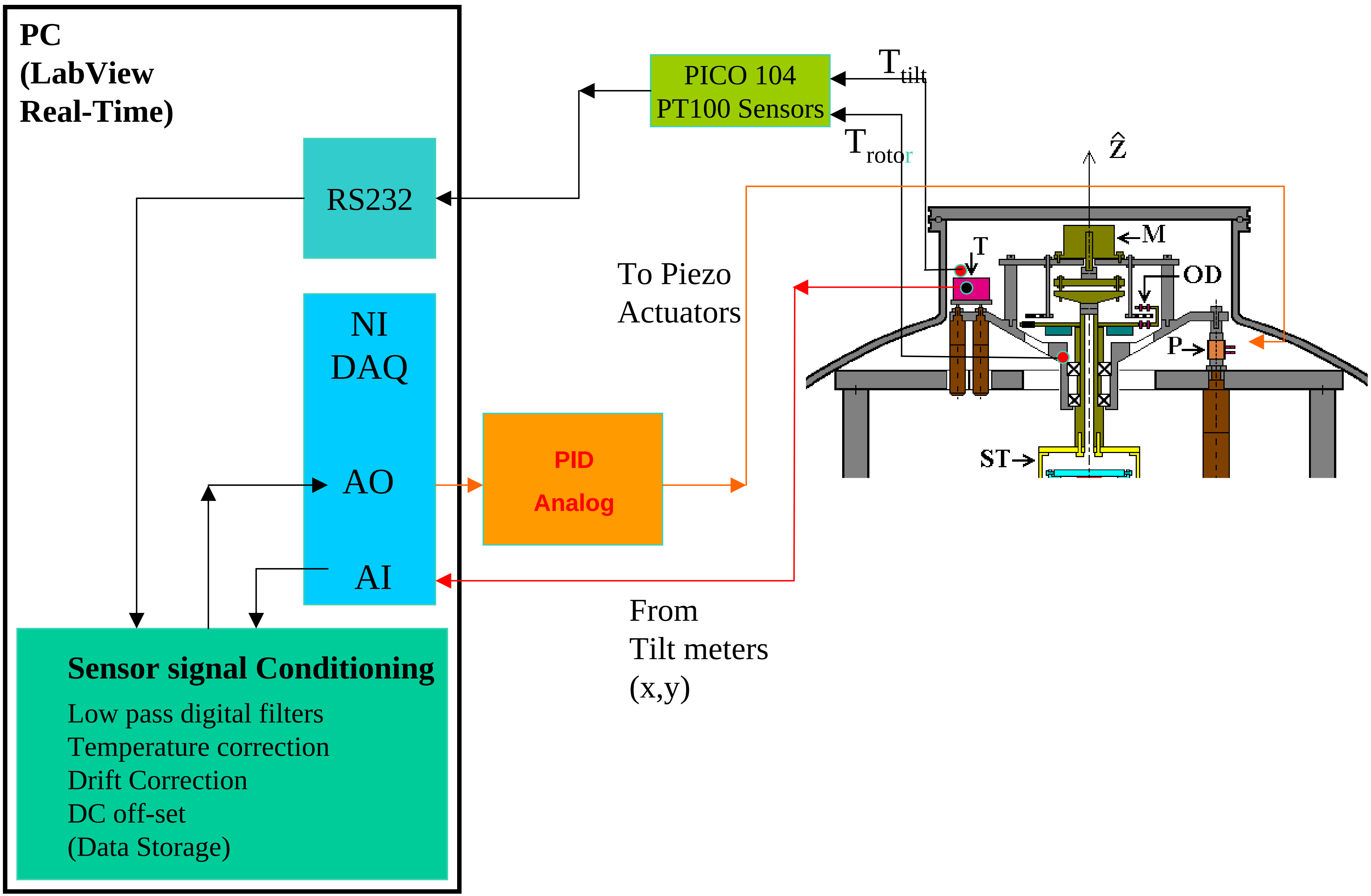
Strategy:

- stabilize temperature inside vacuum chamber
- correlate test masses displacements to thermal variations, characterize thermal dependence of tiltmeter sensor, correct the tiltmeter signal for thermal dependence before sending it to PZT actuators (..use tiltmeters with dependence on tempertaure as small as possible…)

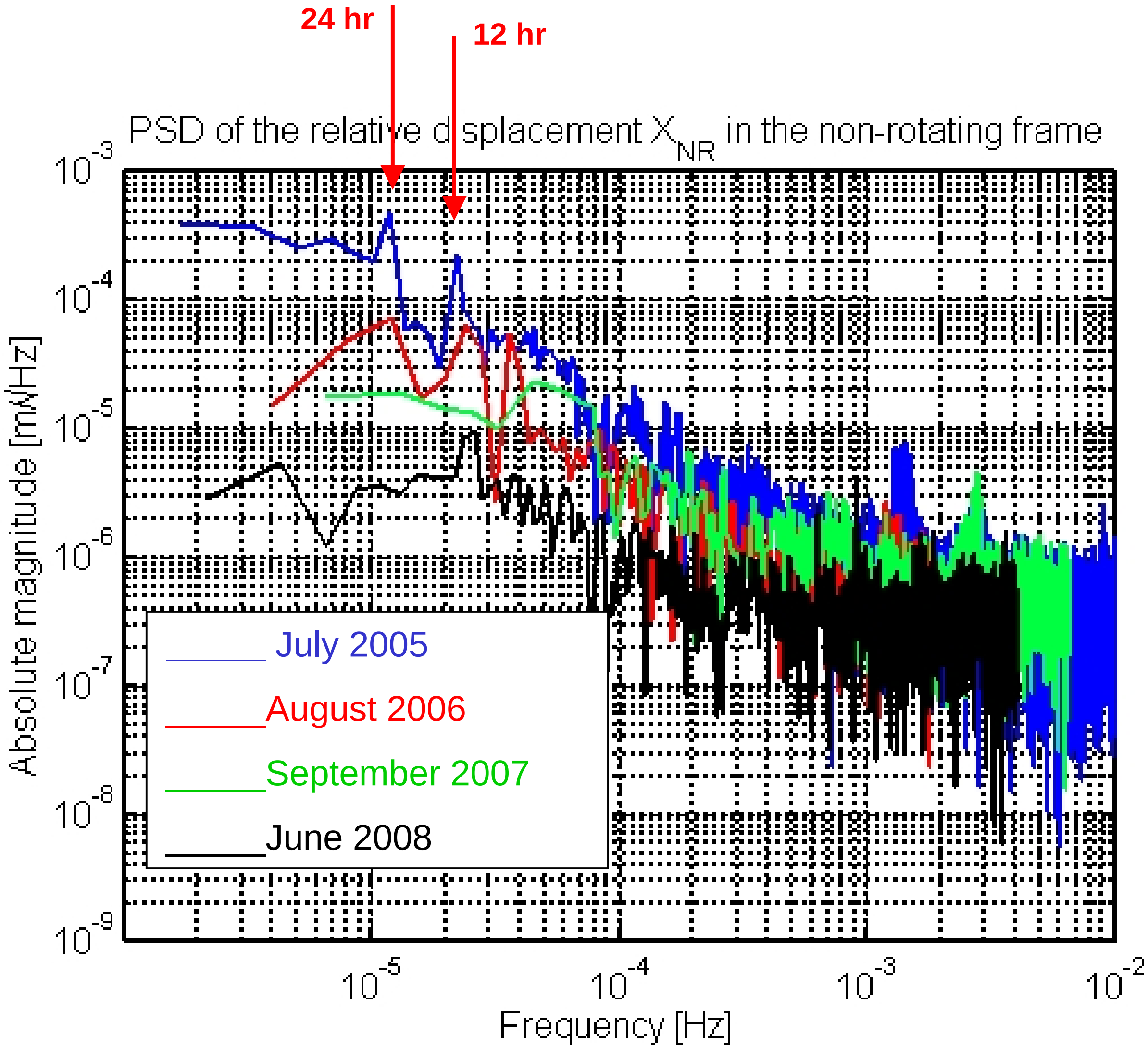
<u>Passive attenuation of GGG tilts would not be affected by thermal variations!</u>

Note: experiment in space NOT affected by spin axis tilts at all! (..the satellite is an isolated system)

Temperature compensated active tilt control



Relative displacements of rotating test cylinders: July 2005 - June 2008



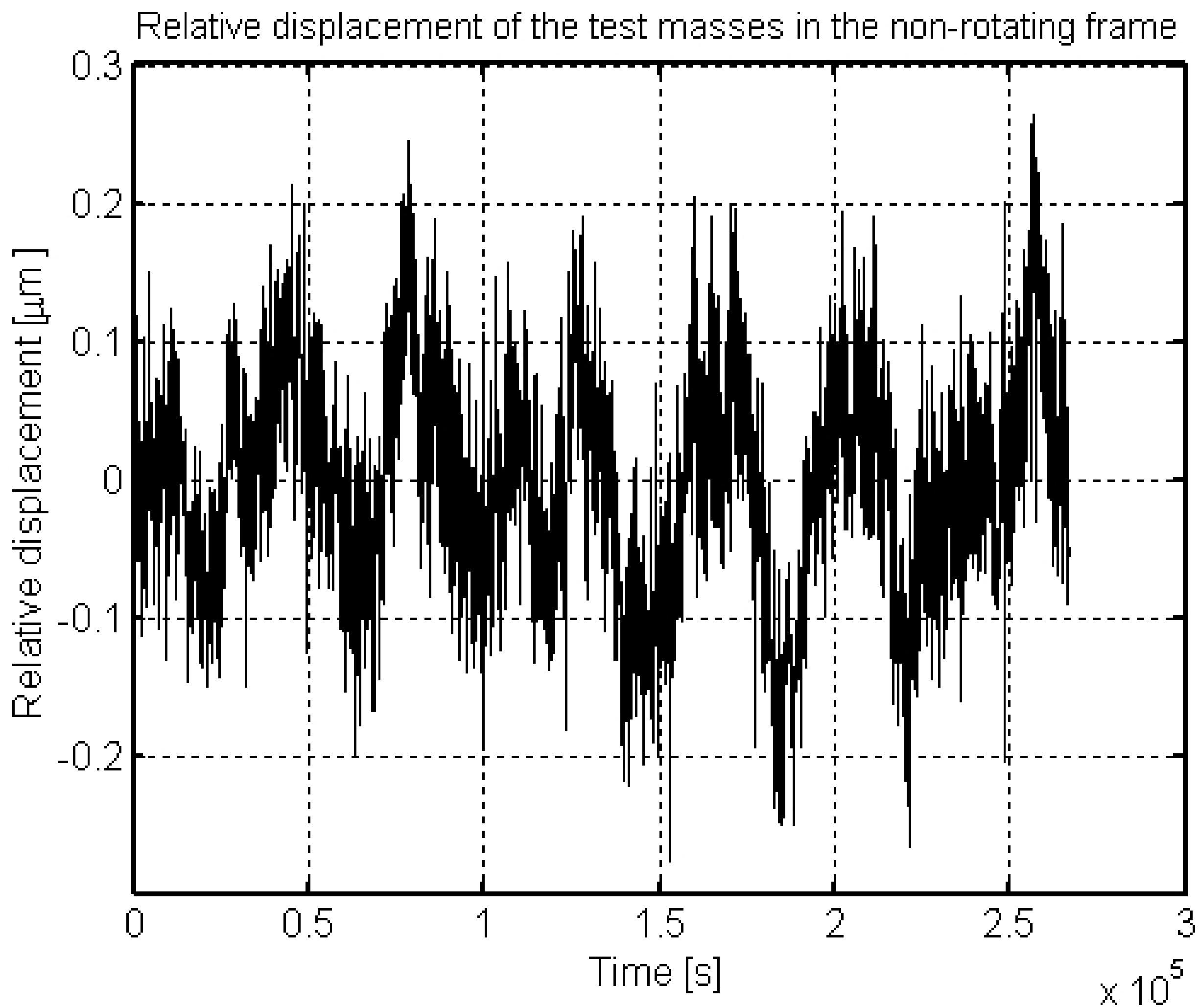
_____ (July 2005) No thermal stabilization, peaks at 24 hr peak & at 12 hr second harmonic both visible

_____ (August 2006) Initial phase of thermal stbalization of chamber , 24 hr and 12 hr peaks smaller

_____ (September 2007) Thermal stability of chamber to 0.1 °C, online temperature correction of tiltmeter signal within tilt control loop; 24 hr and 12 hr peaks disappeared

_____ (June 2008) Thermal stability of chamber to 0.03 °C, online temperature correction of tiltmeter signal within tilt control loop; no 24 hr peak, 12 hr tide signal visible (horizontal component, residual differential effect after common mode rejection by GGG balance)

Relative displacements of rotating test cylinders - June 2008
The 12 hr tidal signal



The signal at about 12 hr is well visible; both solar tide (12 hr) and lunar tide (12 hr 25m) are present, a longer data set is needed to recover the signals

Since the tidal field of the Sun and the Moon is "perfectly" known, this signal can be used to establish experimentally the common mode rejection factor (known so far from theoretical analysis and numerical simulations)

Where do we stand right now and what next?

@ 1.15·10^{-5} Hz (1 d) with a few days timespan of data (few nanometer displacements)

$$\eta_{\odot} \simeq 10^{-7}$$

Inside new vacuum chamber new GGG apparatus to be suspended with an appropriate cardanic suspension (lever effect) so as to achieve good passive attenuation of tilts (in addition to active one…)

Natural differential period can be increased so as to gain factor 10 in sensitivity ($\propto T^2$)

Then, remember that GGG is a full scale prototype but:

- **signal in space 1400 times larger**
- **sensitivity in space still a factor 200 better**

Recent Papers

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)**

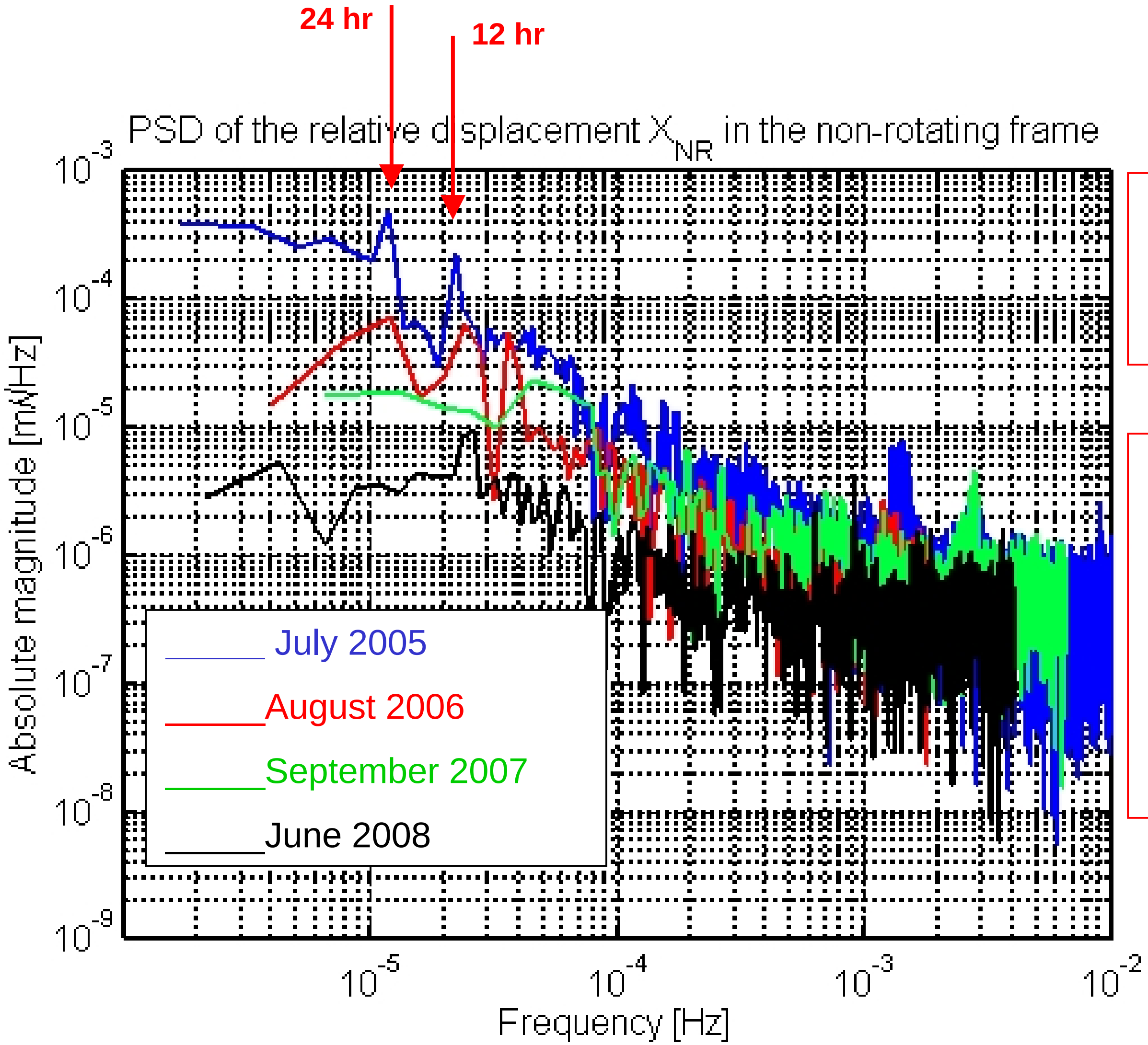
Experimental validation of a high accuracy test of the Equivalence Principle with small satellite "Galileo Galilei- GG", Nobili et al. , **Int. J. Mod. Phys. D, 16, 2259-2270, 2007**

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

"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**, **in press**

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

.. as long as we keep gaining orders of magnitude, it is ok



.. A high accuracy, well controlled, experimental result on EP (even a null one) of extreme importance for physics of next decades…

Modern torsion balances controlled experiments have only improved from 10^{-11} to 10^{-12} in almost 40 yrs!

.. Many different efforts (ground, space, rockets, balloons, macroscopic or miroscopic masses) is a blessing, because it is extremely challenging and difficult to improve..

Macroscopic vs microscopic test masse experiments:

Q: are cold atom people going to push experiments with macroscopic test masses out of busines?

A: … well ,,,,we have got Avogadro's number on our side, and, you know, it is a pretty big number…