GGG: NOTE FOR THE PRESIDENT OF INFN-CSNII PROF. ROBERTO BATTISTON

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CONTENTS

PREMISE

As the acronym says GGG ("GG on the Ground") was born as a 1-g version of the "Galileo Galilei"- GG space experiment aiming to test the Equivalence Principle (EP) to 10^{-17}. More specifically, GGG is the ground version of the GG payload, which is a cylindrical differential rotating accelerometer sensitive in 2-D in the plane perpendicular to the spin/symmetry axis.

Lab testing prior to flight has always been an issue in fundamental physics missions, as the instruments are designed for 0-g and cannot function as such at 1-g. Typically, partial tests of their components are performed in the lab. More recently, very sophisticated numerical simulators are also built –which incorporate the results of lab tests– providing realistic global results on what is to be expected in space. The most interesting such example is the recent GOCE mission, a space geodesy mission flying gradiometers built by ONERA, based on the same principle of electrostatic capacitive accelerometers used for the µSCOPE mission for EP testing. The GOCE simulator, built by Thales Alenia Space-Italy (TAS-I) in Torino has proven to be a crucial asset in the mission construction and its results are now being confirmed in flight.

The case for a ground test of the GG accelerometer is strong and twofold. First –and most importantly– the design of the accelerometer is such that it can be used to test for EP violation on the ground: the plane of sensitivity is aligned to the horizontal plane and the spin/symmetry axis is aligned with the direction of local gravity and used to suspend the instrument. Due to local gravity the test cylinders of the GGG differential accelerometer cannot be coupled as weakly as at 0-g, hence the instrument cannot be as sensitive as in space, but it is full scale. Note that this is a unique property of the GG design made possible by its sensitivity in 2-D rather than along a single axis (as STEP and µSCOPE, which do not have a ground version).

The second reason for a ground test of the GG instrument is a reason of opportunity. The GG design is novel and differs from that of its competitors in a crucial feature from which many important consequences follow. In all cases the accelerometer is made of concentric hollow cylinders. However, in STEP and µSCOPE they form an accelerometer sensitive in 1-D (along the cylinders' symmetry axis, while the satellite and everything inside it rotates –for signal modulation– perpendicularly to the symmetry axis) while in GG it is the opposite: the system rotates around the symmetry axis and the accelerometer is sensitive in the plane perpendicular to it. This simple change allows the system to rotate at frequency larger than the natural coupling frequency of the test cylinders and has profound consequences, the bottom line being that at room temperature and with a much simpler system GG can aim at a target competitive with STEP. The dynamical properties of the GG system are close to the field of mechanical engineering of rotors (though multi-body rather than single-body) and are not too familiar to the community of fundamental physics in space. Hence the need to set up a ground test. As the community and the space agencies become more and more aware of the difficulties of performing sophisticated measurements in space, and the need to minimize risks of failure is more stringent, the importance of ground tests to the best of one's capabilities is valued more and more.

This Note is organized as follows. The Section "*GGG historical layout from experimental results*" starts with a Table reporting –in a compact form– the GGG improvements made with time, as demonstrated by the most relevant experimental measurements, illustrated by Figures which can be consulted individually for a quantitative assessment. The Table refers also to the funding Institutions at the time and to the lab available. The Section includes a few comments on the experiment features which in the past gave rise to major improvements, and recalls the main drivers behind the GGG advanced apparatus initiated in 2008 thanks to additional support from ASI.

The following Section reports on "*GGG current sensitivity in testing the Equivalence Principle, expectations from the advanced apparatus under completion and relevance for the GG experiment in space*". Finally, we provide some references.

<u>*Addendum*</u>: Question posed by R. Battiston on September 24 along with answer given by A. Nobili are reported on pages 20-22

GGG historical layout from experimental results (September 2009)			
Year	**Funding Institution**	**Lab**	**Major steps and results**
1998-1999	ASI (GG Phase A Study) as result of ASI competition for a national space mission	Florence (provided by Laben-Proel, with fully equipped vacuum chamber)	• Demonstration of supercritical rotation for a multibody mechanical system with passive whirl damping
2000-2003 (first half)	ASI (GG Advanced Phase A Study) funded by ASI to establish feasibility of GG in SS orbit, to avoid high launching costs to equatorial orbit	Florence (same as above)	• Active, fine whirl damping based on capacitance sensors-actuators (passive damping used only at resonance crossing) • **Q measurements with full system (Figs. 1 & 2)** • **Measurements of gyroscopic effects (Fig. 3)** • Stable runs, but short duration (about 1 hr) (included in Fig. 4)
2003 (second half)–2005	INFN-CSNII	GGG lab from INFN in Pisa-San Piero a Grado (vacuum chamber and pumps bought second hand from Laben-Proel)	• Set up of new lab and vacuum chamber • **GGG instrument improvements**: Motor on axis; Contactless power transfer; Fine whirl control improved -passive damping at resonance crossing no longer needed- **allows us to prove theory on losses in supercritical rotation – Fig. 4**); **Tilts control (Fig. 5)** • Long duration runs (no longer limited by GGG instrument); **Sensitivity improved by almost 3 orders of magnitude (Fig. 6)**
2006	INFN-CSNII	Pisa-San Piero a Grado (same as above)	• 2 papers published reporting theory, numerical simulation and experimental evidence on GGG rotating differential accelerometer (Comandi et al., Rev. Sci. Instr., 2006 a,b) • **Prove of selfcentring to an equilibrium position determined by physics laws (Figs. 7 & 8))** • **Thermal stabilization to 0.1-0.2 °C at 1 d provides an improvement in sensitivity at diurnal frequency by almost 2 orders of magnitude (Fig. 9)**
2007	INFN-CSNII	Pisa-San Piero a Grado (same as above)	• Geeomechanics tiltmeter broke down (liquid of spirit level evaporated); new one resulted more affected by temperature; structural damages in GGG lab resulted in damages of GGG apparatus as well • Improved ball bearings system (reduces load, power and disturbances) • Implemented 24-bit electronics + time stamp of digitized data with Rb clock (not limited by electronics) • **Thermal stability to 0.02 ° at diurnal frequency (see effects in Fig. 10)**
2008-2009	ASI+ INFN-CSNII	Pisa-San Piero a Grado (same as above)	• Design and setup of new chamber for Advanced GGG funded by ASI. **Will allow the new GGG apparatus to be suspended from cardanic (not rotating) suspension for passive tilt reduction** (in addition to active)**;** simply not possible in old chamber**.** As for now, old GGG moved to new chamber **(**see results **Fig. 11 & 12)** • **Very good thermal stability achieved in new chamber (Fig. 13;** to be published**))** • Design (construction ongoing) of advanced GGG apparatus, to include passive suspension + other improvements (ball bearings design; capacitance plates, power coupler location, tiltmeter) • Procurement and characterization of ISA-like tiltmeter for use with advanced GGG (same sensitivity as Geoomechanics tiltmeter but more stable) • **A new concept, very sensitive double pendulum tiltmeter has been constructed .**Under test **(Fig. 14)** • **Rigorous measurement of the effect of electric patches in GGG (to be published**)

A few comments are worth making in order to fully appreciate the information on GGG provided in the Table above.

GGG looks for an EP violation in the field of the Sun, which would manifest itself as a minute relative displacement of the test cylinders in the horizontal (non rotating) plane of the lab at diurnal frequency. GGG must therefore have very good sensitivity to displacements at very low frequencies. This requires numerous sources of noise trying to be reduced one by one: in absence of EP violation the test cylinders should not move at all relative to each other!

The first big improvement (**see Fig. 6**), whereby stable runs lasting as along as desired became possible, was due to changes made to the rotor (motor on axis, double cardanic joint between motor and rotor, contactless power transfer) and an improved whirl control loop. Once such capability has been acquired and consolidated, reduction of diurnal terrain tilts is crucial to improve sensitivity at low frequencies.

A very good tilt control loop was implemented in 2005, as shown in Fig. 5. However, the tilt sensor on which the loop is closed (a spirit level sensor bought from Geomechanics and used by many other research groups over the world) is affected by temperature variations. Thus, unless good thermal stability is ensured, spurious tilts are going to be reintroduced in the system by the control loop. The effect of thermal stability on the motion of the test cylinders at daily frequency is apparent in **Fig. 10**. The next big improvement in sensitivity was in fact achieved after thermal stabilization (**see Fig. 9**) .

This is why special effort has been devoted to thermal stabilization of the new vacuum chamber (funded by ASI) which will host the new GGG apparatus, also supported by ASI. A new, multi-stage strategy has been adopted. The temperature of the chamber “body” is stabilized (with 4 loops closed on sensors located on the chamber itself); then, in this “good” environment it is relatively easy to stabilize specific internal components, such as the tiltmeter, and requires very little power, obtaining very good results (see **Fig. 13**) despite the fact that the lab building is strongly affected by thermal variations.

One should also try to use in the loop a tiltmeter which is less temperature dependent and more sensitive, especially at low frequencies. For the new chamber an ISA-like (mechanical) tiltmeter is already available and has been tested for GGG, in order to replace the one from Geomechanics. A new concept double pendulum tiltmeter has been recently constructed in the GGG lab and is being tested (see Fig. 14).

However, unless the GGG apparatus is suspended for **passive tilt reduction** (in addition to the active one) it will be severely limited by the tilt sensor. We identified this issue and studied the problem quite some time ago, but in the old vacuum chamber such a suspension is impossible (just for lack of room) . This is why the new chamber (in addition to having a more appropriate design and lower platform noise) was designed, together with the new GGG apparatus, for it to be suspended from an appropriate cardanic suspension (ready). In this respect the contribution from ASI is warmly acknowledged. The new chamber is available hosting for the time being the old GGG apparatus (not suspended). Thermal stabilization as achieved recently is satisfactory. The new GGG apparatus is under completion.

Below follow all the Figures referred to in the GGG historical layout Table

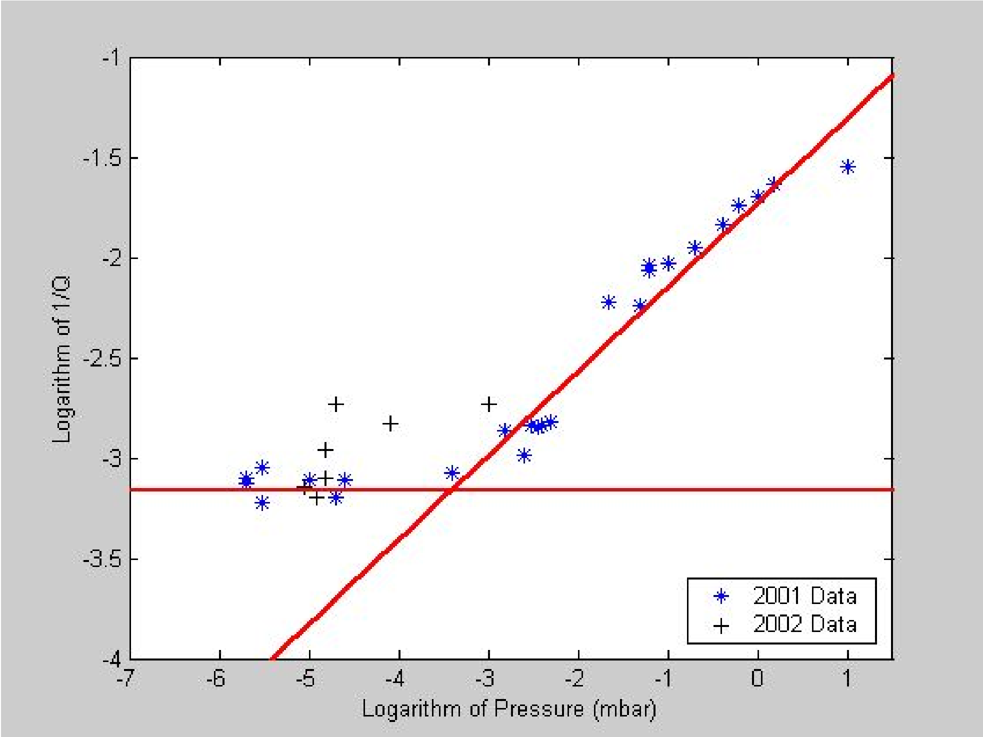


Fig. 1: Log-Log plot of the 1/Q value of the natural differential oscillations (about 8 s period;), at zero spin rate, as function of the residual air pressure in the chamber with linear best fits to the two sets of data, above and below 10^{-3} mbar. Each point refers to a separate run. For pressures greater than about 10^{-3} mbar the value of Q decreases as pressure increases. For lower pressures the value of Q reaches about 1590 and is then independent of pressure since it is the maximum value allowed by losses in the laminar suspensions. (Taken from Fig. 11 of Nobili et al., New Astronomy, 8, pp. 371-390, 2003)

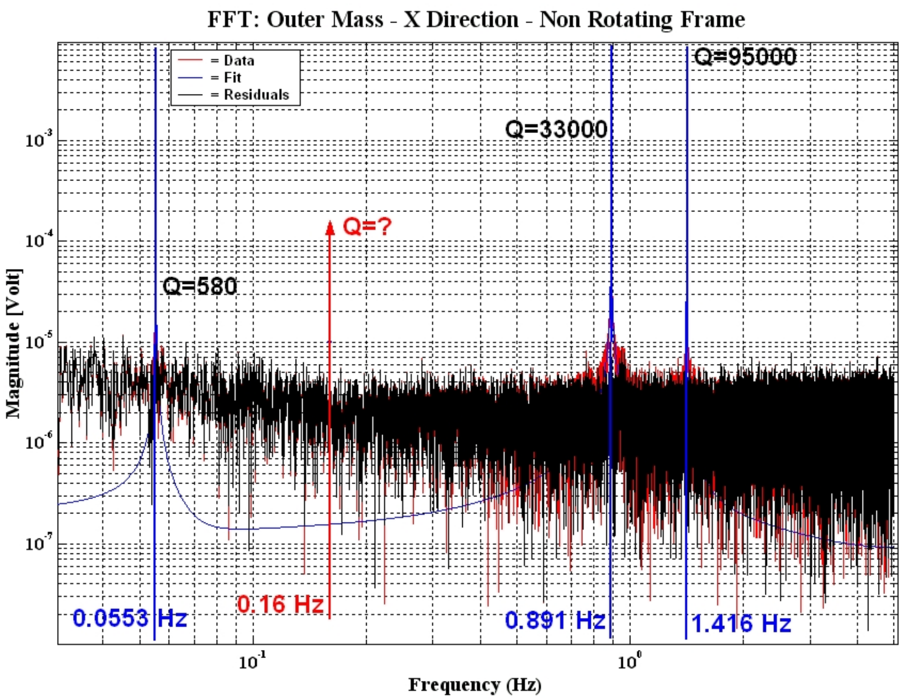


Fig. 2: Resulting quality factors of the GGG accelerometer at the natural frequencies (at zero spin) as obtained by measuring the oscillation decay of the system. The blue curve is the FFT of the fitted output data. The runs refer to a system set up (with improved cardanic suspensions) of June 2003. (Taken from Fig. 5 of Comandi et al, Physics Letters A 318 (2003) 213-222)**.** The plot shows clearly that the same suspensions have much smaller

losses at higher oscillation frequencies. Note that, since the GGG system has 3 natural frequencies, by monitoring the decay of the oscillation amplitude (either with the capacitance bridge sensors in between the test cylinders or with the bridge sensors normally used to sense -and control- the oscillations of the outer test cylinder) we can measure the Q values only at these 3 frequencies. Q values at other frequencies (as at the question marks) can be measured from the whirl growth with the system spinning at that frequency (see Fig. 4)..

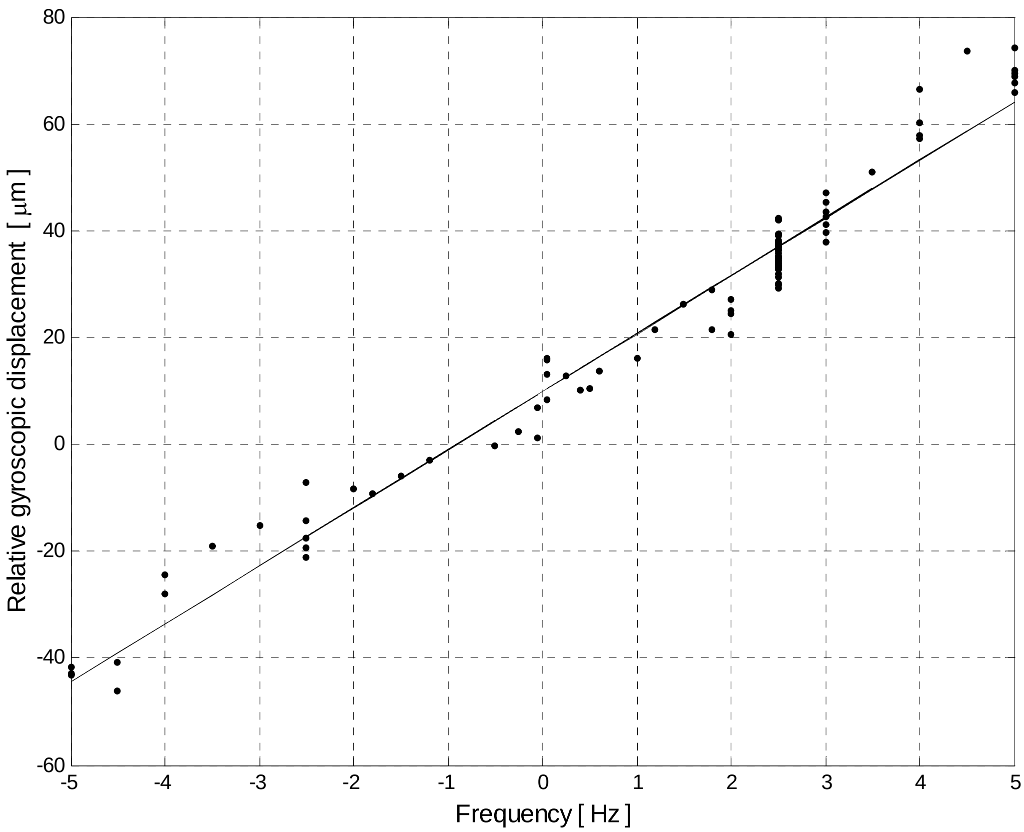
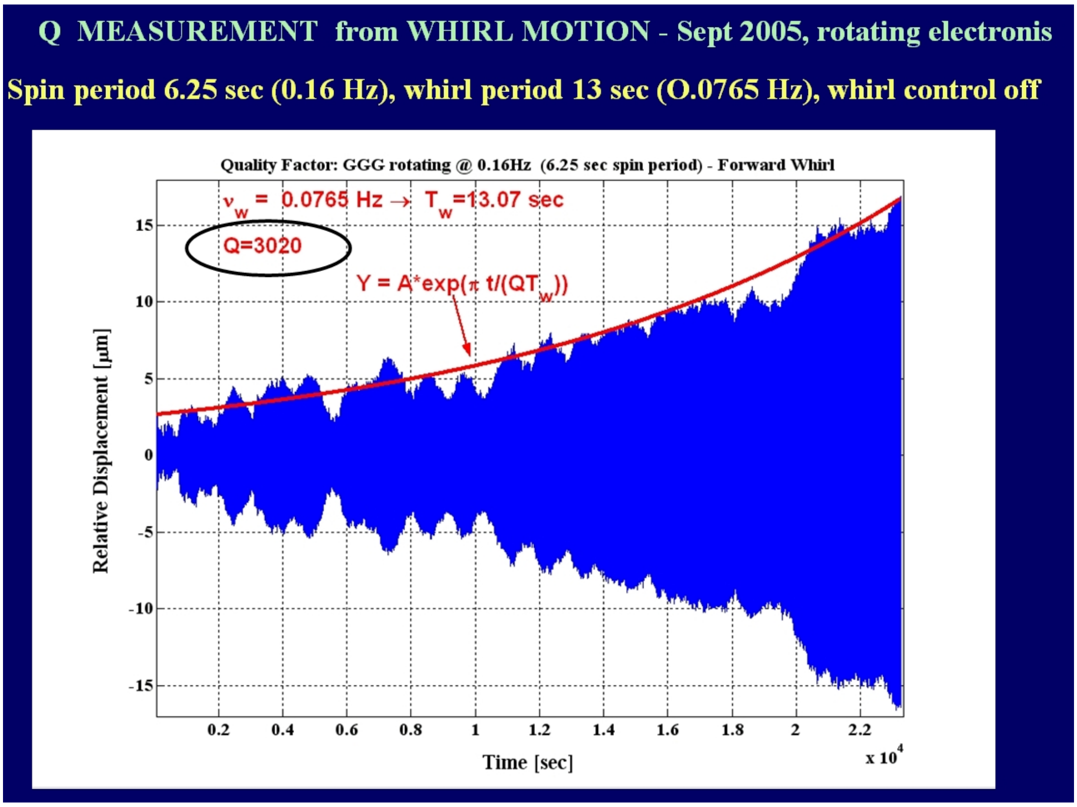


Fig. 3: Relative displacements (crosses) of the test cylinders, fixed in the horizontal plane of the laboratory, as function of the spin frequency and the sense of rotation, with linear fit to a straight line (on the frequency axis, counterclockwise spin frequencies are indicated as positive, clockwise ones as negative). The linear increase with the spin rate and the change of sign can be ascribed to the gyroscopic effect. The offset at zero spin is due to a residual inclination of the suspension shaft from the vertical. (Taken from Fig. 12 of Nobili et al., New Astronomy, 8, pp. 371-390, 2003). Gyroscopic effects would mask an Equivalence Principle violation signal in the field of the Earth and therefore the GGG accelerometer is used for testing the EP in the filed of the Sun.



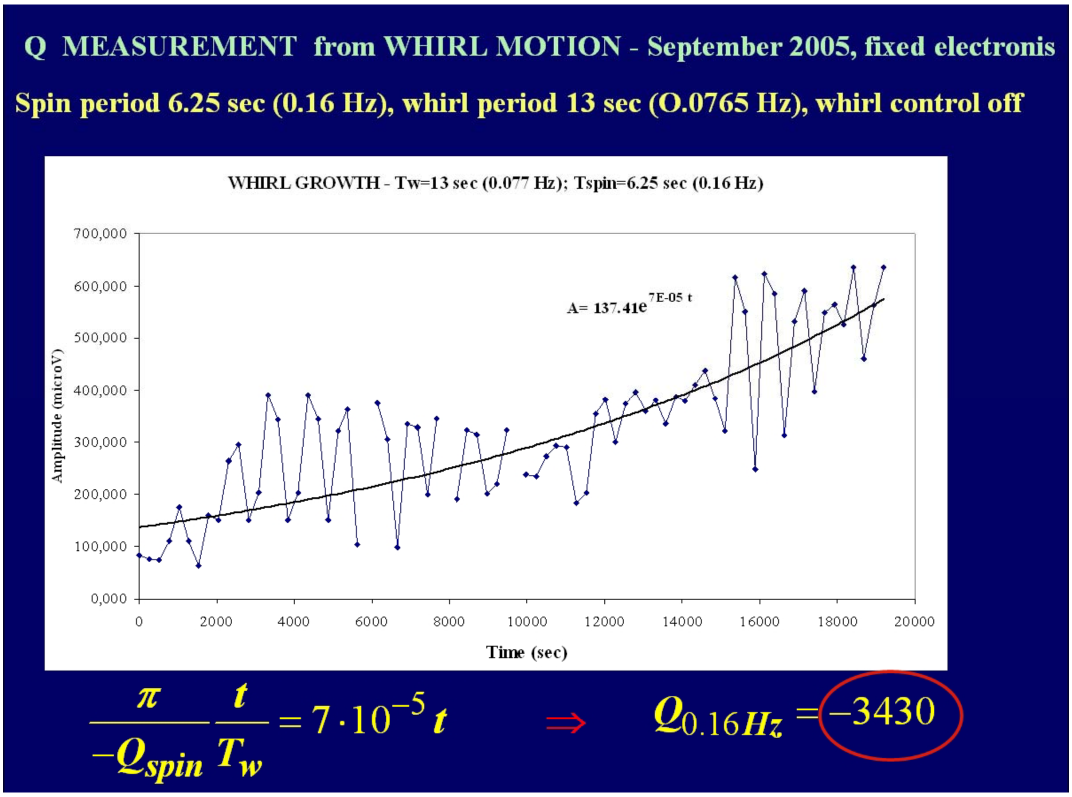


Fig. 4: Theory predicts that the relevant losses of a supercritical rotor are those at the spin frequency, not at the (lower) natural frequency for which rotation is supercritical (in this case the differential frequency of 0.055 Hz) . Therefore, by measuring then growth of whirl motion, which is determined by such losses, we can measure the Q of the system at the spin frequency, in this case 0.16 Hz. We get, by two different measurements, about 3000. From Fog. 2, it is apparent that this is a reasonable value for the GGG system thus indicating that the theoretical prediction is correct also in the case of the multibody GGG rotor.

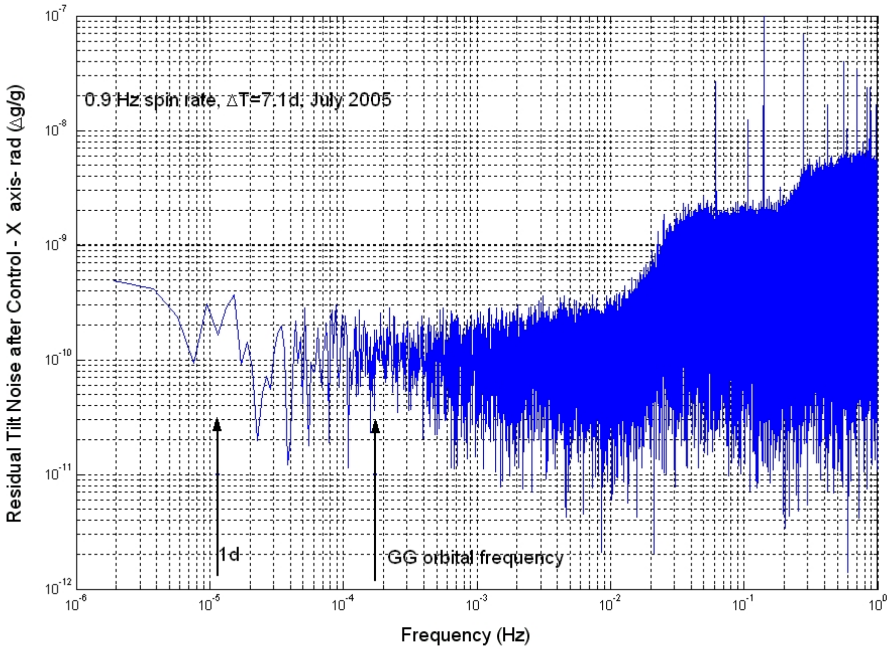


Fig. 5: Fast Fourier Transform of the residual tilt noise after applying tilt control in closed loop for 7.1 days with the GGG apparatus spinning at 0.9 Hz. The test shows that at the low frequencies of interest (the GG orbital frequency and the diurnal frequency), the tilt measurement signal of the sensor used to close the loop can be “zeroed” to a few 10^{-10} rad (10^{-10} rad corresponding, in the current set up, to a relative displacement of the test cylinders of about $0.5{\cdot}10^{-10}$ m). This is the best result which can be obtained given the sensitivity of the tilt meter used. However, while the performance of the loop is very good, we must stress that, because the tilt sensor is affected by temperature variations, part of the tilt signal sent to the PZT actuators for correction is indeed not due to real tilts but instead to thermal effects. Spurious tilts are in this way reintroduced in the system. Apart from trying to have a tiltmeter affected by temperature as little as possible, the mainsolution is to provide thermal stability. Corrections for temperature dependence (online or offline) also help.

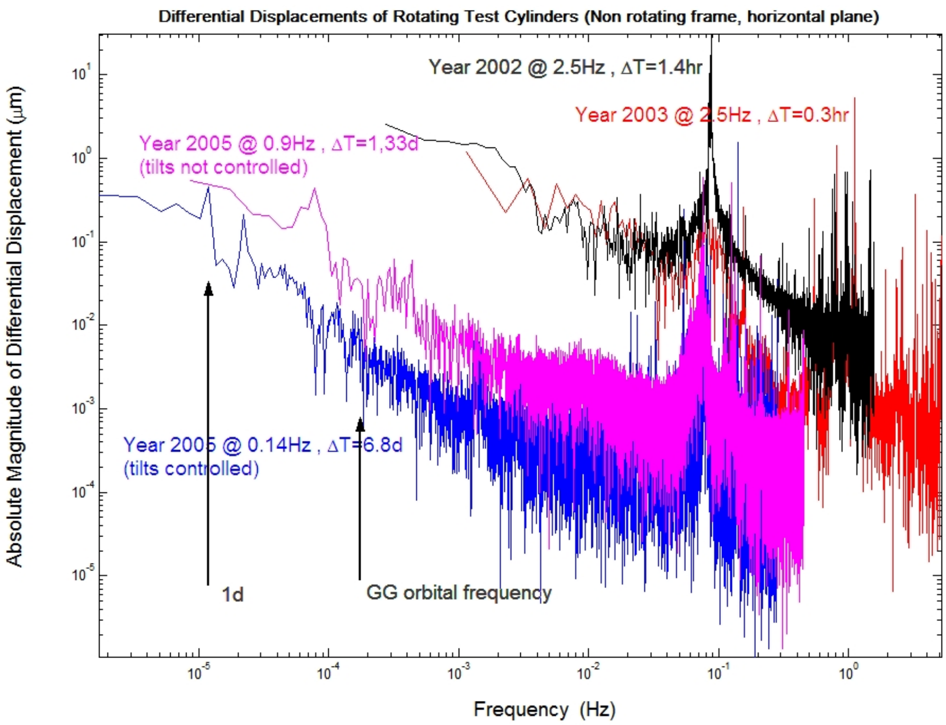


Fig. 6: FFT of the relative displacements of the GGG test cylinders (in micron) showing a very big improvement from 2002-2003 to 2005. The main issue is the duration of the experimental runs: while in 2002-

2003 they lasted about 1 hr, since 2005 (after the improvements recalled in the comments) it is possible to run the GGG experiment as long as desired; in particular, testing EP in the field of the Sun requires to be sensitive at the very low diurnal frequency.

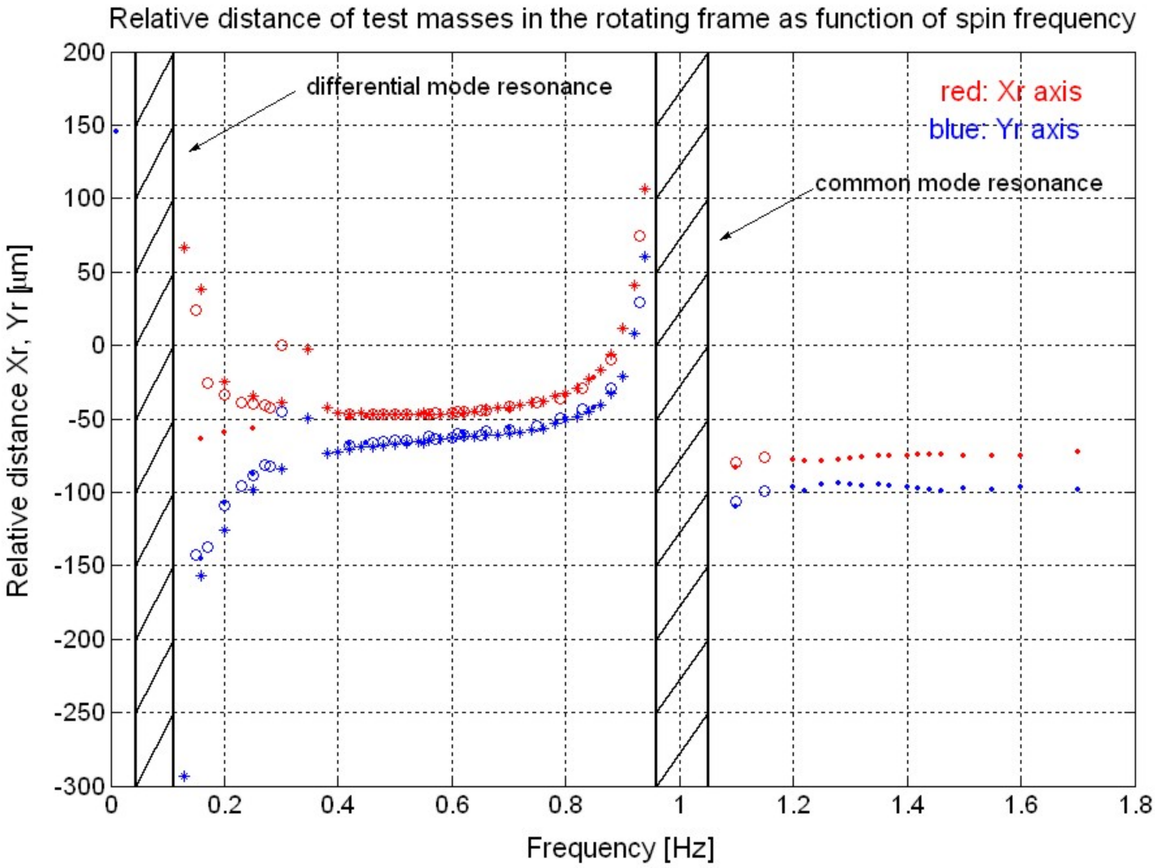


Fig. 7: This figure and the next one demonstrate that the GGG test cylinders behave as expected from theory, namely that, for a given hardware set up of the system, they always reach the same position of relative equilibrium determined by physical laws and independent from the initial conditions of the run. Her is plotted the relative distance of the test cylinders in the rotating reference frame as a function of the spin speed. Xr component is red colored. Yr component is blue colored. Different symbols are used for different measurement sessions: crosses correspond to measurement #1 of Fig. 8, circles correspond to measurement #2 and dots to measurements #3. Each data point refers to a run of several hours. The black dashed areas mark the instability regions which correspond to the normal modes of the system. As the spin frequency increases from 0Hz towards the first resonance at 0.075Hz (data labeled L in Fig. 8) the relative distance increases. Between the two resonances (i.e. between 0.12Hz and 0.89Hz; M in Fig. 8) the system reaches always the same equilibrium position: as the spin frequency is increased past the instability region the cylinders start self-centering and the relative distance decreases rapidly. For spin frequencies in the range 0.4Hz - 0.6Hz, the relative distance is independent of the initial conditions and the three lines (crosses, circles and dots) in the figure coincide. When the spin frequency approaches the second instability region the relative distance grows again. At higher frequencies, above both the resonances (H-high) the system reaches another equilibrium position.

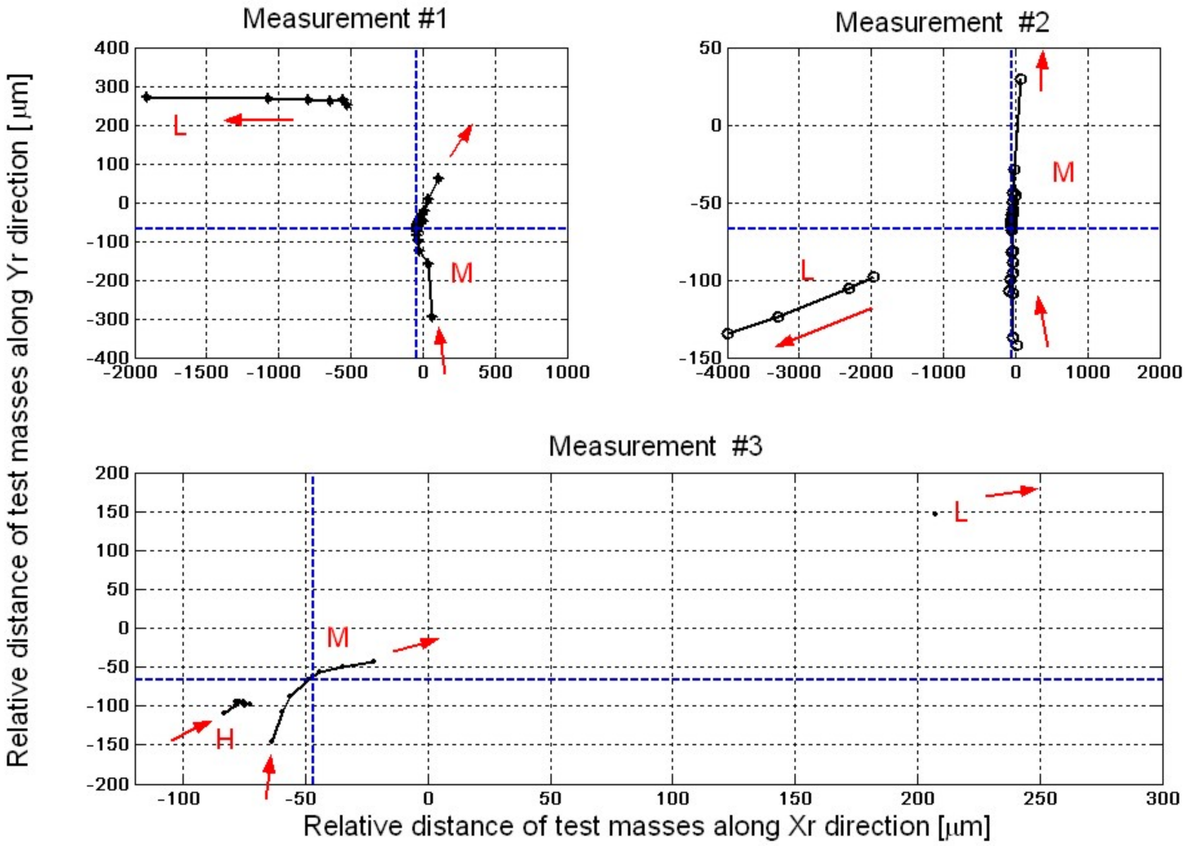


Fig. 8: Experimental evidence for auto-centering of the test cylinders in supercritical rotation in the horizontal plane (Xr,Yr) of the rotating reference frame fixed with rotor. As the spin frequency increases (along red arrow) from 0Hz below the first resonance (L data), the relative distance increases. In between the two resonances (M data), t**he two test cylinders self-center reaching the equilibrium position determined by the intersection of the 2 dashed lines (always the same position in the three panels, independent of their initial conditions)**. Above both resonances (H data) they reach another equilibrium position.

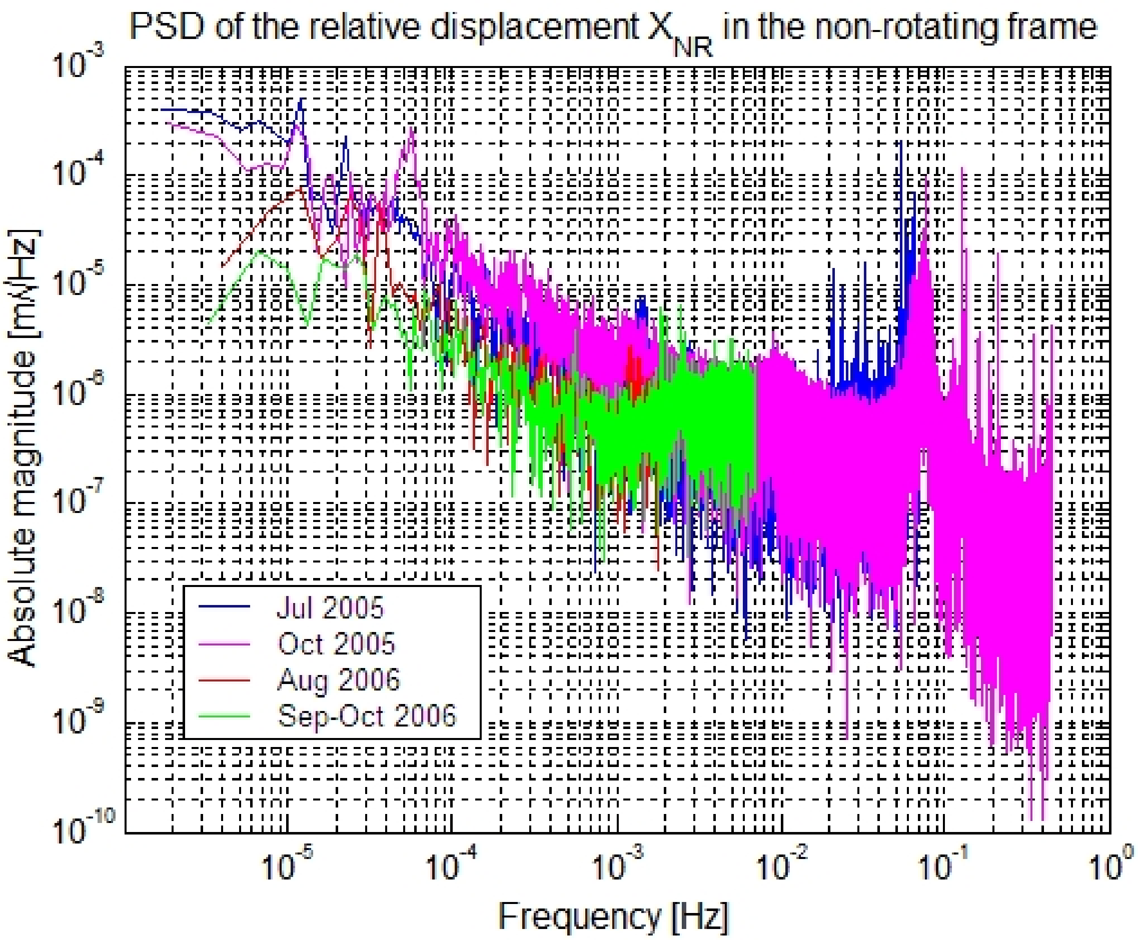


Fig. 9: The figure plots the Power Spectral Density of the relative displacements of the GGG test cylinders in the horizontal (non rotating) plane of the lab (in m/√Hz) as function of frequency down to very low frequencies. The reason for plotting the PSD rather than the FFT is to compared unambiguously runs of different duration. In the horizontal plane of the lab and EP violation in the field of the Sun would give rise to a differential displacement at the diurnal frequency of $1.16\text{x}10^{-5}$ Hz. The figure shows the considerable improvement at this frequency from 2005 to the fall 2006 run. It was due mainly to improved thermal stability (see Fig. 10).

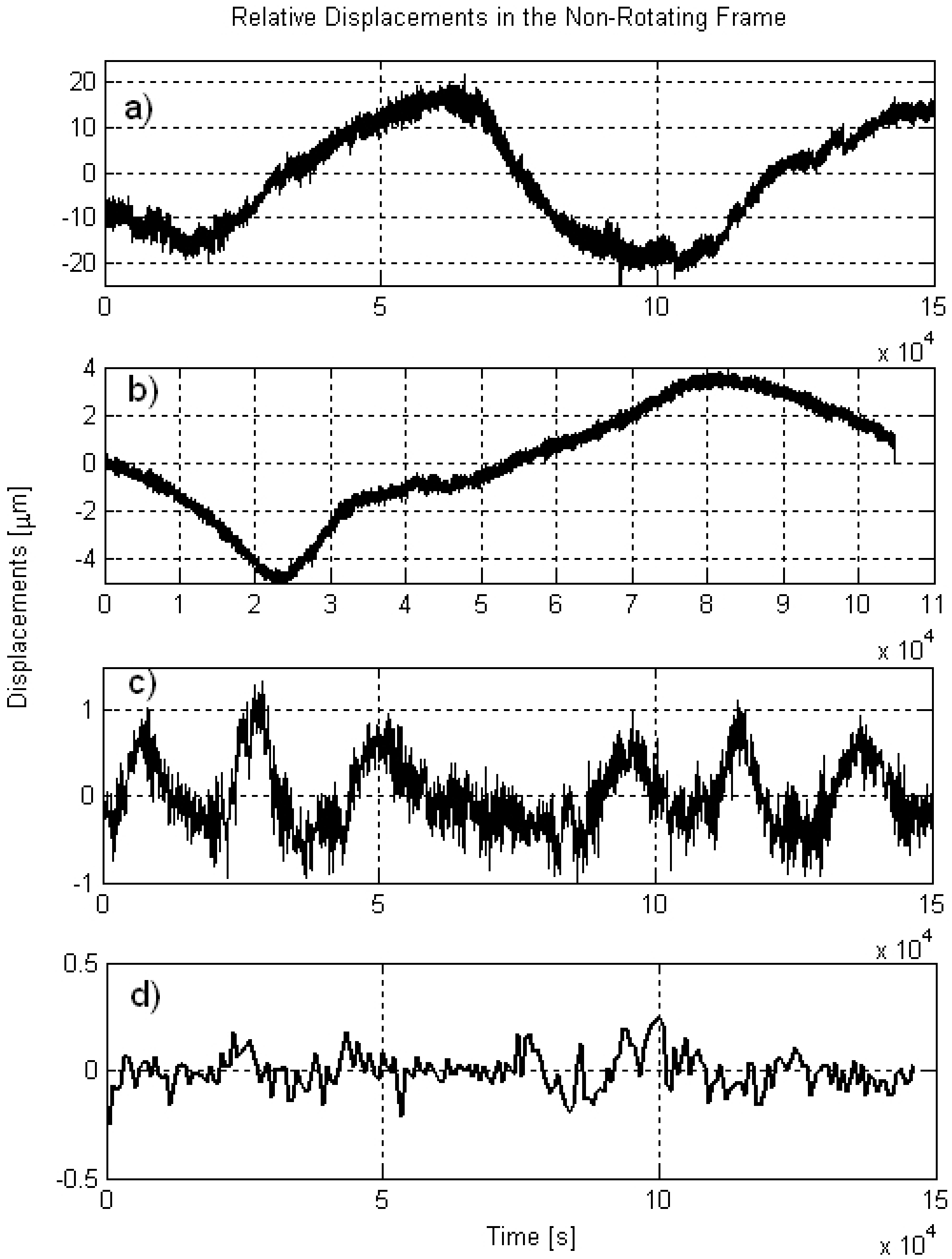


Fig. 10: The figure demonstrates the advantages of thermal stabilization of the vacuum chamber enclosing the GGG experiment. The plots show the relative displacements (in microns) between the centers of mass of the test cylinders in the horizontal plane of the laboratory (once transformed from the rotating reference frame). Each run lasts about 2 days. Diurnal variations are apparent in the two upper plots, while they are no longer visible in the bottom ones; from plot a) to plot d) the amplitude of the largest relative displacements has decreased from 20 to 0.2 μm. The improvement therefore amounts to 2 orders of magnitude. It has been obtained by improving the thermal stability of the chamber. Starting with the run reported in plot b) a thermal stabilization loop of the chamber was implemented and gradually improved during the following runs till reaching the level of 0.02 °C/d during the run reported in plot d).

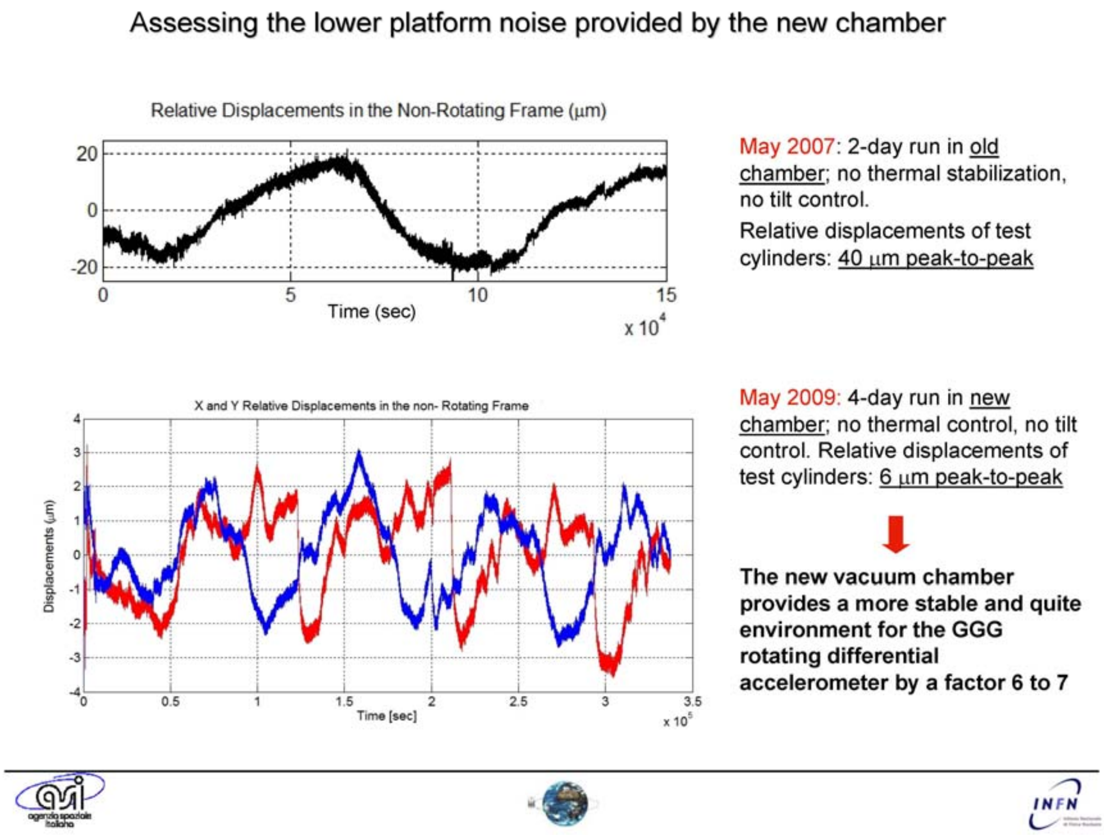


Fig. 11: Evidence of reduced platform noise in the new chamber.

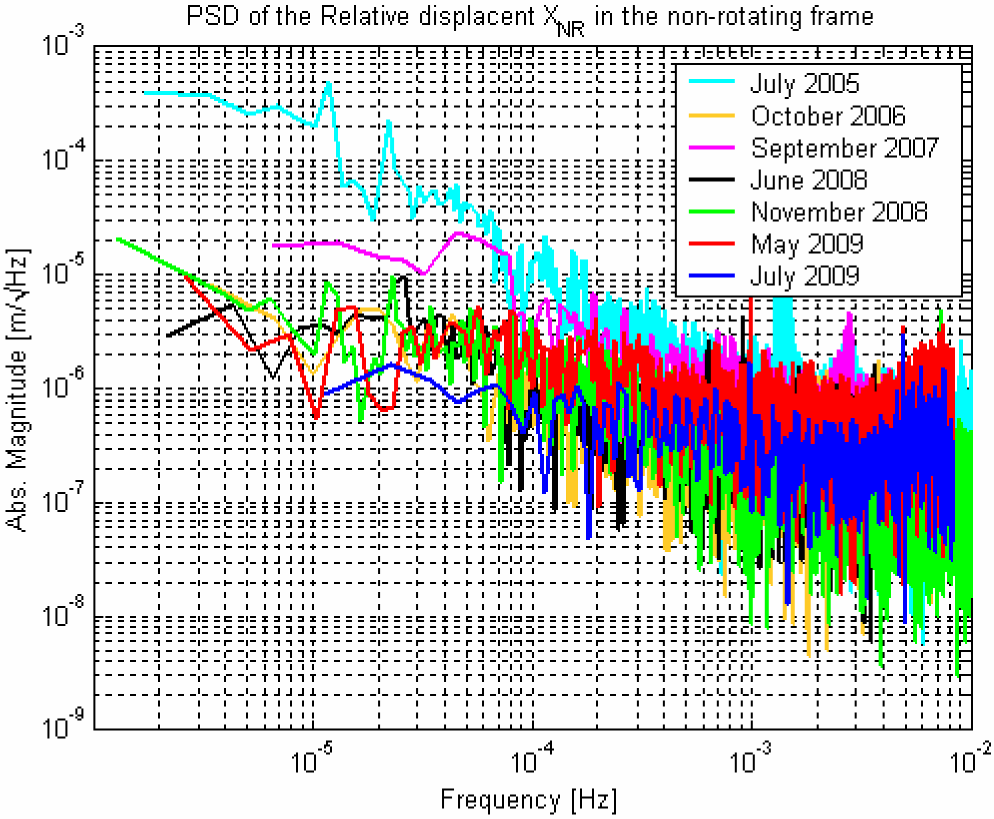


Fig.12 : PSD of the relative displacements of the GGG test cylinders in the horizontal non rotating plane of the lab (as in Fig. 9). The bad performance in 2007 (pink curve) was due to serious damages in the lab which resulted also in damages to the GGG instrumentation. The last two runs have been performed after the GGG apparatus was moved in the new chamber (whose thermal stabilization was also being implemented) and started working. Results comparable to those in the old chamber have been obtained but with no improvement so far. Once the new GGG apparatus is ready, it will be suspended in the new chamber and the old GGG will go back to the old chamber, to be used for various tests (its capability to run will be maintained and no spare parts are going to be used for the new experiment. Due to the low frequencies of interest, tests are time consumimg and having 2 instruments is very useful).

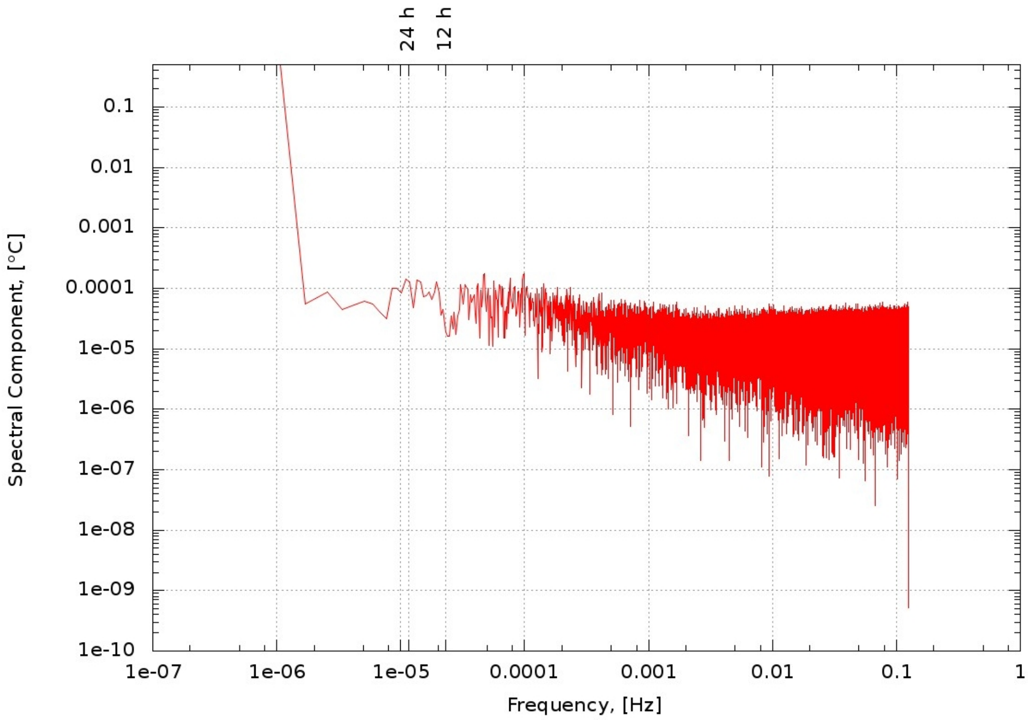


Fig. 13: FFT of the tiltmeter temperature, located on the GGG apparatus (not rotating) inside the new vacuum chamber. After chamber stabilization, a very good theremal stability of the tiltmeter is achieved with only about 20mW, reaming below 10^{-4}°C at all frequencies down to very low ones (thermal stabilization is obtained by heating only)

Fig. 14: Picture shows the new double pendulum tiltimeter designed in the GGG lab recently mounted for testing (with its capacitance sensing plates and measurement electronics). It is based on knife edge suspensions and the two masses are coupled by a weak cantilever. It is designed to reach long oscillation periods, hence high sensitivity to low frequency terrain tilts. At first test has reached 34.8 s, thus being as sensitive to terrain tilts as a simple pendulum of 300 m length. By adjusting the alignment and the pendulum mass we plan to reach 100 s period (equivalent to a 2500 m simple pendulum). The oscillation of the pendulum mass is sensed by means of two capacitance plates on opposite sides, the difference being read with a small ad hoc electronic board developed in the lab based on the AD7745 24 bit capacitance to digital converter capable to measure up to 4 picoFarad to a few tenths of femtoFarad. No additional electronics is needed outside the vacuum chamber; data are transferred to the computer outside via USB port.

The GGG differential accelerometer measures the relative displacements Δr_{diff} of the test cylinders around their position of relative equilibrium (provided by physics laws and by the hardware setup – see Figs. 7 & 8 for proof). The differential acceleration Δa_{diff} responsible for such displacements is easily derived given the natural period of oscillation of the cylinders relative to each other T_{diff}, as $\Delta a_{diff} \simeq \left(4\pi^2 / T_{diff}^2\right) \cdot \Delta r_{diff}$. The dimensionless Eötvös parameter quantifying the EP violation level is defined (in the field of the Sun as for GGG) as $\eta \equiv \Delta a_{diff} / a_{sun}$ ($a_{sun} \simeq 6 \cdot 10^{-3}\,\mathrm{m\,s^{-2}}$); it should be zero for no violation and has been tested (with slowly rotating torsion balances) to 10^{-13} (Schlamminger et al., 2008) . Thus, in the non rotating horizontal plane of the lab, GGG should measure –at the frequency $\nu_{sun} = 1/86164 = 1.16 \cdot 10^{-5}\,\mathrm{Hz}$– differential displacements as small as possible. This requires all sources of noise at this very low frequency to be reduced. Then, the longer T_{diff} the better the sensitivity in η ($\eta \propto 1/T_{diff}^2$) , which requires its test cylinders to be very weakly coupled and very well balanced.

The current sensitivity of GGG is thus inferred from the measurement reported below in Fig. 15, showing the FFT of the relative displacements (in μm) of the test cylinders at frequencies down below the diurnal frequency of interest. This is the best result so far; it has been obtained in the old chamber and confirmed after moving the old GGG apparatus to the new chamber, for which with thermal stabilization tests were ongoing. We can see that at diurnal frequency $\Delta r_{diff\,1d} \simeq 6 \cdot 10^{-9}\,\mathrm{m}$. The differential period obtained with the CuBe cardanic suspensions in use since a few years is $T_{diff} = 13\,\mathrm{s}$ thus we have:

$$\eta_{GGG\,sun} \simeq \frac{4\pi^2}{T_{diff}^2} \cdot \Delta r_{diff\,1d} \cdot \frac{1}{a_{sun}} \simeq \frac{4\pi^2}{13^2} \cdot 6 \cdot 10^{-9} \cdot \frac{1}{6 \cdot 10^{-3}} \simeq 2.3 \cdot 10^{-7} \qquad (\Delta r_{diff\,1d} \simeq 6 \cdot 10^{-9}\,\mathrm{m}\ ,\ T_{diff} = 13\,\mathrm{s}) \tag{1}$$

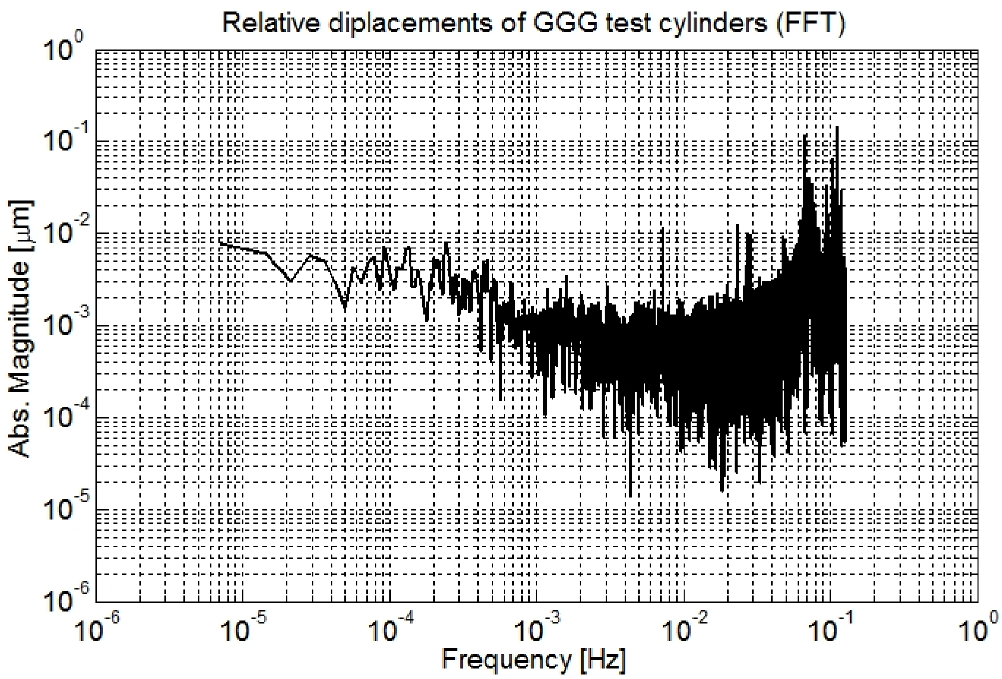


Fig. 15: FFT of the relative displacements (in μm) of the GGG test cylinders as measured in the old vacuum chamber. After moving the GGG apparatus to the new chamber (not suspended) in April 2009 the rotor runs properly and the result has been confirmed but not yet improved

We have experimental evidence that in the current GGG the effect of terrain tilts on the test cylinders is as follows:

a tilt angle by $1\,\mu\text{rad}$ gives rise to a relative displacement of the test cylinders by $0.5\,\mu\text{m}$

We also know from independent measurements that terrain tilts in the lab at diurnal frequency have an amplitude up to $10\,\mu\text{rad}$. Since GGG has measured (Fig. 15) $6\cdot 10^{-3}\,\mu\text{m}$, it follows that –thanks to the tilt control loop– it did not experience tilts larger than $1.2\cdot 10^{-2}\,\mu\text{rad}$, which means that the loop provided an "effective" attenuation by about a factor 800. The limitation does not come from the control loop design, neither from the PZT actuators, but from the tiltmeter and its temperature dependence. With active tilt control only (and no passive suspension for further attenuation) the only way is to improve on that, as we have done so far (see Figs. 9 & 10). This explains also our efforts in acquiring a better tiltmeter and even constructing our own (see Fig. 14).

However, a much bigger improvement can be obtained only by means of a passive cardanic suspension of the GGG apparatus. The issue has been investigated quantitatively (Nobili et al., 2003) and was reported in the presentation to INFN-CSNII (CSNII meeting in Venice, March 2003) when the GGG experiment was approved. The quantitative argument given in the paper (based on exploiting the lever effect) and on cardanic suspensions similar to those already in use (simpler, because low Q is required for attenuation) tells us that it is feasible to passively reduce terrain tilts on GGG by more than 3 orders of magnitude. The attenuation factor is:

$$\chi_{tilt\ pass} \simeq \frac{mgl}{k_{susp}\lambda^2} \simeq \frac{70\cdot 9.8\cdot 0.6}{3\cdot 10^3\cdot(5\cdot 10^{-3})^2} \simeq 5500 \qquad (2)$$

where $m \simeq 70\,\text{kg}$ is the mass of the apparatus suspended, $l \simeq 0.6\,\text{m}$ the suspension arm, $k_{susp} \simeq 3\cdot 10^3\ \text{Nm}^{-1}$ the stiffness of the suspension whose flexible strip is $\lambda = 5\cdot 10^{-3}\ \text{m}$ long (such a cardanic suspension has already been manufactured). In the newly constructed vacuum chamber such a passive attenuation will be implemented.

The target proposed to INFN-CSNII for GGG at its approval in 2003 was $\eta_{\text{target}\,2003} = 10^{-9}$. Assuming passive tilt attenuation by a factor 300 only instead of the expected value given above (in addition to active control at the same level as achieved so far), tilt noise at diurnal frequency should go down accordingly from 6nm to 20pm, thus reaching (see (1)) $\eta_{sun} \simeq 8\cdot 10^{-10}$. Obviously this requires that no other sources of noise show up as we reduce tilts, and that the read out electronics noise is below 20pm. An improved electronics is in preparation for the new rotor and it is expected (also from other groups experience) to be up to the task (and indeed better). As for other sources of noise, a feared candidate is ball bearings noise –which is very hard to predict quantitatively– and this is why we have devoted considerable efforts in a new design of ball bearings for the new rotor (ready).

In order to reasonably assess the ultimate target for EP testing with GGG we argue as follows. We are confident that the GGG electronics will reasonably sense $1\,\text{pm}$ displacements; for tilt effects to be below that, we need a further reduction from the current situation (see (1)) by about a factor 6000 (i.e. from 6nm to 1pm displacements), to be achieved by also improving on the active tilt control; in this case, with $T_{diff} = 13\,\text{s}$ as at present, we would be at $\eta \simeq 4\cdot 10^{-11}$. Abating the GGG noise so as to detect relative displacements to the pm level would provide extremely strong evidence that GG can reach its target in space (see below).

Then, we can start improving on the coupling of the test cylinders in the GGG accelerometer; they can be more weakly coupled and better balanced, which would result in a longer oscillation period in differential mode. The GGG rotor runs very smoothly since quite some time already; no passive damping device is needed at resonance crossing (when spin speed is increased to supercritical regime) and we have considered manufacturing thinner suspensions. It can be envisaged that the differential period can reach $50\mathrm{s}$. In this case, for the same measured displacements of $1\mathrm{pm}$ the sensitivity as an EP test (see (1)) would be a factor $(50/13)^2 = 14.8$ better, thus reaching $\eta \simeq 3\cdot 10^{-12}$.

This would be a factor 30 worse than the 10^{-13} best EP test performed with slowly rotating torsion balances. However, it would be based on a very different apparatus; in addition, it should be noted that no other very sensitive lab tests exist based on macroscopic test masses. As for the new EP tests based on cold atoms, they have reached 10^{-7} with atoms differing by 2 neutrons only (Fray et al., 2004) and $\Delta g/g \simeq 10^{-9}$ as a measure of g with the same atoms (Peters, Chung & Chu, 1999).

Most importantly, GGG is the only ground apparatus for EP testing designed for use in space ,where it can aim at reaching much higher sensitivity with the GG satellite. GGG mimics the accelerometer to fly with GG in all its main dynamical features. to 1:1 scale. Key physical features of the accelerometer design –mechanical transducer, read out electronics, whirl control strategy etc.. – are the same in both cases. Many solutions implemented in GGG and measurements performed in the lab are already applicable to GG. The major feature of GG which lacks in GGG is obviously drag free control, which therefore cannot be tested as such in GGG.

To the contrary, GGG not being an isolated system as the GG satellite in space, it needs a motor and must face local terrain tilts as well as ball bearings noise. As discussed above, at present GGG sensitivity is limited by terrain tilts. GGG has clearly proved that the GG novel accelerometer design is suitable to test the Equivalence Principle. On a quantitative basis, all GG mission studies confirm that in order to meet its goal to test EP to 10^{-17} (4 orders of magnitude improvement) the GG accelerometer must be able to measure relative displacements of the test masses of 0.5 pm. For GGG to reach the pm level, terrain tilts must be reduced as discussed above, and the implementation of passive suspension appears to be up to the task.

The reason why reaching pm level with GGG would be a very strong result for GG is simple. For GGG it with the current 13s differential period it would mean an EP test to $4\cdot 10^{-11}$, as we have seen. GG in space has two major advantages over GGG: the signal from Earth is 8.1 ms^{-2} (at 600 km altitude) to be compared with $a_{sun} \simeq 6\cdot 10^{-3}\,\mathrm{ms}^{-2}$ in GGG, with a gain factor of 1300 **and** the test cylinders can be coupled –because of weightlessness– much more weakly than on ground, with a natural differential period of 540s rather than 13s, thus gaining a factor of $(540/13)^2$=1700. The net result is that measuring pm displacements in GGG would strongly suggest that GG can achieve 10^{-17}.

We plan to have the new GGG suspended apparatus assembled and running by June 2010. and to assess the sensitivity achieved by the end of 2010.

REFERENCES

G.L. Comandi, A.M. Nobili, D. Bramanti, R. Toncelli, E. Polacco, M.L.Chiofalo: "Galileo Galilei on the Ground – GGG": experimental results and perspectives, Physics Letters A, 318, 213-222, 2003

G.L. Comandi, PhD thesis "A fast rotating differential accelerometer for testing the Equivalence Principle: Preliminary Results" (Defended 2004) http://eotvos.dm.unipi.it/comandi_thesis/index.html

G.L. Comandi, M.L. Chiofalo, R. Toncelli, D. Bramanti, E. Polacco and A.M. Nobili: Dynamical Response of the Galileo Galilei rotor for a Ground test of the Equivalence Principle: theory, simulation and experiment. Part I: the normal modes, Review of Scientific Instruments, 77, 034501(1-15), 2006

G.L. Comandi, R. Toncelli, M.L. Chiofalo, D. Bramanti and A.M. Nobili: Dynamical Response of the Galileo Galilei rotor for a Ground test of the Equivalence Principle: theory, simulation and experiment. Part II: the rejection behavior, Review of Scientific Instruments, 77, 034502(1-10), 2006

Fray, S., Alvarez Diez, C., Hansch, T.W. and Weitz, M., , Phys. Rev. Lett. 93, 240404, 2004

A.M. Nobili, D. Bramanti, G.L. Comandi, R. Toncelli, E. Polacco: A rotating differential accelerometer for testing the equivalence principle in space: results from laboratory tests of a ground prototype, New Astronomy, 8, 371-390, 2003

A.M. Nobili, D. Bramanti, G.L. Comandi, R. Toncelli, E. Polacco, M.L. Chiofalo: in Proceedings of the XXXVIIIth Rencontres de Moriond "Gravitational Waves and Experimental Gravity",J. Dumarchez and J. Tran Thanh Van Eds., The Gioi Publishers, Vietnam, pp. 371-376, 2003

A.M. Nobili, G.L. Comandi, S. Doravari, F. Maccarrone, D. Bramanti, E. Polacco: Experimental validation of a high accuracy test of the Equivalence Principle with small satellite "Galileo Galilei-GG", International Journal of Modern Physics D, 16, 2259-2270, 2007

A.M. Nobili, G.L. Comandi, D. Bramanti, S. Doravari, D. Lucchesi, F. Maccarrone: Limitations to testing the equivalence with satellite laser ranging, General Relativity and Gravitation, 40, 1533-1544, 2008

A. Peters, Chung, K.Y. & Chu, S., Measurement of gravitational acceleration by dropping atoms, Nature 400, 849, 1999

Schlamminger, S., Choi K.-Y., Wagner T. A., Gundlach , J.H. & Adelberger E. G 2008, Test of the equivalence principle using a rotating torsion balance, Phys. Rev. Lett. 100, 041101, 2008

Da Roberto Battiston, richiesta di chiarimento - 24 Settembre 2009

Un chiarimento, nel testo e nelle tabelle parli di importanti miglioramenti:

Long duration runs (no longer limited by GGG instrument); Sensitivity improved by almost 3 orders of magnitude (Fig. 6)

Thermal stabilization to 0.1-0.2 °C at 1 d provides an improvement in sensitivity at diurnal frequency by almost 2 orders of magnitude (Fig. 9)

Da queste frasi deduco che c'è stato un miglioramento di quasi 5 ordini di grandezza.....

Poi pero' affermi che la precisione raggiunta ad oggi è di 2,3 10^{-7}.
Cosa devo dedurre che all'inizio della sperimentazione era dell'ordine di 10^{-2}?

Oppure non è possibile combinare i due miglioramenti di cui parli ?

Grazie Roberto

Risposta- 25 Settembre 2009

Le misure del 2002-2003 (Fig. 6 riportata di nuovo qui sotto) non si possono considerare un test di EP nel campo del Sole perchè durano circa 1hr e quindi non arrivano alla frequenza diurna. Però dimostrano che il rotore era sensibile a spostamenti relativi dei cilindri di prova inferiori ad l μm. Un ulteriore lavoro era stato fatto per capire come recuperare un segnale in presenza del whirl; il risultato è mostrato nelle due figure che ti riporto in Fig. A1 (tratte dalla presentazione alla CSNII a Venezia il 15 Marzo 2003 quando GGG fu approvato; pubblicate in Comandi et al., Phys. Lett. A (2003)). Da queste figure si vede che si raggiungeva una sensibilità di 0.1 μm (anche se non a frequenze così basse come quella diurna). Assumendo di poter contare su questa sensibilità anche ad 1 giorno, siccome all'epoca operavamo con un periodo differenziale di 15s, usando la formula (1) della Nota risulta $\eta\sim3\cdot10^{-6}$. Per questo, in quella presentazione alla CSNII affermavamo di partire da circa 10^{-6}.

Da allora in poi, il buon Ugo Gastaldi mi ha giustamente impedito di citare una sensibilità a meno di non avere una misura che la dimostrasse senza estrapolazioni.

Le misure fatte a Pisa nel 2005, oltre a raggiungere frequenze inferiori al giorno con run di lunga durata, mostrano che la sensibilità è molto migliorata: alle frequenze più basse raggiunte nel 2002 (un pò sotto il mHz - curva nera di Fig. 6,), il miglioramento nel 2005, grazie anche al controllo dei tilt del terreno, risulta essere di 3 ordini di grandezza (curva blu, stesse frequenze). Questo è un miglioramento decisamente significativo, ed è quello che tu citi all'inizio del tuo messaggio.

Per quanto riguarda la sensibilità in η ad 1 giorno, la migliore curva del 2005 (curva blu, Fig. 6) mostra che alle basse frequenze c'è un peggioramento e a quella diurna siamo sotto al μm, ma non ancora al decimo di μm che credevamo di poter raggiungere.

Ci siamo convinti che ciò fosse dovuto soprattutto agli effetti delle variazioni giornaliere di temperatura sul tiltmetro utilizzato nel loop di controllo, e che quindi fosse necessario stabilizzare la camera. E infatti nell'autunno del 2006 alla frequenza diurna il miglioramento rispetto al 2005 era di 2 ordini di grandezza (Fig. 9, espresso in PSD).

Questo è il significato dei due miglioramenti di cui mi chiedi. Entrambi sono significativi ma non si possono cumulare come miglioramenti in η nel campo del Sole.

Anna

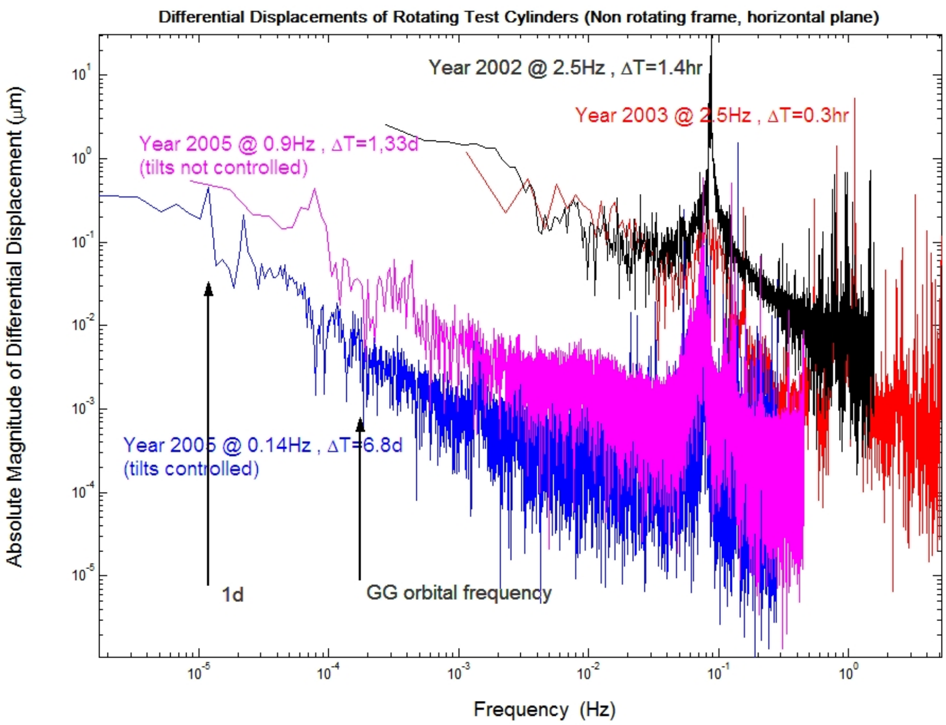


Fig. 6: FFT of the relative displacements of the GGG test cylinders (in micron) showing a very big improvement from 2002-2003 to 2005. The main issue is the duration of the experimental runs: while in 2002-2003 they lasted about 1 hr, since 2005 (after the improvements recalled in the comments) it is possible to run the GGG experiment as long as desired; in particular, testing EP in the field of the Sun requires to be sensitive at the very low diurnal frequency.

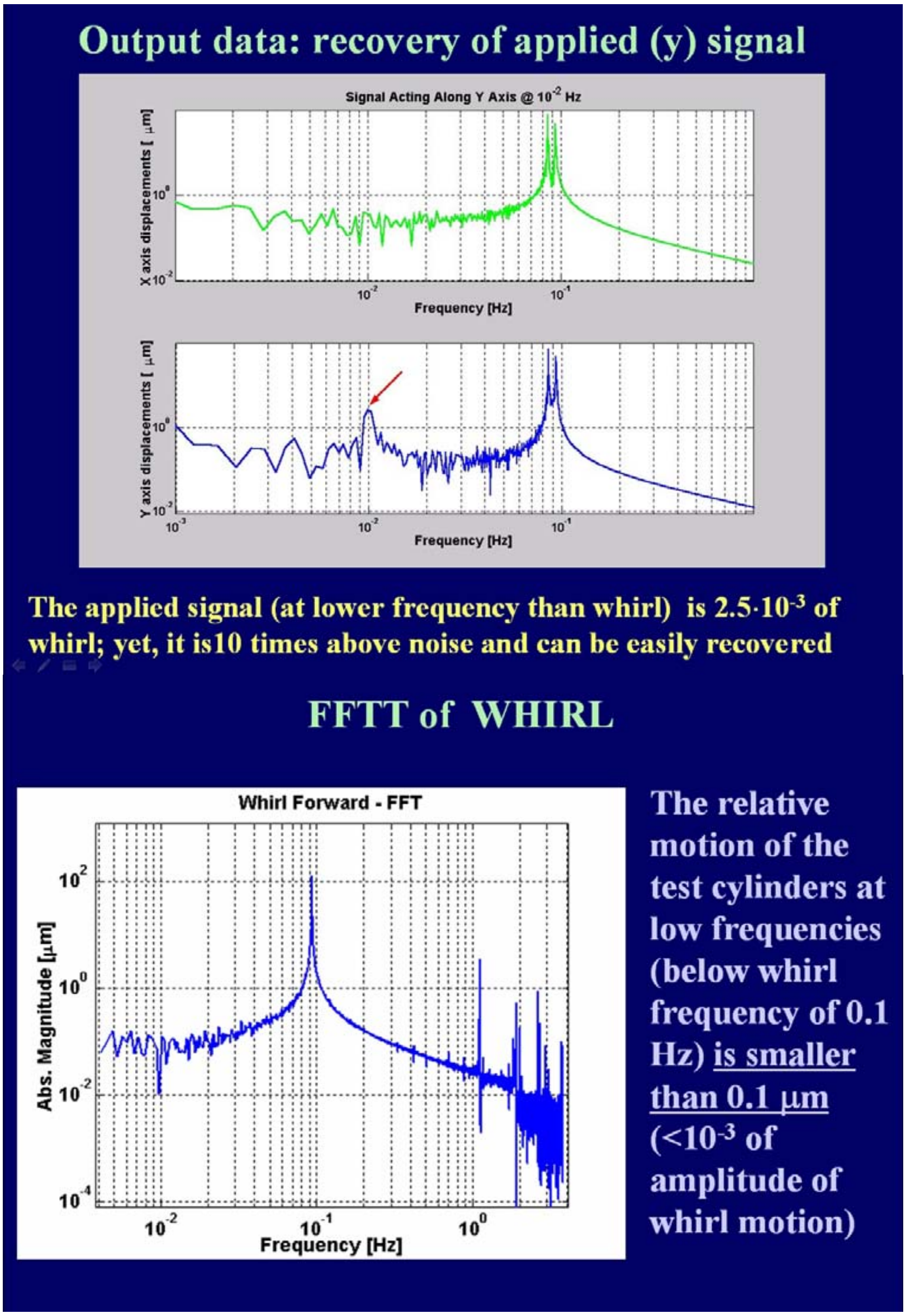


Fig: A1: Presentazione GGG alla CSNII per approvazione – Venezia 15 Marzo 2003 (risultati pubblicati in G.L. Comandi et al., Phys. Lett. A 318, 213-222, 2003)