Galileo Galilei – GG

Candidate proposal for the M4 mission of ESA

Presentation to the
Science Assessment Review Panel – SARP

by

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GG: a mission to test the founding pillar of GR to 10^{-17} and beyond

- GR rests on the "fact of Nature" that in a gravitational field all bodies fall with the same acceleration regardless of their mass and composition (UFF/WEP) and Einstein was well aware that experimental evidence is crucial

In the Editorial of CQG 2012 Focus Issue devoted to WEP, by Will & Speake we read:

"Einstein took WEP for granted in his construction of general relativity, never once referring to the epochal experiments by Baron Eötvös".

But it is not so!

In ***"The foundation of the General Theory of Relativity"*** *(1916)* § 2 *The need for an extension of the postulate of relativity*, **Einstein wrote**:

... *"This view is made possible for us by the teaching of experience as to the existence of a field of force, namely the gravitational field, which possesses the remarkable property of imparting the same acceleration to all bodies.*

Footnote: ***Eötvös has proved experimentally that the gravitational field has this property in great accuracy.***"

This footnote was not added in the English translation; it is there in the original paper in German!

Nobili et al., AJP 2013

- GG will test UFF/WEP to $\eta = 10^{-17}$ by measuring the differential acceleration between two test masses of different composition $\Delta a = g(h)\,\eta = 8.1 \cdot 10^{-17}\,\mathrm{m/s^2}$ while orbiting the Earth at $h \simeq 630\,\mathrm{km}$

4 orders of magnitude improvement over current best tests at 10^{-13} ***in the field of Earth obtained in lab controlled experiments with slowly rotating torsion balances (same level reached by LLR in the field of the Sun)***

(10 orders of magnitude improvement over best cold atoms drop tests)

2 orders of magnitude improvement over Microscope (to be launched April 2016)

GG baseline mission: $\eta = 10^{-17}$

- Be vs Ti ($\Delta a = 8.1 \cdot 10^{-17}\,\mathrm{m/s^2}$)
- Signal up-converted from $\nu_{orb} = 1.7 \cdot 10^{-4}\,\mathrm{Hz}$ to $\nu_{spin} = 1\,\mathrm{Hz} \Rightarrow$ very low thermal noise, 3.5 hr integration time, 1 full measurement test per day

  Pegna et al., PRL 2011; Nobili et al., PRD 2014

- $\sim$ 300 measurements during 1-yr mission in different dynamical conditions (orbit plane nodal regression by 1°/day and spin axis fixed in space) allow firm separation of systematics from signal by offline data analysis
- Laser gauge vs cap gauge readout: $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ @ 1 Hz noise, large gap ($\Rightarrow$ low gas damping noise & negligible patch effects), very good rejection of common modes
- GGG prototype (cap readout) has reached $\Delta a_{GGG@1.7e-4Hz} \simeq 4.7 \cdot 10^{-12}\,\mathrm{m/s^2}$
  - Stiffer coupling at 1-g (*unavoidable*) $\Rightarrow$ GGG 1600 times less sensitive than GG in absence of weight
  - GGG will reach its limit as ground demonstrator when motor/bearings rotation noise & tilt noise (both absent in GG) will be further reduced by factor 37

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GG advanced mission: $\eta_{adv} = 10^{-18}$ *(I)*

- Reach same differential acceleration sensitivity as in baseline mission $\Delta a = 8.1 \cdot 10^{-17}\,\mathrm{m/s^2}$ using C_2H_4 (H rich Polyethylene) vs Pb which have been shown to have about 1 order of magnitude better probing power for the same acceleration sensitivity

Hohensee et al., PRL 2013

- In GG rotation around the symmetry axis of test cylinders (and sensitivity in the plane $\perp$ to it) makes mass anomalies DC (if constant), minimizing the effects of construction errors ... Other issues remain to be investigated ... can be tested with GGG ...

GG advanced mission: $\eta_{adv} = 10^{-18}$ *(II)*

- Use "classical" materials but improve sensitivity to differential accelerations by 1 order of magnitude, to $\Delta a_{adv} = 8.1 \cdot 10^{-18}\,\mathrm{m/s^2}$. With the same thermal noise $\Rightarrow$ integration time of about 11 d

  - Laser gauge crucial (rejection of common modes much easier than with cap bridges & picometer sensitivity in 1 s). Better rejection from balance possible. Drag free control can be the same as in the baseline mission

  - All experiment drivers and requirements have been assessed for improvements

No show-stoppers have been identified, but careful investigation during definition study should tell which way is better to reach 10^{-18}

Why testing UFF/WEP? (see Q6)

- GR and the Standard Model cannot be reconciled with each other
- Because of UFF/WEP, gravity couples in the same way to all forms of mass-energy, and such universal coupling makes it different from all known forces described by the SM
- Most of the mass of the Universe is not understood

Experiment can break the lock by testing UFF/WEP to extremely high precision.

- A violation would make a revolution in Physics: Is GR to be amended? Is a new force of Nature at play?
- A null result after such deep probing will get rid of all theories which, in their attempts to solve the current impasse, predict violations of UFF/WEP. They will simply become less and less credible.
  ... remember what happened after Michelson & Morley experiment!

Physics is an experimental science: either way, a high precision test of UFF/WEP is a building block on which Physics will rest for decades to come

Current theories to be constrained by GG

- Fishbach et al. computed the contribution from neutrino-antineutrino interaction to the energy of a nucleus and find that a 10^{-17} WEP test would constrain coupling of gravity to neutrinos and higher order weak interactions
- String theories predict new fields which couple to composition and violate WEP. Dilaton scenario (Damour & coworkers) "estimate" violation between 10^{-13} and 10^{-18} (effect depends on many phenomenological parameters of the theory..)
- Search for Lorentz violation within SME framework (Kostelecky & coworkers). The gravitational sector of SME developed in recent years already includes WEP tests (and GG in particular). Tight constrains expected.
- Theories that predict variations of fundamental constants. WEP test sensitive to all couplings. Would be constrained by GG
- "Chamaleon" theories predict violations in a wide range that GG would tightly limit
- Tests of self-gravity contribution to UFF performed by LLR with Earth and Moon need WEP tests for separation

Why in space?

How GG exploits space

- Signal from Earth only slightly smaller than in drop tests ($\simeq 8\,\mathrm{m/s^2}$)
  $\simeq 500$ **times stronger than in ground balances with Earth as source**
  No such gain for drop tests

- Absence of weight: on ground the balance is suspended against $1\,g$, in space against $a_{iner-drag} \simeq 10^{-8}\,g$ (the largest acceleration on TMs is the inertial acceleration in response to air drag of the s/c) $\Rightarrow$
  suspending 100 kg mass in GG is like suspending $1\,\mathrm{mg}$ **on ground!**
  $\Rightarrow$ low stiffness, low natural frequency, high sensitivity

- "lab" (spacecraft) isolated in space: local disturbances ("terrain" tilts, nearby masses..) negligible; you can spin the "whole lab"

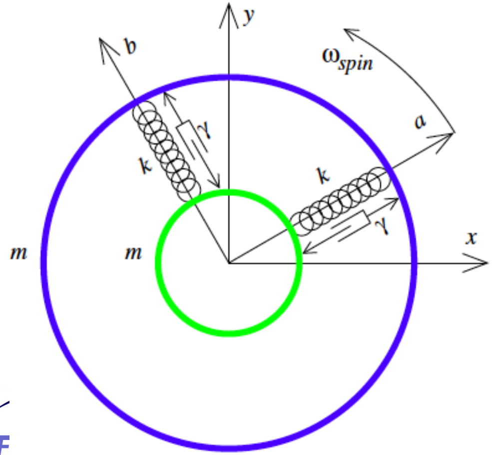
- Violation signal at orbital frequency (5800 s period) is up-converted to s/c spin frequency. GG stabilized by 1-axis rotation with 1 s period, provided once for all at mission start. **Angular momentum conservation, no motor, no bearings, whole "lab" co-rotating**.

  Like Earth's "passive" rotation in Dicke/Braginsky torsion balance test in the field of the Sun: yielded 3 to 4 orders of magnitude improvement over Eötvös torsion balance tests in the field of Earth...

Why GG?

GG driven solely by the violation signal

- Signal differential and extremely small $\Rightarrow$ test masses must be weakly coupled (very low differential frequency) as in a balance: torsion balance cannot fly as such, but we have learned the lesson
(*free floating test masses not competitive due to release errors: well studied and firmly demonstrated*)
- Test masses in space must be concentric (for small classical tidal/differential effects)
- Tests masses ("the balance") should spin –the faster the better– to up-convert the signal to higher frequency (another lesson from torsion balances)



A rotating 2D harmonic oscillator with $\nu_{dm} \ll \nu_{spin}$ (natural differential frequency much smaller than spin frequency) is by definition a supercritical rotor for which autocentering is ensured by physics:

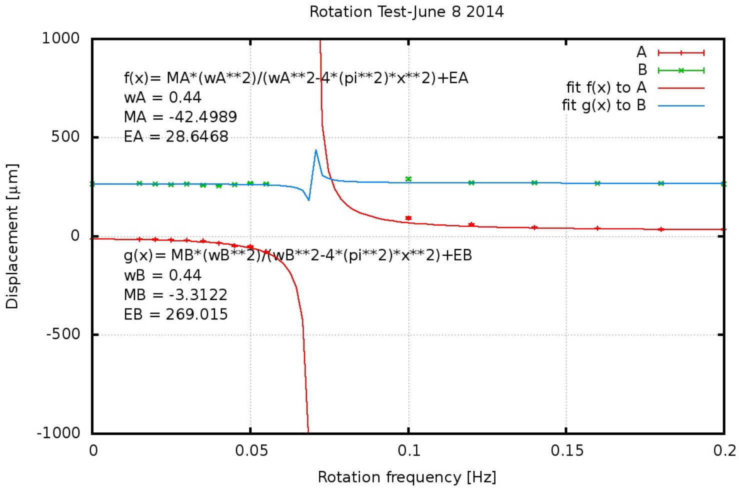
$$\Delta\vec{r}_{cc} \simeq -\vec{\varepsilon}\left(\frac{\omega_{dm}}{\omega_{spin}}\right)^2$$

How physics allows rapid rotation in 2D

Test cylinders cannot be perfectly concentric. The offset vector $\vec{\varepsilon}$ (fixed with the rotating masses) is not zero, but in 2D it is reduced by the factor $\omega_{diff}^2/\omega_{spin}^2$. The solution (in the non rotating frame) is:

$$\vec{r}(t) \simeq -\varepsilon \left(\frac{\omega_{diff}^2}{\omega_{spin}^2 - \omega_{diff}^2} \right) \begin{pmatrix} \cos(\omega_{spin} t + \varphi) \\ \sin(\omega_{spin} t + \varphi) \end{pmatrix} \simeq -\varepsilon \left(\frac{\omega_{diff}^2}{\omega_{spin}^2} \right) \begin{pmatrix} \cos(\omega_{spin} t + \varphi) \\ \sin(\omega_{spin} t + \varphi) \end{pmatrix}$$

GGG proof masses centered on one another by physics:



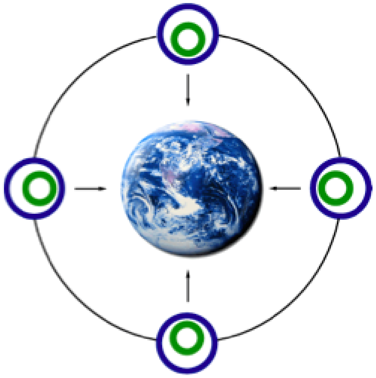
Experimental data from the GGG accelerometer agree with the theoretical curves in both directions α, β of the rotating plane and allow the mechanical unbalance to be separated out from the electrical one (so as to be reduced, hence improving self-centering):

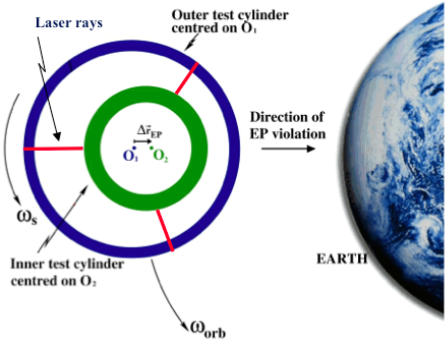
GGG: $(\nu_{dm}/\nu_{spin})^2 = (6.25/13.5)^2 = 0.2$

GG: $(\nu_{dm}/\nu_{spin})^2 = (1/540)^2 = 3.4 \cdot 10^{-6} \Rightarrow$

with construction/mounting offsets of $10\,\mu$m GG test masses will autocenter to $34\,$pm (in the non rotating frame)
No active centring needed!!

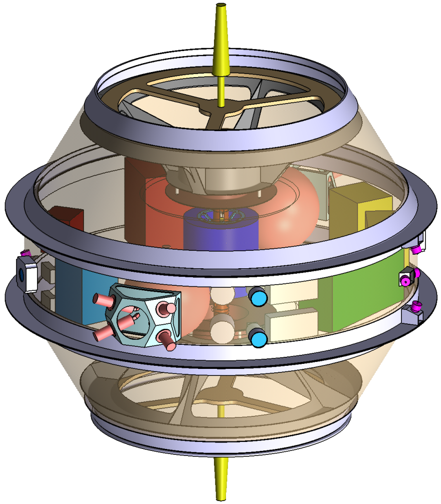
GG: experiment design vs brute force





A 2D harmonic oscillator made of concentric test cylinders (very weakly coupled) in orbit around the Earth. Violation signal is at the orbital frequency
Spin around the symmetry axis up-converts it to the much higher spin frequency away from high thermal noise.

Pegna et al., PRL 2011



Rotation around symmetry axis and sensitivity in the plane ⊥ to it respects the symmetry of the system, it is the right physics choice and allows passive s/c stabilization.
2D sensitivity ensures:
a) rotation above the coupling frequency (unstable in 1D)
b) that the signal is not attenuated (as it is in 1D)
Experiment killers like radiometer effect simply go away!

Nobili et al., PRD 2001; Nobili et al., NA 2002

Q1: What is the effect of the Earth's rotation and of the test cylinders rotation on their differential motion?

Precessions of an Earth orbiting gyroscope

$$\Omega_{\text{geodetic}\oplus} \sim \frac{c}{r}\left(\frac{GM_\oplus}{c^2 r}\right)^{\frac{3}{2}} \sim 10^{-12}\ \text{rad/s} \qquad 6\,\text{as in 1 year mission}$$

$$\Omega_{\text{gravitomagnetic}} \sim \frac{GJ_\oplus}{c^2 r^3} \sim 10^{-14}\ \text{rad/s} \qquad 39\,\text{mas in 1 year mission}$$

.. both measured by GPB ... differential effect very much smaller

$$\Omega_{\text{geodetic}\odot} \sim \frac{c}{d_{\oplus\odot}}\left(\frac{GM_\odot}{c^2 d_{\odot\oplus}}\right)^{\frac{3}{2}} \sim 10^{-15}\ \text{rad/s}$$

.. smaller & the same on both test cylinders (involves only Earth's motion relative to the Sun)

Linear acceleration on an orbiting body from $J_\oplus$

In GR the angular momentum of the Earth $J_\oplus$ affects the motion of free falling bodies. For an orbiting, non spinning body at distance r and with velocity v, the largest radial acceleration is:

$$a^r_{\mathrm{geodetic}\oplus} \sim \frac{GJ_\oplus}{c^2 r^3} v \sim 9.5 \cdot 10^{-11}\ \mathrm{m/s}^2$$

The fractional differential acceleration between the test masses, whose centres of mass are separated by Δr_{cc} yields:

$$\frac{\Delta a}{g(h)} \simeq 3 \frac{\Delta r_{cc}}{r} \frac{a^r_{\mathrm{geo}\oplus}}{g(h)} \approx 5 \cdot 10^{-18} \Delta r_{cc}$$

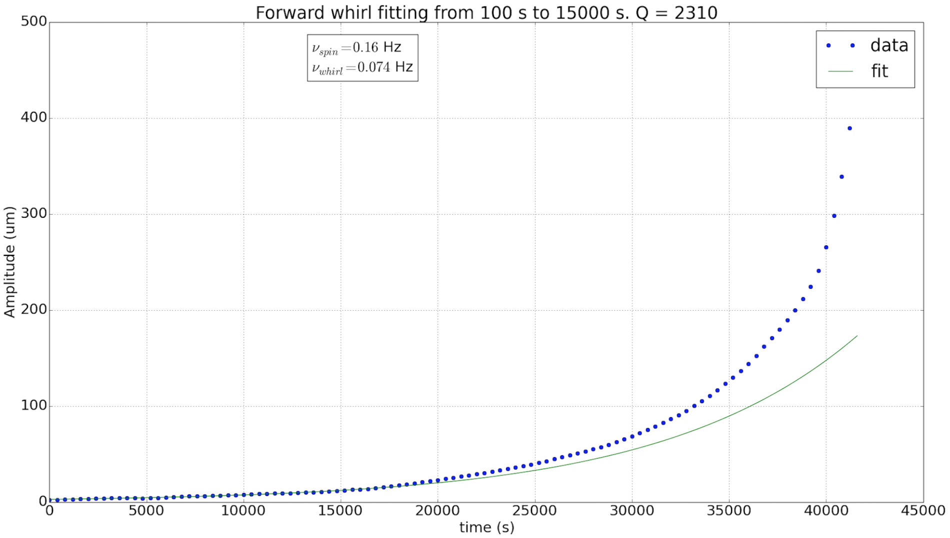
In GG the TMs stay within 1 nm (whirl motion not allowed to grow more than this), hence $\frac{\Delta a}{g(h)} \approx 5 \cdot 10^{-27}$

Spin-spin interaction is second order, hence even smaller

Q2: Test bodies deformations? None

Q3: Could whirl motions become chaotic? How are they modelled in the GG simulator?

- Reported whirl chaos refers to rotors with bearings/motor, high dissipation and high noise
- No whirl chaos observed from GG simulator. Whirls controlled in GGG, no chaos observed
- Key theoretical prediction on whirls recently verified by GGG:

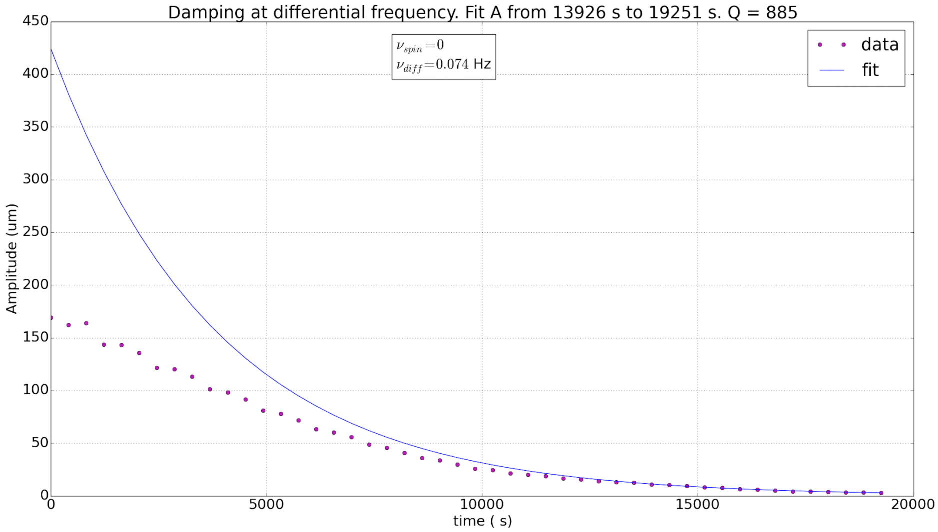


In low dissipation supercritical rotors whirl has the same frequency as the corresponding natural frequency and should grow as

$$A(t) = A(t_o)e^{i(\omega_w(t-t_o)/2Q)} \Rightarrow$$
$$t - t_o = \frac{Q}{\pi}T_w \ln\frac{A(t)}{A(t_o)}$$

and Q is at the spin frequency, not at the natural/whirl frequency, hence it must be higher

Here (for small whirl radius), the whirl grows with: $Q = 2310$ ($\nu_{spin} = 0.16\,\mathrm{Hz}, \quad \nu_w = 0.074\,\mathrm{Hz}$)



GG is not spinning, the natural differential frequency at $\nu_{dm} = 0.074\,\mathrm{Hz}$ is initially dominant and must decay with Q at this frequency, which is smaller than at the higher spin frequency of 0.16 Hz

From the small amplitude portion we find: Q=885

Rotordynamics theory is confirmed and the advantage of supercritical rotation is apparent
(The simple physical explanation is that in supercritical rotation flexures are deformed at the spin, not at the natural frequency)

See slides on GG simulator for whirl control

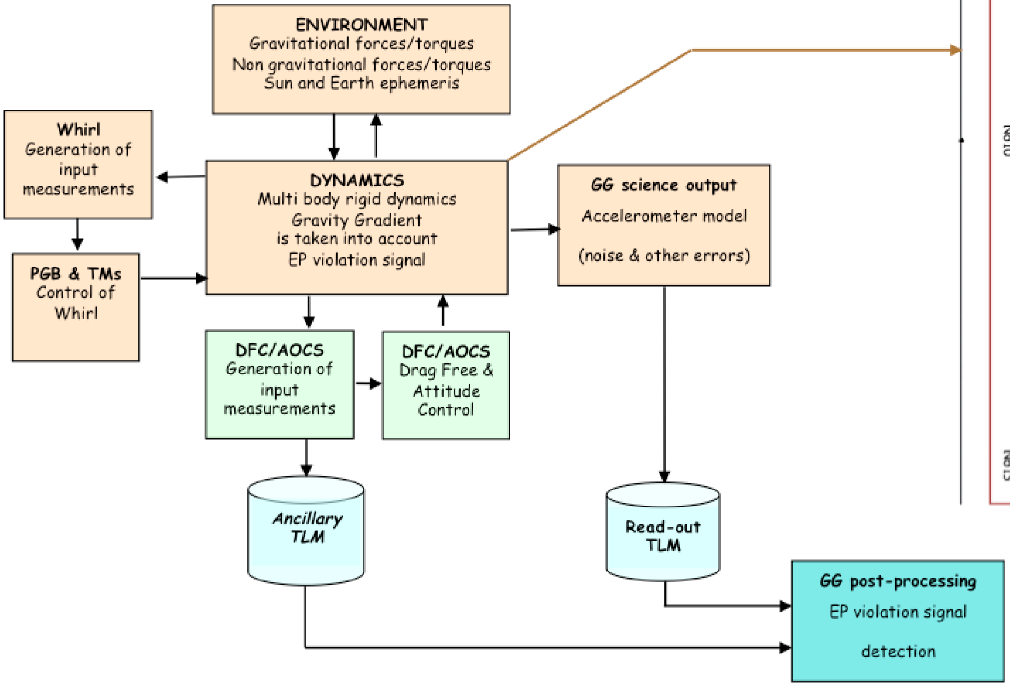
Q4: How is the error budget obtained? How are the electromagnetic effects obtained? How is the GG system modelled and what are the equations of motion used in the simulator?

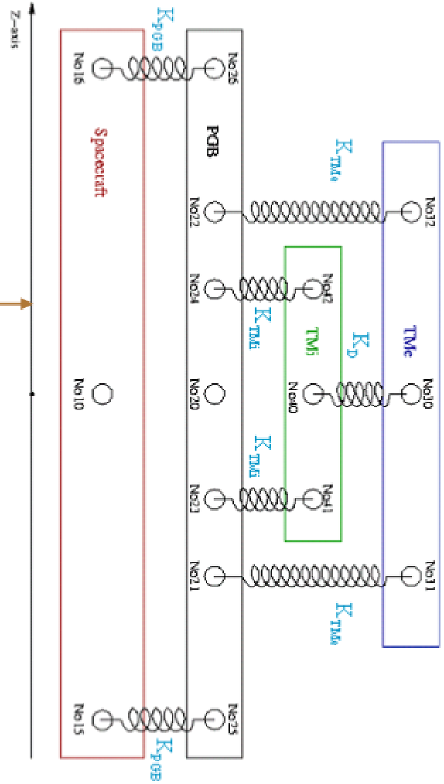
The GG performance simulator
(GOCE heritage)

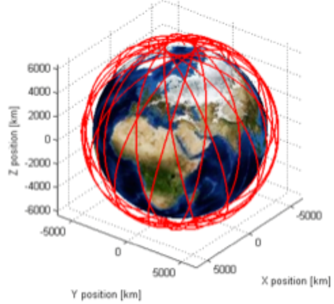
Simulator for GG spinning @1 Hz with DCAP8/DCAP16

- Spacecraft shell, PGB, TMi, TMo, dummy body for not solving the orbit motion in a rapidly spinning reference frame: 27 DoFs, more than 50 nodes
- Gravity and gravity gradient are "on" (both with J2 term, EGM96 model)
- Current mass/inertia properties for all bodies (included proof masses quadrupole moment)
- Orbit altitude h = 630 km to match the reference non gravitational acceleration 2×10^{-7} m/s^2
- Stiffness are reproducing PGB modes and common and differential proof masses modes in the XY plane and along Z according to the mission requirements
- Mechanical quality factor is lowered for TMs in order to amplify whirl motion
- Environment fully modeled
- $\eta = 10^{-17}$ for all the science simulations (science target)
- Quadruple precision DCAP16 simulations are carried out in order to predict science performance of the mission: dynamics range = 21 orders of magnitude (drawback: quadruple precision simulation speed 20 times slower than double precision one)

GG simulator functional block diagram

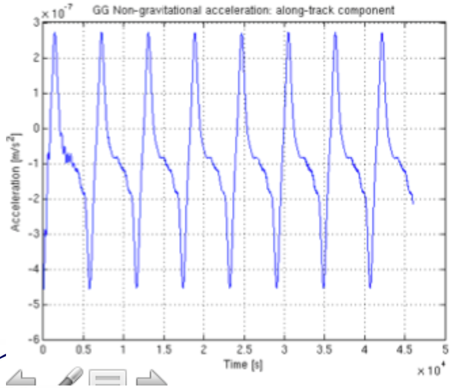


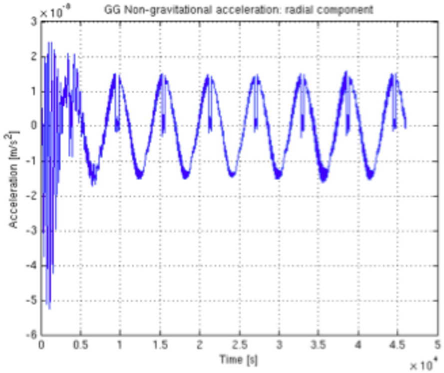


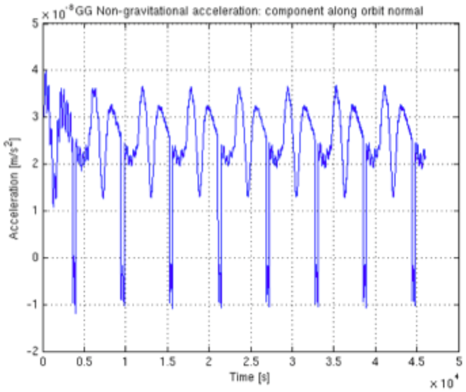


Simulation orbit and environment

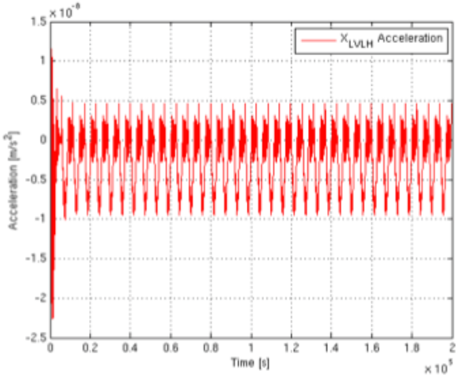
- GG orbiting the Earth with h = 630 km along sun-synchronous orbit (simulated equatorial orbit, too)
  - Date: 2018 July 12th
  - Atmospheric model: MSIS '86
  - Solar radiation included (F10=120, F10B=120, Geomagnetic Index = 8)
- Force violating the EEP acting along X-axis in the WEP reference frame, with amplitude $F_{EP} = m_{TM} \cdot g(h) \cdot \eta = 8.4 \cdot 10^{-16}$ N
- Sun-synchronous non gravitational accelerations

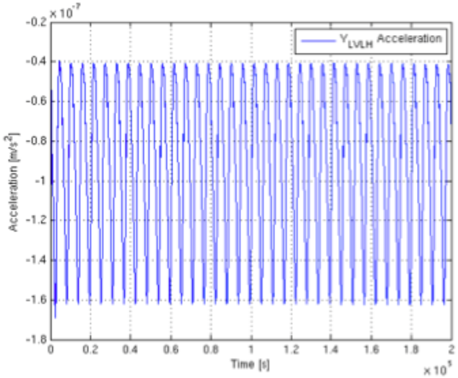


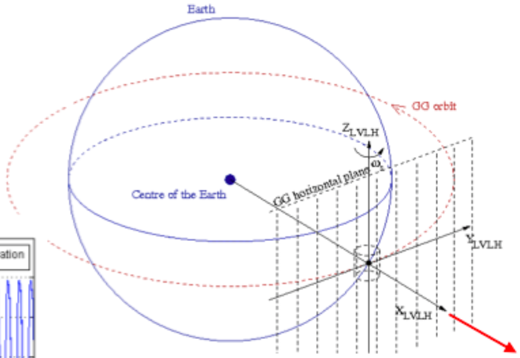


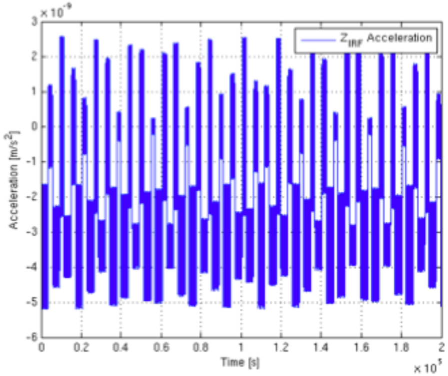


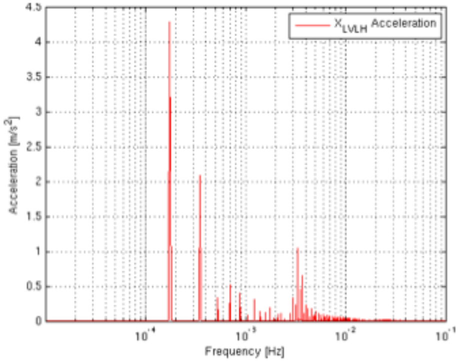
■ Equatorial orbit non gravitational acceleration on s/c

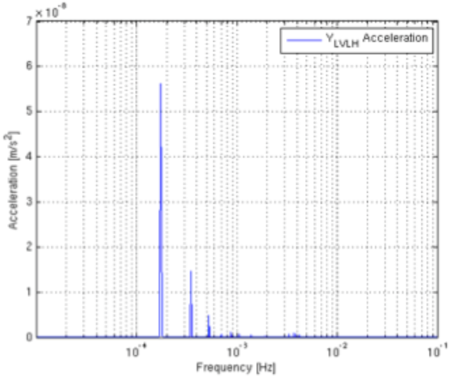












S/C acceleration, not GG CM acceleration

AS in the LVLH shows the acc. components at the orbit frequency and its multiple and the acceleration due to relative motion wrt PGB ($\nu \approx 3$ mHz)

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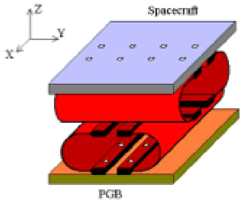
Simulation of suspensions

- Model of mechanical suspensions
  - Representative stiffness and mechanical quality factor for the PGB mechanical suspensions: K_{PGB}=0.01 N/m & Q_{Kpgb} = 90
  - Representative stiffness for the test masses suspension: K_{TM}=0.01 N/m
  - No representative mechanical quality factor for the proof masses suspension, Q_{Ktm} = 500 << 20000, in order to obtain a reasonable (for simulation purposes) whirl radius doubling time $t_{rw2} \approx$ 10000 s
  - Spring connecting the two test masses with negative stiffness, in order to have representative differential period:

$$\ddot{x}_D \approx -\frac{K_{TM} + 2K_D}{m_t} \cdot x_D \quad \Longrightarrow \quad K_D = -0.009 \text{ N/m to have } T_D = 500 \text{ s}$$

  - Representative stiffness and mechanical quality factor for suspensions acting on Z translation DoFs and on the rotational DoFs



The Whirl

- Suspension dissipation
  - Suspension dissipation continuously transforms very very small fractions of kinetic energy into PGB and test masses angular momentum with increasing radius
- Whirl active control
  - The whirl active control works @10 Hz
  - The active force applied by the whirl control is $F_c \approx K \times \delta r_w / Q$, it is not orders of magnitude bigger than the elastic force due to the whirl radius variation
  - The capacitance sensor/actuators must be suitable to develop the active whirl control → $\sigma_{displPGB} \approx 0.01\ \mu m$ $\sigma_{force} < K \times \delta r_w / Q$
- Suspension Mounting errors and residual offset due to @1 Hz spin
  - PGB/spacecraft suspension point $\approx$ 25 μm from rotation axis, offset = 2×10^{-10} m
  - TM/PGB suspension point $\approx$ 5 μm from rotation axis, offset = 2×10^{-11} m
  - Accelerometer/PGB suspension point $\approx$ 0.25 μm from rotation axis, offset = 3×10^{-10} m

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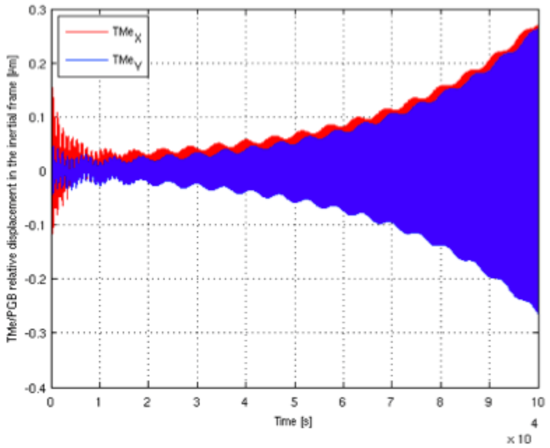
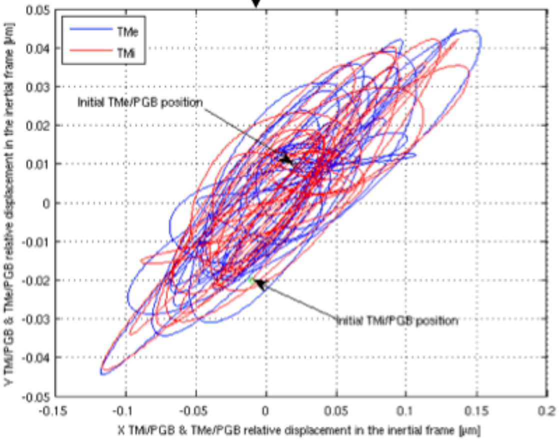
Simulation analysis: whirl control

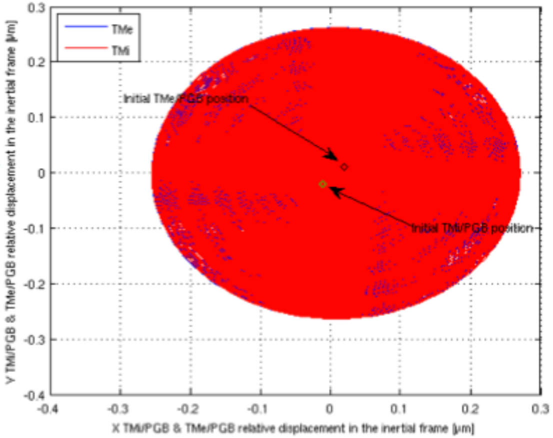
- Open loop for test mass whirl
  - Whirl radius increasing according to GG simulator rotating damping coefficients



Test mass displacement in 0÷2500 s

Test mass displacement in 0÷100000 s





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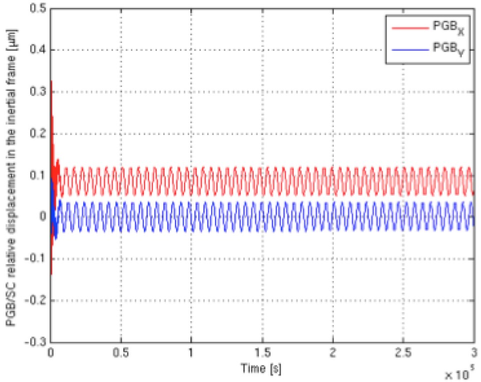
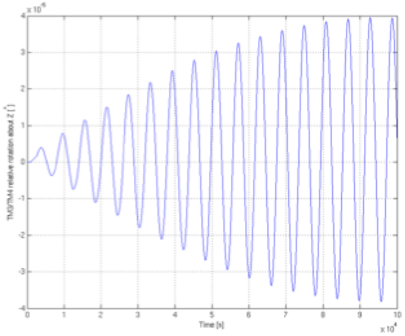
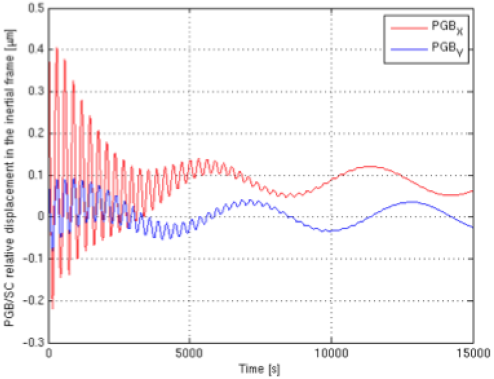
Simulation analysis: science scenario

- Closed loop for PGB whirl
- Closed loop for test masses whirl before science operational mode
- Open loop for test masses whirl during science measurement operational mode (t_{MOR} = 150000÷300000 s)
- EP violating signal switched on



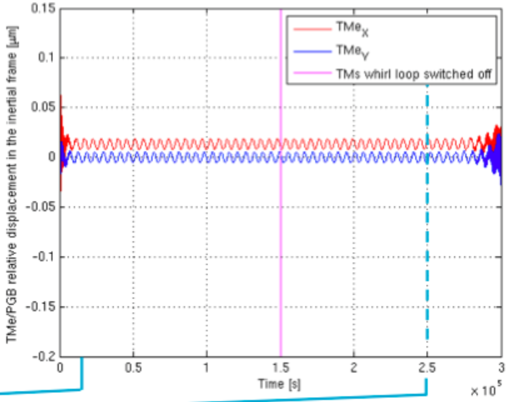
TM3-TM4 differential angle z time series, differential angle about x & y same order of magnitude

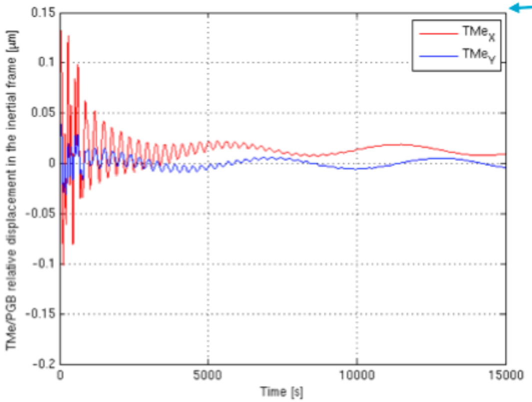


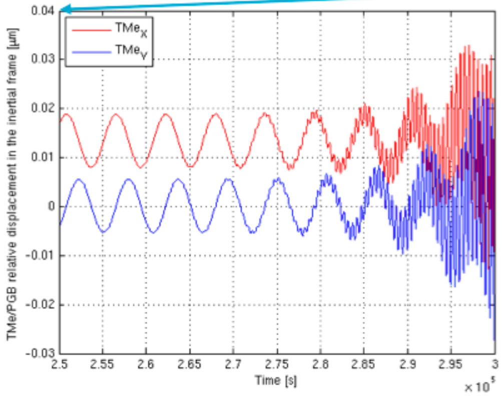


Simulation analysis: science scenario

- Test masses whirl control in closed loop till t = 150000
- Science mode is fine at least for 100000 s
- The utilisation of Q = 500 for the test mass suspension mechanical quality factor is here clarified…



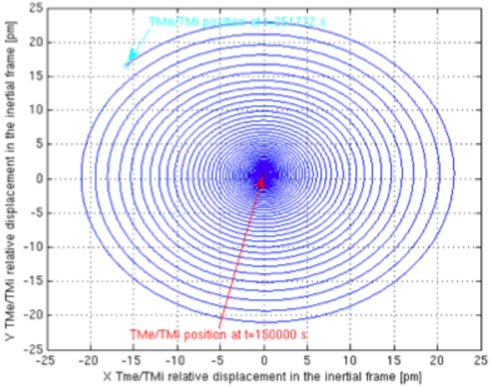


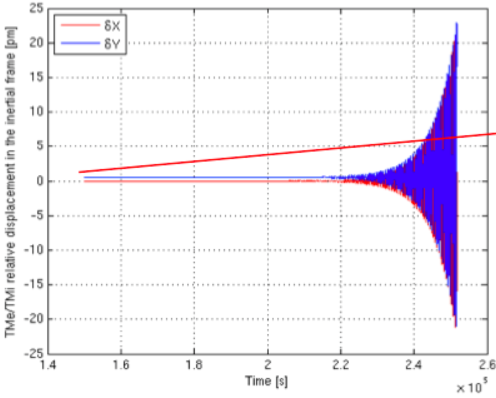


Simulation analysis: test masses scenario

- Test masses differential mode
  - $\Delta x_D = 0$ (CMRR = ∞)
  - $\Delta y_D = F_{EP}/m_t/\omega^2_{TMdiff}$

$$\omega^2_{TMdiff} = \frac{K_{TM} + 2 \cdot K_D}{m_t} = \frac{0.02 - 2 \cdot 9.21 \cdot 10^{-3}}{10} = 2.49 \cdot 10^{-8}\ rad^2/s^2$$





- Expected differential displacement along Y (in the inertial reference frame): $\Delta y_D = F_{EP}/m_t/\omega 2_{TMdiff} = 5.3 \cdot 10\text{-}13$ m
- From simulation, averaging the differential displacement along y over a time span of 900 test mass whirling period (from t = 150000 s to t = 251772 s):

  $\Delta y_D = 5.28 \cdot 10\text{-}13$ m
- Perfect agreement with expected result

Conclusions

- GG is orbiting the Earth
- Tides are taken into account
- Non gravitational forces are affecting the spacecraft
- Main drawback: double precision simulator code (DACP8) is not enough for the sub-pico (≈ 10^{-14} m) to orbit (≈ 10^{7} m) dynamics range that is ≈ 10^{21} with the default implementation of the multi-body software package
    - Performance simulator: used quadruple precision (DCAP16) to detect EP violation signal with significant digits
        - ✓ CPU time required to complete the simulation spanning $2 \cdot 10^{5}$ s:

          ```
          user time 3428m24.592s = 205704 s
          ```

          The simulator has almost the real time speed on a dual Xeon @3.4 GHz
- Simulation with no detection of EP violation are performed with double precision code, which is ≈ 20 times faster
- Dedicated simulations for science performance and ad hoc modification of the multi-body software package (DCAP16 from DCAP8)

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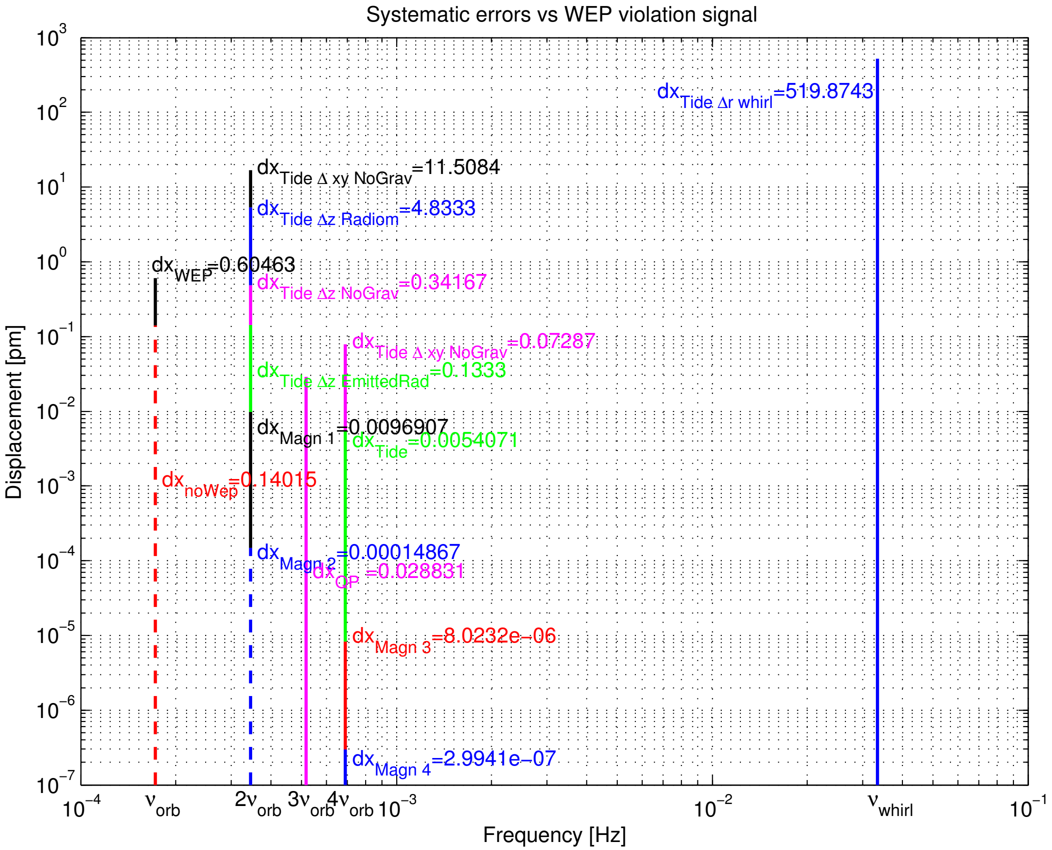
GG error budget in compact graphical form



Amplitude spectrum of test masses displacements, in the non rotating frame, due to WEP/UFF violation and disturbing accelerations.

The time history of residual non gravitational acceleration is provided by the GG simulator.

Quadrupole mass coupling, tidal and magnetic effects are computed by using an orbit time series of 90 days, during which the angle between GG spin axis and orbit normal changes by 1°/d. The signature of the disturbances depends on these changes and can be correctly evaluated over such long timespan only (due to their amplitude time variation).

In so doing, all these disturbances are firmly discriminated from the signal.

Only the residual non gravitational disturbance remains which must be smaller than the signal (partially by drag compensation, partially by common mode rejection)

Separation of systematics: no additional accelerometer needed

Error budget shows that with 1 measurement per day & dynamical evolution in sun synchronous orbit GG can firmly separate all known systematics from signal

In the past GG thermal noise had had been overestimated, and these checks could not be as stringent. A GG version was designed with two accelerometers, one inside the other, the outer one with equal composition for zero check.

They were both centred on the center of mass of the spacecraft (unique to GG!), hence avoided a major issue (the s/c has only one center of mass, and if the two accelerometers are in different locations there maybe differences..) but it is hard to reach exactly the same level of disturbances and performance.
No longer needed...

Driver # 5: Electromagnetic disturbances (I)

Magnetic disturbances inside the PGB are due to:

- interactions of magnetized TMs materials μ_{TM1}, μ_{TM2} or magnetizable materials χ_{TM1}, χ_{TM2} between themselves
- interactions between μ_{TM1}, μ_{TM2} or χ_{TM1}, χ_{TM2} with $B_\oplus$

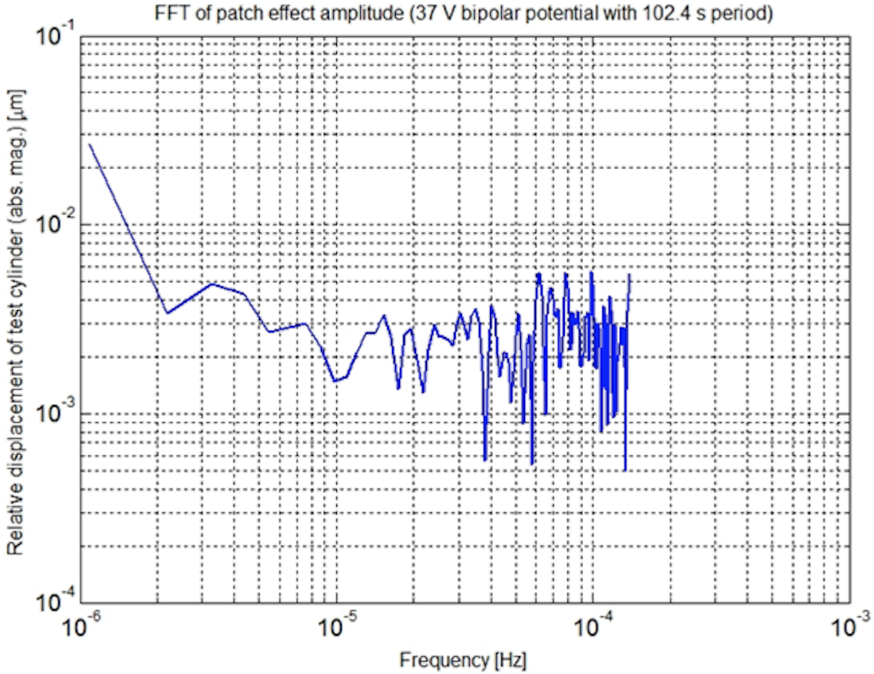
GG in sun-synchronous almost polar orbit modulates $B_\oplus$ at $2\,\nu_{\rm orb} \Rightarrow$

Disturbing accelerations on the TMs will be at frequencies:
$\nu = 0$, $\nu = 2\,\nu_{orb}$ and $\nu = 4\,\nu_{orb}$
(effects not depending on $B_\oplus$, effects linear in $B_\oplus$, effects depending on $B_\oplus^2$)

The most important effect is due to the coupling one mass magnetic impurity μ_{TM1} with the induced magnetization $\chi_{TM2} B_\oplus$ of the other mass (at $2\,\nu_{orb}$). A μ-metal shield is implemented on the PGB to reduce $B_\oplus$ by 150.

Driver # 5: Electromagnetic disturbances (II)

- **Plasma effects** caused by venting to outer space (to get vacuum at zero cost). Solved as in BepposSax, see *Vannaroni & Bruno, Internal Note 2009*
- **Patch effects**: Large gaps (2.5 cm) thanks to laser gauge (300 μm in GOCE, 600 μm in Microscope) Effect of patched measured directly in GGG (when sign of an applied potential is changed, sign of the applied charge changes too, while sign of the patch charge does not; effect of patch charge also amplified in the test).



We have performed the test on GGG (while spinning) for 10.6 days, in order to measure the low frequency time variations of the patch amplitude. Low frequency variations (with no coating and small surface) are of a few μV

Q5: Provide details on the laser gauge

- Laser gauge is linear $\Rightarrow$ large gaps between test masses (2.5 cm in GG for low gas damping noise and negligible patch effects) (Cap gauge $\propto 1/D \Rightarrow$ needs small gaps; 600 μm in Microscope).

  - Differential measurements with 1 pm/$\sqrt{\text{Hz}}$ @ 1 Hz noise more or less routine

  - Common mode effects at 10s nm level are not a problem ($<$ 12 nm in GG: answers Q5a)

- Laser gauge does not require cryogenics like SQUIDs for STEP

- Mike Shao (JPL) realized it for SIM about 10 years ago.

  - Heterodyne laser interferometer based on spatial separation rather than polarisation separation of the beams to reduce cyclic error (COmmon–Path Heterodyne Interferometer - COPHI)

  - 1 pm/$\sqrt{\text{Hz}}$ @ 1 Hz demonstrated up to 10 m separation (lower noise than SQUID and cap gauge)

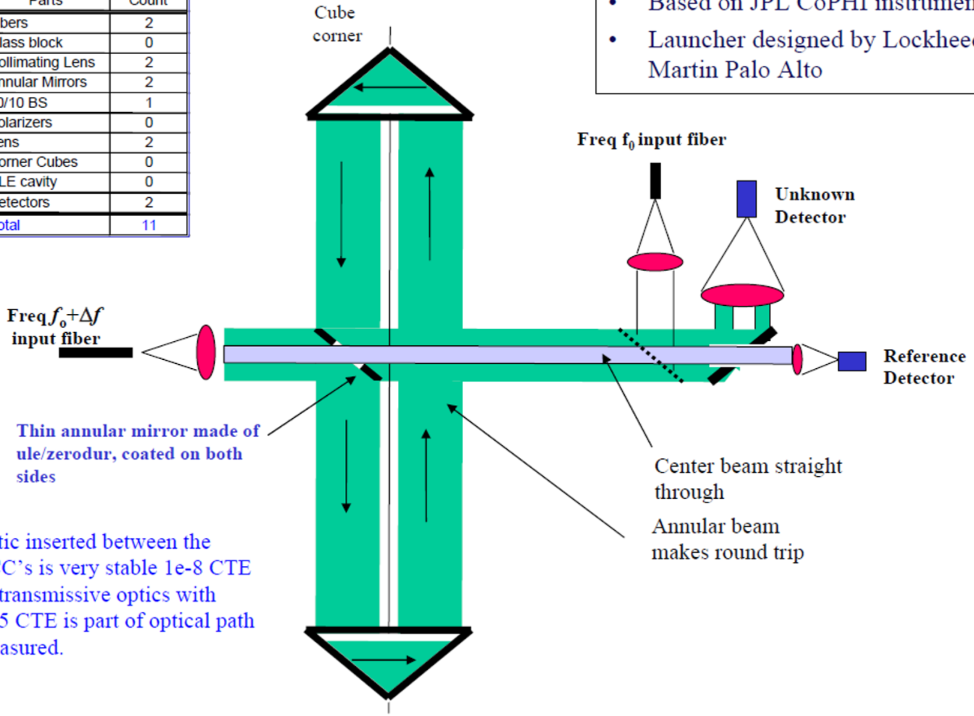
  - Mike proposed a version for GG in 2010 in order to exploit GG low thermal noise and short integration time to separate systematics from signal (investigated during 2.5-month study of GG at JPL)

Spatially separated heterodyne laser gauge for SIM & noise (I)

Spatially Separated Heterodyne Gauge

Parts	Count
Fibers	2
Glass block	0
Collimating Lens	2
Annular Mirrors	2
90/10 BS	1
Polarizers	0
Lens	2
Corner Cubes	0
ULE cavity	0
Detectors	2
Total	11

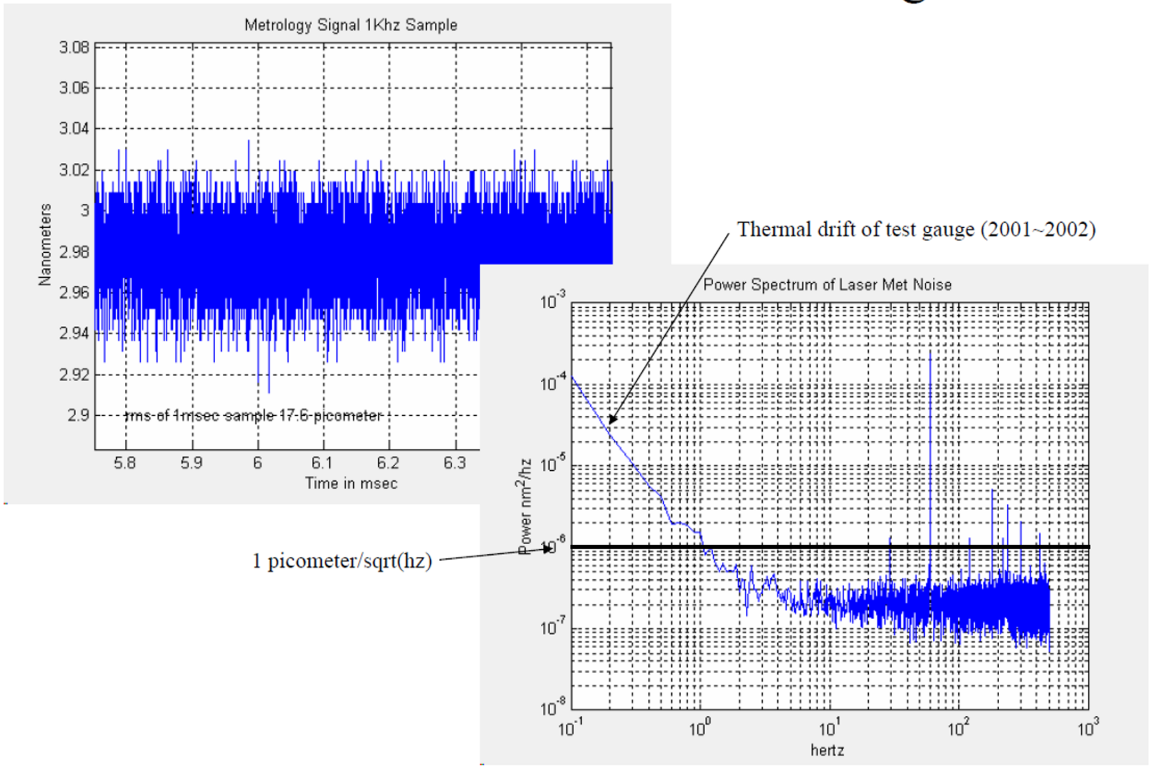
- Based on JPL CoPHI instrument
- Launcher designed by Lockheed-Martin Palo Alto



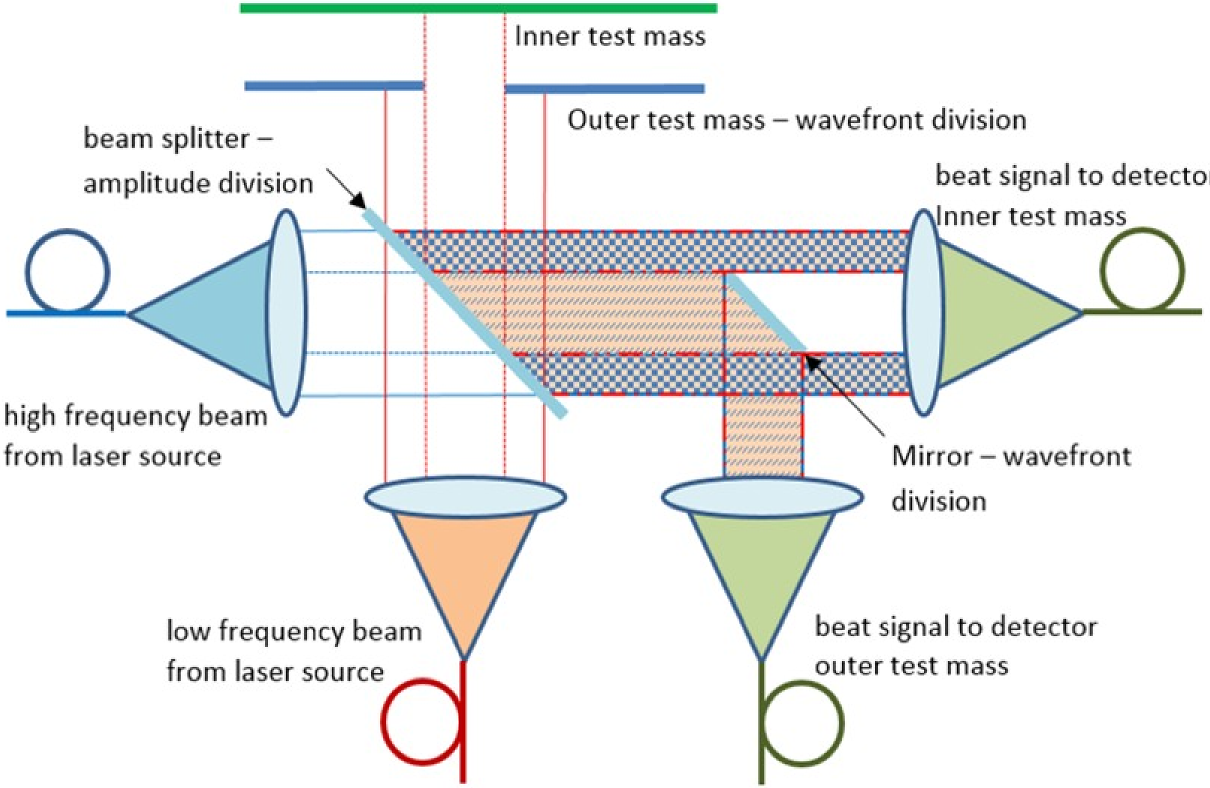
Optic inserted between the
1 CC's is very stable 1e-8 CTE
no transmissive optics with
1e-5 CTE is part of optical path
Measured.

Spatially separated heterodyne laser gauge for SIM & noise (II)

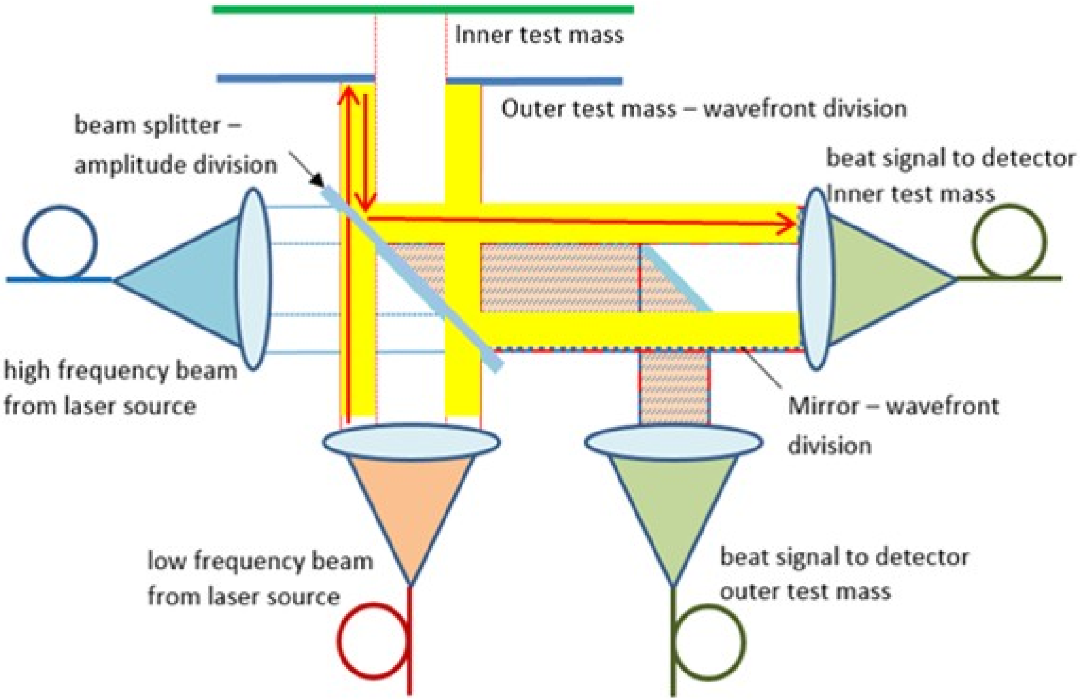
SIM Laser Gauge Noise



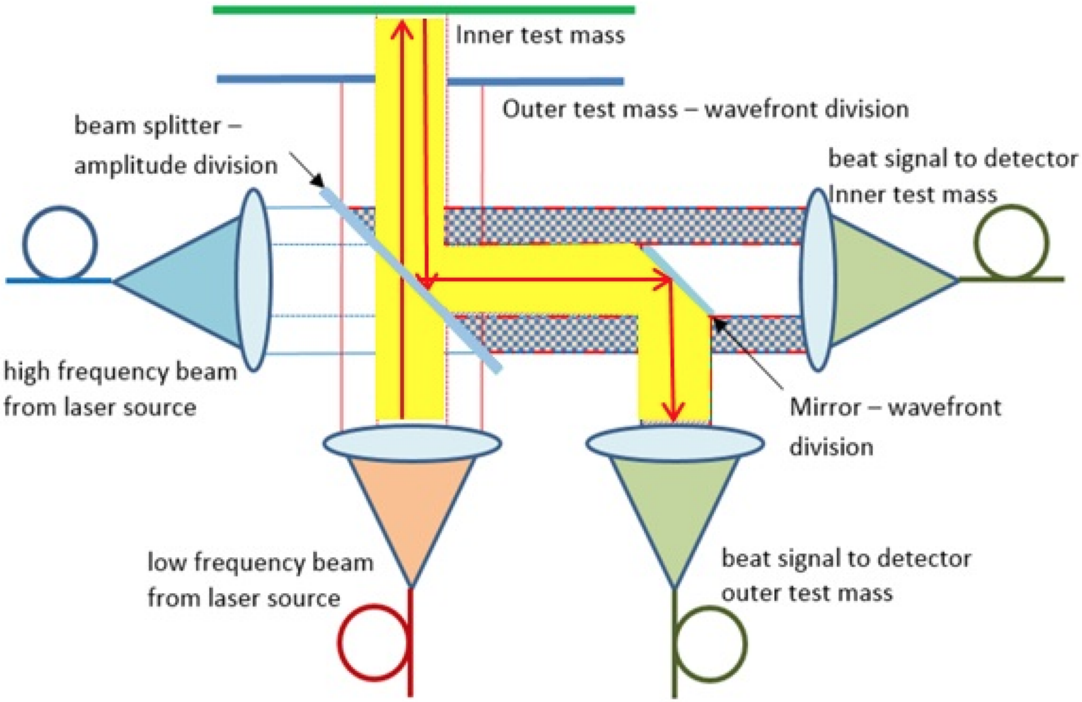
Spatially separated heterodyne laser gauge for GG



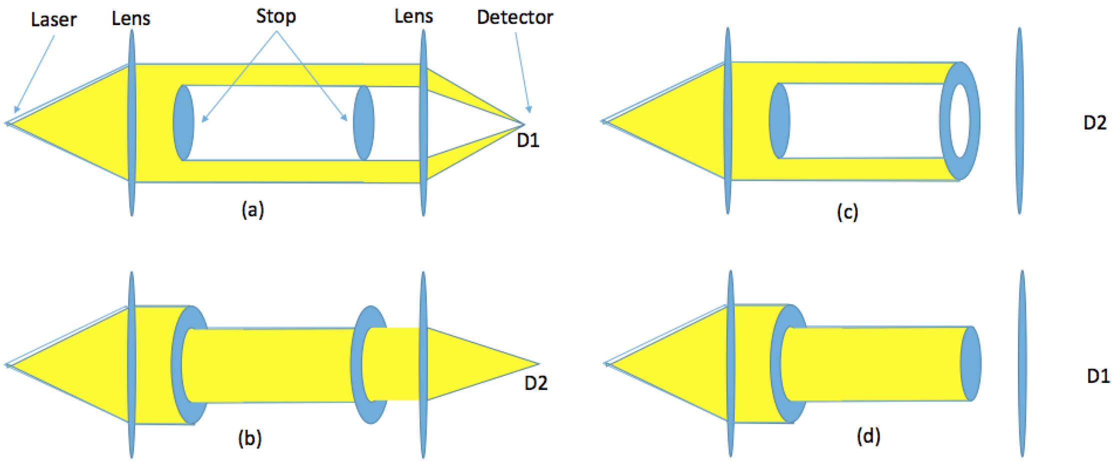
Spatially separated heterodyne gauge for GG Laser interrogation of outer test cylinder



Spatially separated heterodyne gauge for GG
Laser interrogation of inner test cylinder



Diffraction free beam separation (no cross talk)



Mass reflectors are represented as stop for a portion of the beam (first stop starting from left). The beam is represented in a straight path from the fiber laser source (left), to the fiber detector (right).

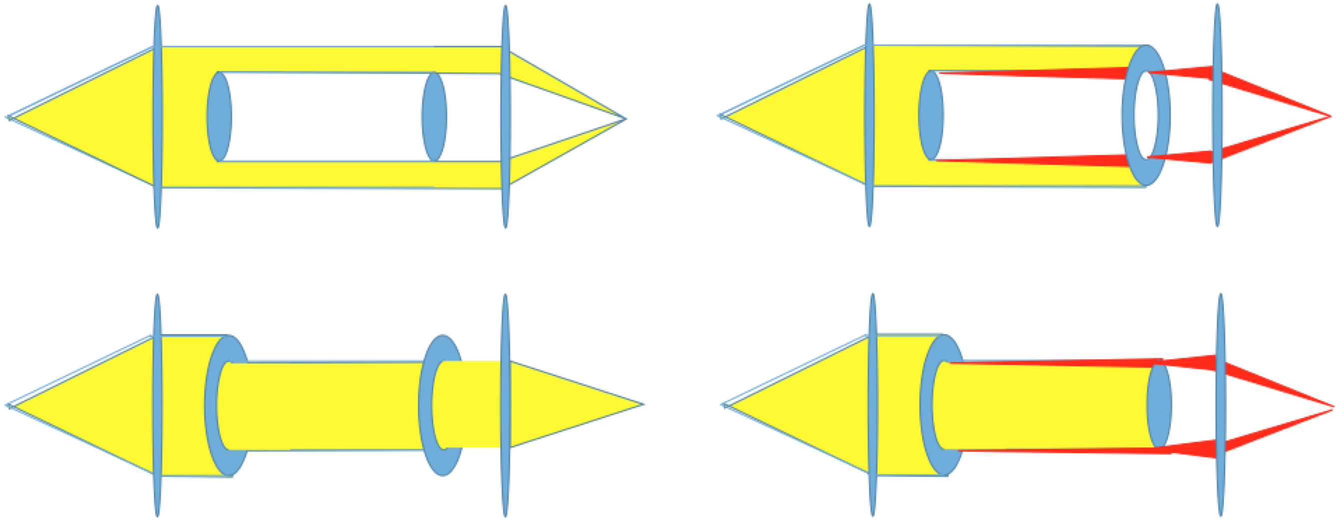
a) path of the laser reflected on the external mass reaching the detector D1.

b) path of the laser reflected on the internal mass reaching detector D2.

c) path of the laser reflected on the external mass stopped to prevent reaching detector D1.

d) path of the laser reflected by the internal mass stopped to prevent reaching detector D2.

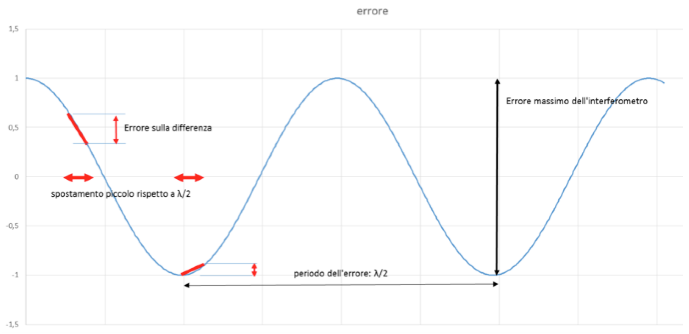
Cross talk due to diffraction



Whenever the laser beam is truncated by a stop, diffraction occurs. This effect causes part of the beam to deviate off the right path and eventually reach the "wrong" detector: the stops are not able to completely cancel the undesired signal

Error caused by diffraction in GG

Error is smaller for small displacements



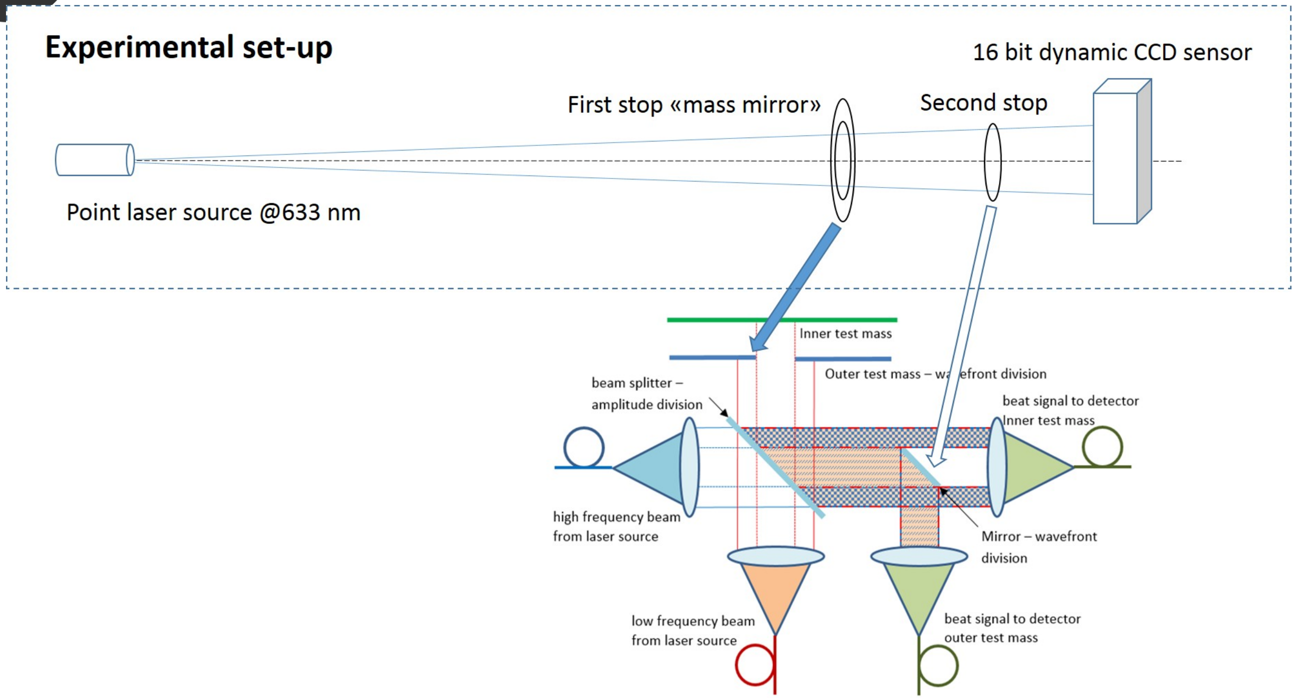
- 0.01% error in beam separation $\Rightarrow$ maximum error ($\lambda = 1064\,\mathrm{nm}$)

$\Delta_{max} \sim 0.01\% \cdot \frac{\lambda}{2} \sim 50\,\mathrm{pm} \Rightarrow$

- error for GG TMs (with 1 nm maximum separation)

$\Delta_{max} \cdot \frac{1\,\mathrm{nm}}{\lambda/4\,\mathrm{nm}} \sim 0.2\,\mathrm{pm}$

Simulations and lab tests performed at INRIM in response to Q5 show that a maximum $< 0.01\%$ error in beam separation is well feasible



Experimental set-up for the evaluation of the diffraction effect in GG. The first stop represents the "mass mirror"; it is an aperture/stop simulating the inner/outer test mass. The second stop represents the mirror used to reflect the beam towards the detectors. Different stop and iris diameters have been tested. Diameter size and distance between the stops and the detector are scaled to take into account the different wavelengths of the laser used for the test (633 nm) and the GG laser (1064 nm).

Experimental results: minimization of the spurious radiation. A stop with diameter of 8 mm is used to reduce the spurious signal. The selected stop diameter provides a ratio between the residual from diffraction and the wanted signal by about 10^{-4}

Q5d: laser power fluctuations and tilts

- $1\,\mu$W laser power sufficient ($\lambda = 1064\,$nm) & typical detector noise $< 1\,$pW$/\sqrt{\mathrm{Hz}}$

$\Downarrow$

- SNR$= 10^6$ and $< 1\,$pm in $1\,$s
- Laser force: $F = 2 \cdot 10^{-6}/c = 6.7 \cdot 10^{-15}\,$N (symmetric around center of mass)

Maximum torque: $T \sim 6.7 \cdot 10^{-15} \cdot 0.3\,$Nm $\sim 2 \cdot 10^{-15}\,$J

To be compared with the spin energy of the test mass

$\frac{1}{2} I_{TM} \omega^2_{spin} \sim 0.5 \cdot 0.14 \cdot 2\pi^2 \sim 2.8\,$J

$\Downarrow$

Tilt $< 1.4 \cdot 10^{-15}\,$rad

GG test masses are big and spin fast $\Rightarrow$ effect of all non gravitational forces, including thermal noise, reduced; tilt disturbances negligible

Q5e: beam alignment jitter & temperature fluctuations

- Direct effect on optical path:

$D\cos\vartheta$ — error due to jitter ϑ over path distance D

$D\sin\vartheta_{static}\Delta\vartheta_{1Hz}$ — what matters is jitter at measurement/spin frequency

With: $D \sim 30\,\mathrm{cm}$, $\vartheta_{static} \sim 10\,\mu\mathrm{rad}$, $\vartheta_{1Hz} \simeq 100\,\mathrm{nrad}$

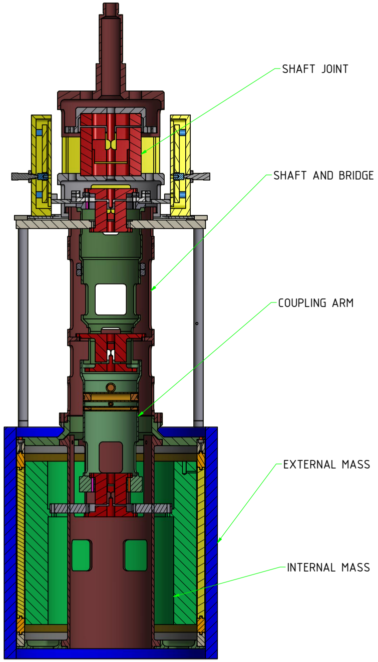
$\Downarrow$

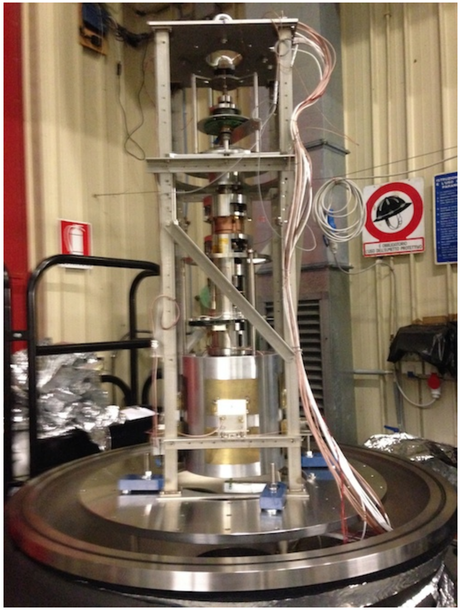
$0.3 \cdot 10^{-6} \cdot 10^{-7}\,\mathrm{m} \sim 0.03\,\mathrm{pm}$

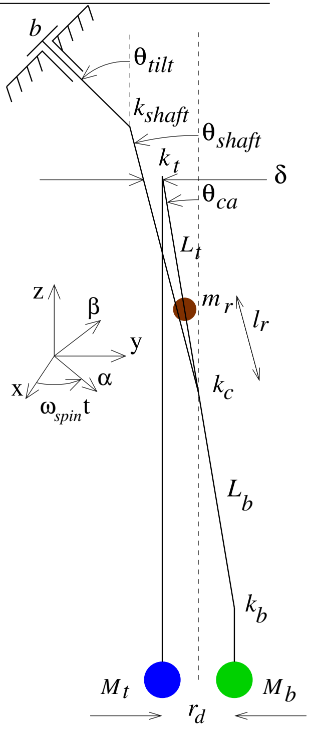
- Small change in intensity on the detector $\Rightarrow$ second order effect on the phase measurement. Hard to model, expected to be negligible; will be evaluated experimentally during development of the laser gauge.

Q7: Show GGG improvements since 2012

The GGG prototype







GGG is a full scale prototype with same number of degrees of freedom.
GG in space needs no motor no bearings, is isolated in space (no "terrain" tilts...), has weaker coupling and higher sensitivity by more than 3 orders of magnitude
GG must deal with drag but know how is available...

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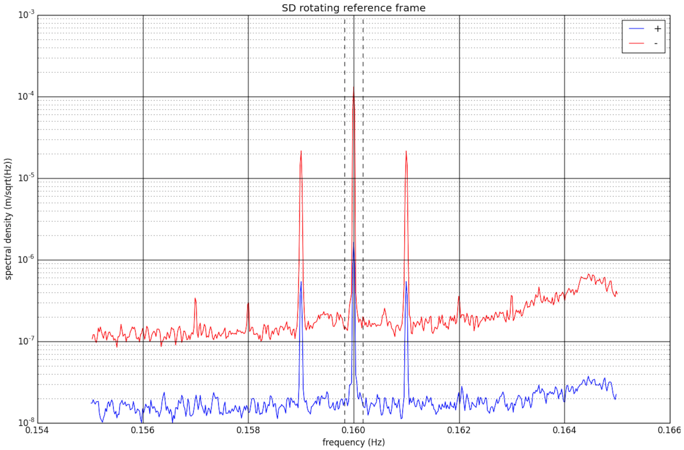
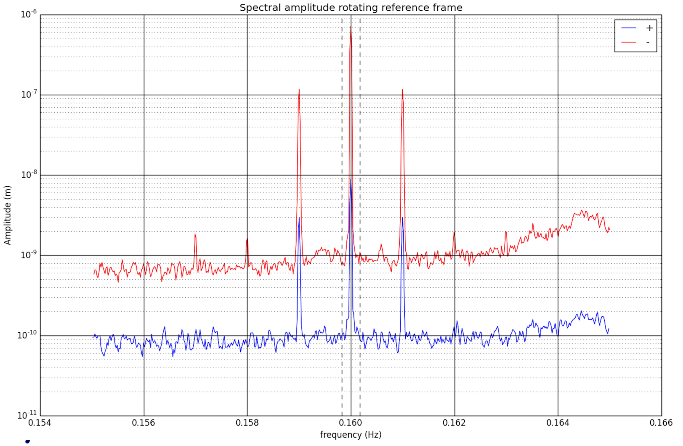
GGG best sensitivity at $\nu_{orb} = 1.7 \cdot 10^{-4}\,\mathrm{Hz}$ *(I)*



Improved capacitance readout electronics; new matched set of ceramic ball bearings with improved vacuum lubrication
Complex Fourier analysis exploits cap bridges in both directions of sensitive plane and information on sign of spin to separate motor/bearings rotation noise and partially reject it.

$\simeq 2 \cdot 10^{-8}\,\mathrm{m}/\sqrt{\mathrm{Hz}} \qquad (\nu_{spin} = 0.16\,\mathrm{Hz},\ \nu_{orb} = 0.074\,\mathrm{Hz})$
$\simeq 4.3 \cdot 10^{-9}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$



$\nu_{sampl} = 32\,\nu_{spin}, \quad T_{res} = 86400\,\mathrm{s}$
Lowest relative displacement noise (20 days):
$\simeq 2.2 \cdot 10^{-11}\,\mathrm{m}$
Lowest differential acceleration noise (20 days):
$\simeq 4.76 \cdot 10^{-12}\,\mathrm{m/s^2}$

GGG best sensitivity at $\nu_{orb} = 1.7 \cdot 10^{-4}\,\mathrm{Hz}$ *(II)*

$\Delta a_{GGGprototype1.7\cdot10^{-4}\mathrm{Hz}} \simeq 4.76 \cdot 10^{-12}\,\mathrm{m/s^2}$ (15.7 improvement since 2012)

$\Delta a_{GGtarget} = 8.1 \cdot 10^{-17}\,\mathrm{m/s^2}$

GGG is $\frac{4.76\cdot10^{-12}}{8.1\cdot10^{-17}} = 5.9 \cdot 10^4$ away from GG target

It is also $\left(\frac{540}{13.5}\right)^2 = 1600$ times less sensitive at 1-g $\Rightarrow$

If GGG will improve by another factor $\frac{5.9\cdot10^4}{1.6\cdot10^3} = 37$ it will reach its limit as prototype of GG

On ground the best and most sensitive instrument is the torsion balance

GG incorporates its key features while making it suitable for space