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

GG error budget from the end-to-end simulator developed at TAS-I

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INRIM – ISTITUTO NAZIONALE DI RICERCA METROLOGICA

POLITECNICO DI TORINO 1859 1906

ALTA ALTEC DTM TECHNOLOGIES

Template reference : 100181670S-EN

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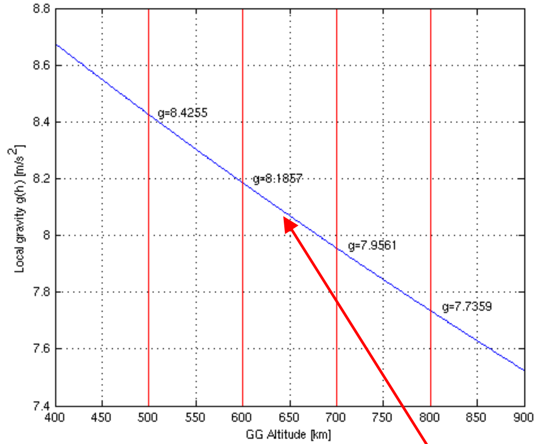
GG: the signal



The Signal (1)

- Scientific objective: $\eta = 10^{-17}$
- Signal optimization: choice of the test masses materials
- Signal optimization: choice of the orbit
  - TMs differential acceleration due to EP violation:

$$a_{EP} = g(h) \cdot 10^{-17} \text{ m/s}^2$$

↓

- Orbit altitude h as low as possible to maximise g(h), but h as high as possible to match air drag reference acceleration (depending on s/c A/M and solar activity during flight) $a_{NG_{xy}}^{ext} \approx 2 \times 10^{-7}$ m/s^2
- GG Phase A2 study spacecraft final configuration:
  - $m_{s/c}$ = 346.21 kg (launch mass, no margin)
  - $A_{s/c}$ = 2.9 m^2

→ h = 630 km (≈ GPB!)

$g(h) = 8.116$ m/s^2

The Signal (2)

- Signal optimization: equatorial orbit
  - Inclination depends on the launch site latitude, Kourou → $I \leq 5°$
  - Eccentricity is not zero: $e \leq 0.01$

↓

  - Period of longitude variation of ascending node $T_{asc\_node} \approx 48$ days
  - Spin axis initially aligned with the orbit angular velocity within $\delta I_0 \leq 1°$
  - The angle between the spin axis and the orbit angular velocity changes also due to the gravity gradient and magnetic torque acting on the satellite:

$$\delta I = \delta I_0(\text{launch}) + \delta I_{orbit} + \delta I_{Torques} \approx 15\text{-}20° \text{ after about 1-2 years}$$

  - But: angle is changing very slowly, each fundamental experiment is carried out with constant driving signal

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GG: the signal

The Signal (3)

- Performance check vs. simulated results
- Signal to Noise Ratio
  - The science measurement is: $\Delta x_{EP} = a_{EP} \times (T_{diff})^2/(4 \times \pi^2)$
  - T_{diff} according to the simulator, $T_{diff} = 500$ s
  - Science measurements are affected by systematic errors $d_x(t)$ and by stochastic errors $\tilde{n}(t)$

$$\Delta x'_{EP}(t) = \Delta x_{EP}(t) + d_x(t) + \tilde{n}_x(t)$$

measurement

EP violation signal, $\Delta x_{EP} \approx 0.5 \times 10^{-12}$ m

  - Same allocation (50%) for deterministic and stochastic errors
  - Error allocation such that SNR ≥ 2
  - The deterministic effects with the EP signature must be reduced as much as possible: spin modulation "takes away" a lot of disturbances due to the spacecraft (DC effects in the Body Fixed reference frame)
  - The stochastic effects define T_{int}: thermal noise (worst case) → Tint ≈1 week
  - Mission duration ≈ 2 years → Number of Tint ≈ 100 (rich statistics!)

Non Gravitational Forces Acting on the Spacecraft (1)

- Non-gravitational forces are sensed as inertial acceleration from test masses → ideally pure common mode, but:
  - test masses mechanical suspension is not ideal → a fraction χ_{CMRRxy} of common mode acceleration is sensed as differential one

↓

  - Orbit altitude h = 630 km in order to have $a^{ext}_{NGxy} \approx 2\times10^{-7}$ m/s^2
  - The Drag Free Control partially compensates the non-gravitational forces (@ orbit frequency in IRF) → $a_{CMxy} = \chi_{DFCxy} \times a^{ext}_{NGxy}$

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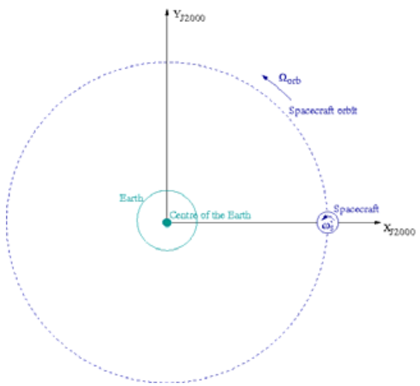


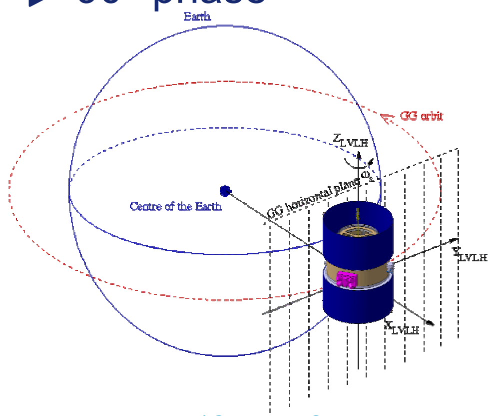
✓ reduced mechanical balance requirement for the capacitance bridge
✓ reduced inertial acceleration acting on PGB, i.e. smaller displacement
✓ reduced test masses common mode acceleration, i.e. smaller displacement

GG: drag forces

Non Gravitational Forces Acting on the Spacecraft (2)

- Main non-gravitational force component along Y_{LVLH} → 90° phase difference wrt EP signal, SNR = 2

$$a^{ext}_{NGxy} \times \chi_{DFCxy} \times \chi_{CMRRxy} \leq a_{EP} \times 1/SNR$$



↓

$$\chi_{CMRRxy} \leq 10^{-5}$$

$$\chi_{DFCxy} \leq 2 \times 10^{-5}$$

↓

- Maximum inertial acceleration sensed from PGB $a_{CMxy} = 4 \times 10^{-12}$ m/s^2
- PGB XY_{plane} oscillation period $T_{PGBxy} \sim 381.24$ s → displacement << capacitance gap, whirl period is slow
- TM XY_{plane} common mode period $T_{CM} = 104.17$ s → TM displacement << capacitance gap, whirl period is slow

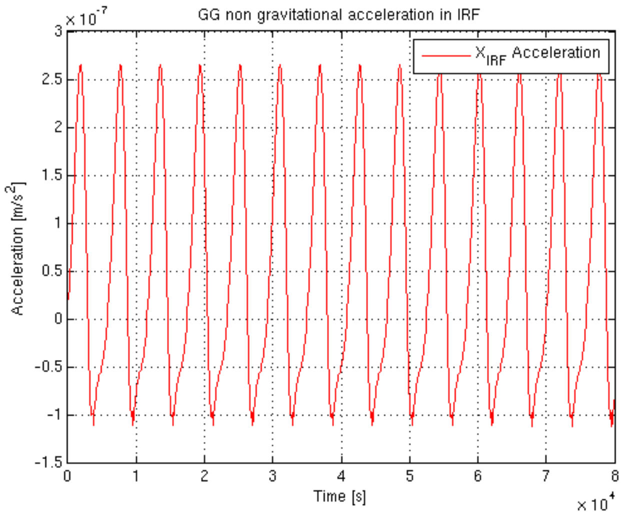
- Mechanical balance of capacitance bridge $\chi_{bridge}(T_{CM} = 104\ s) = 6 \times 10^{-4}$

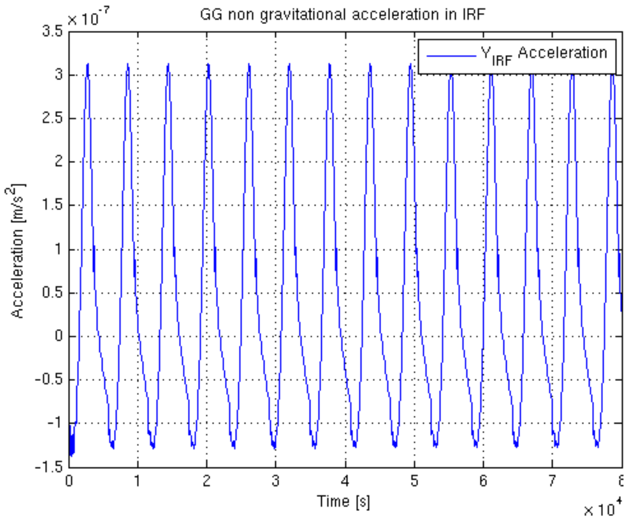
→ a-b << 3 μm over a gap a ≈ 5 mm

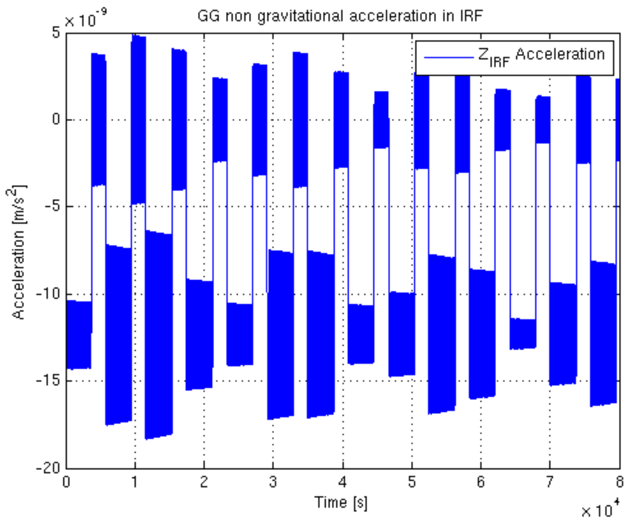
GG: drag forces

Non Gravitational Forces Acting on the Spacecraft (in IRF) (3)

- Non-gravitational acceleration time series (frozen values for $m_{s/c}$ and $A_{s/c}$)
  - Date: 2013 July 12th
  - GG altitude h = 630 km
  - Atmospheric model: MSIS ‘86 (above 120 km MSIS ’86 = MSIS2000)
  - Solar radiation included (F10=180, F10B=160, Geomagnetic Index = 8)

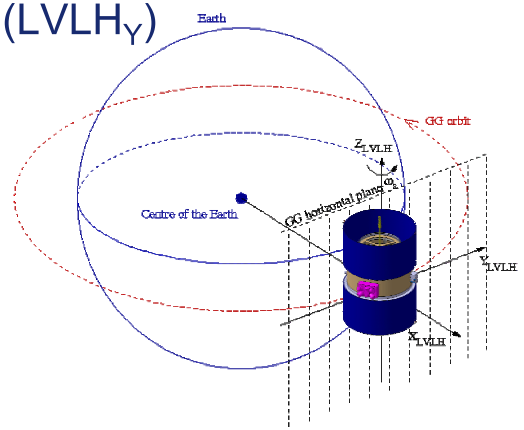


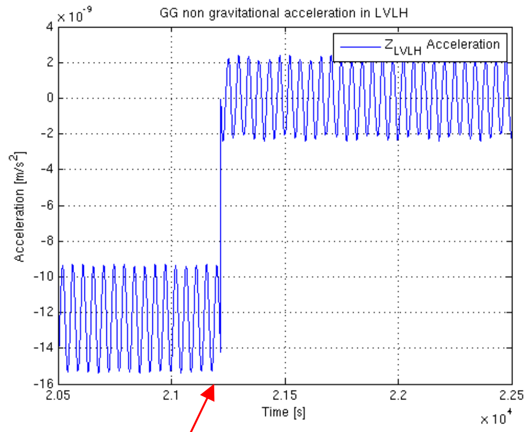




Non Gravitational Forces Acting on the Spacecraft (in LVLH) (4)

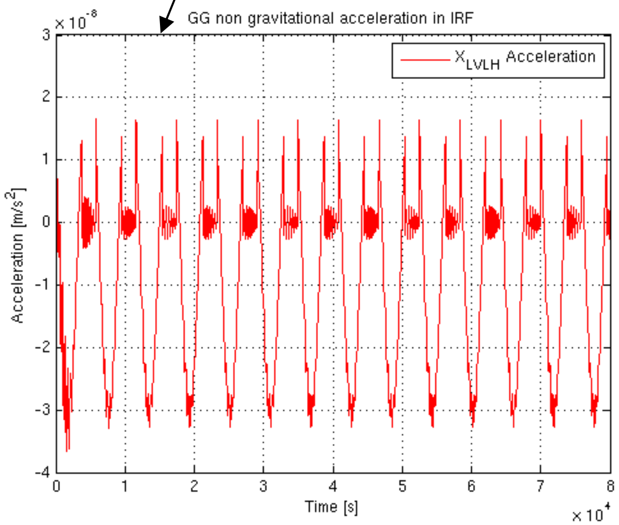
- Main component along track ($LVLH_Y$)

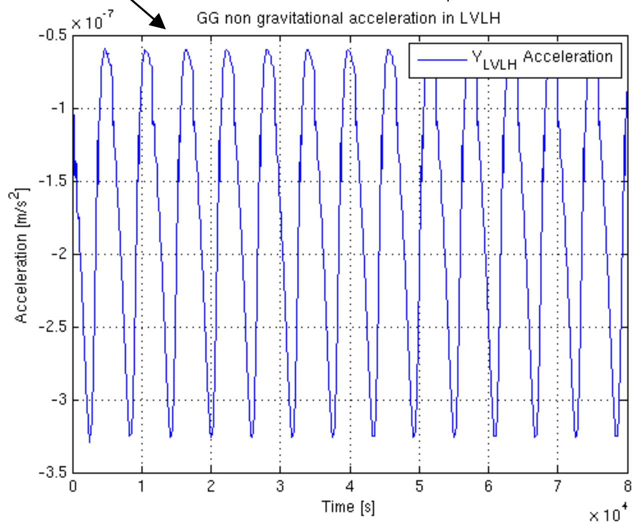


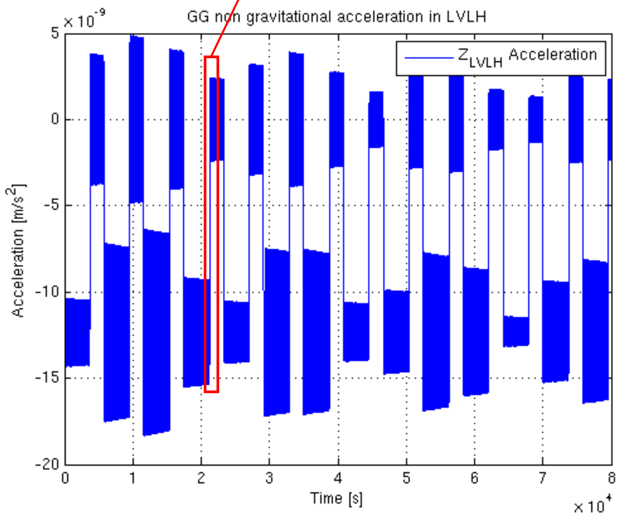


Radial NG_X acceleration

Along track NG_Y acceleration

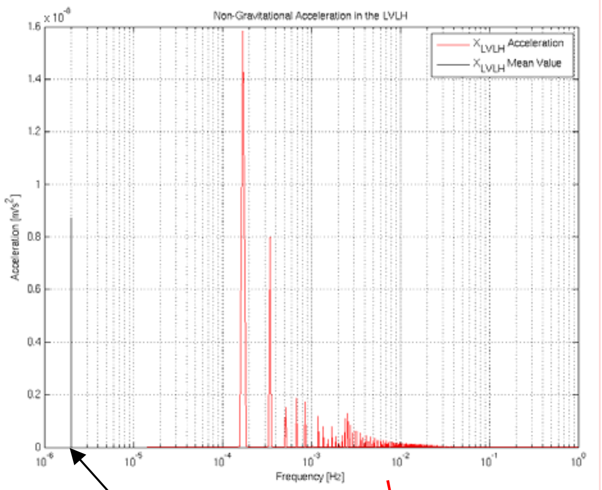




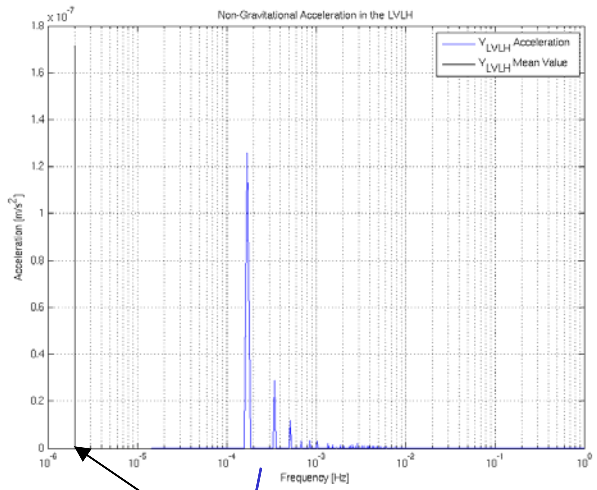


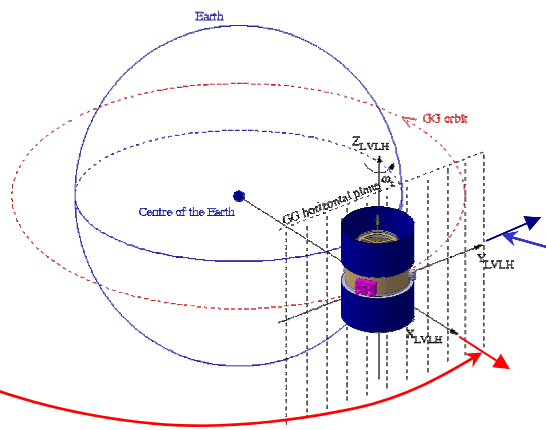
Non Gravitational Forces Acting on the Spacecraft (5)

- Main non-gravitational acceleration component along Y_{LVLH} ➡ 90° phase difference wrt EP signal, but SNR = 2 …



The EP violation signal is always along X in the LVLH Frame and almost constant during an elementary science experiment.



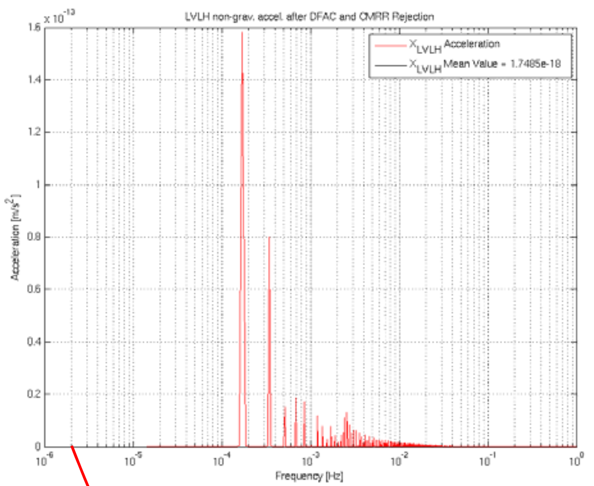


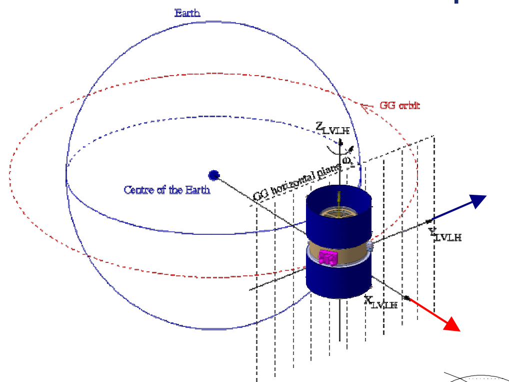
mean value of a_{LVLHx}
Like EP violation!!

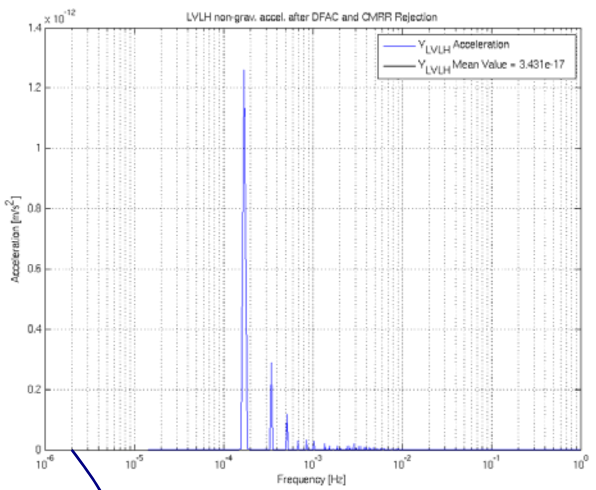
mean value of a_{LVLHy}
Like EP violation, but 90° out of phase!!

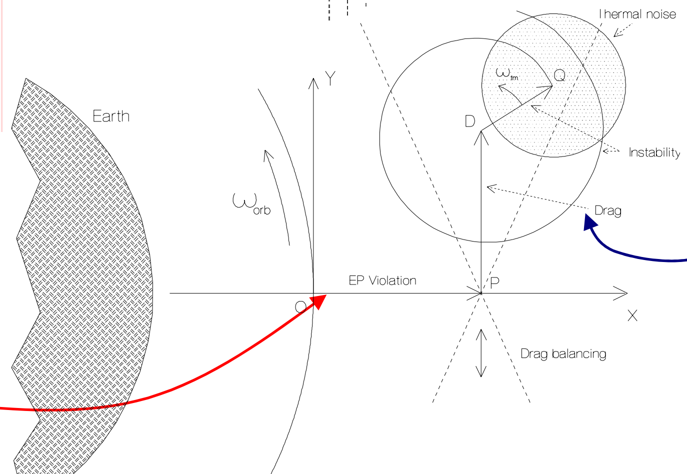
Non Gravitational Forces Acting on the Spacecraft (6)

- Main non-gravitational acceleration after DFC compensation and suspension rejection – CMRR- fulfills the requirement









dy_{ang}=0.217 pm

dx_{ang}=0.011 pm

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The Gravitational Forces

- TM higher mass moment coupling with Earth monopole
  - TM quadrupole mass moment couples with Earth monopole

↓

  - Inner TM $\delta J_i/J_i = -0.0116$ Outer TM $\delta J_o/J_o = -0.0065$
  - Test masses quadrupole are both small and of the same order

Differential acceleration = 9.3×10^{-18} m/s^2 $\approx 0.1 \times a_{EP}$

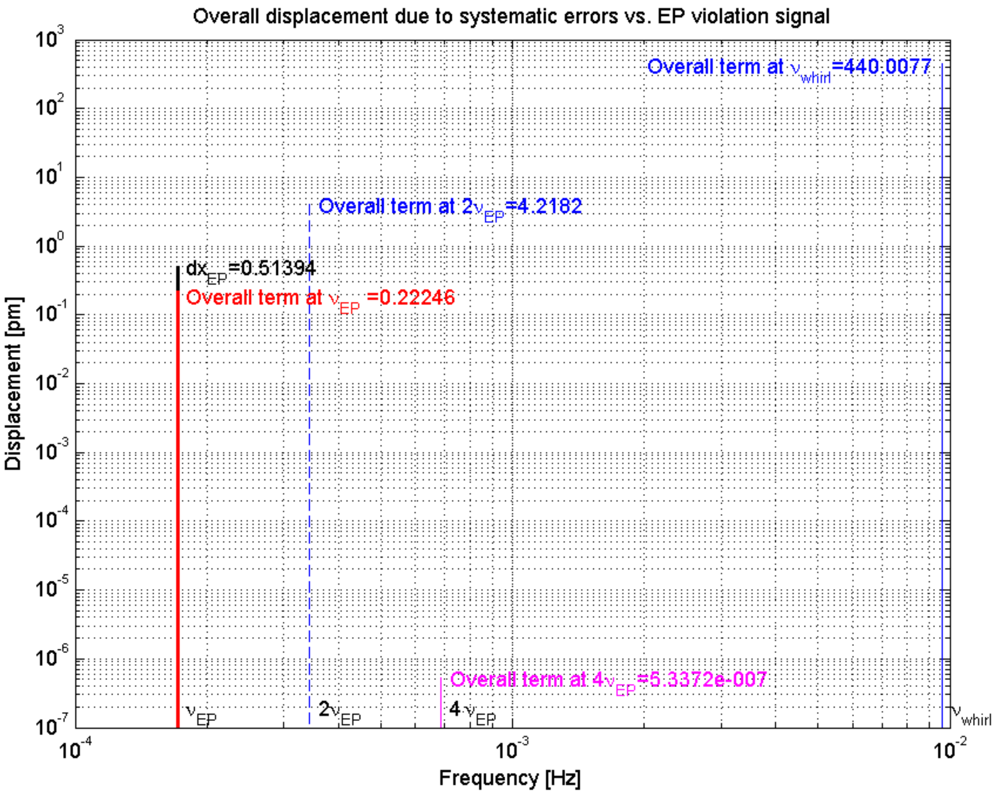
- Tidal effects (displacements on XY plane)
  - Gravity gradient T_{jj} magnitude corresponding to the GG local gravity:
    $T_{jj}(h_{GG}) = 3 \times 10^{-6}$ m/s^2/m $T_{jk}(h_{GG}) = 3 \times 10^{-7}$ m/s^2/m (worst case)
  - Signature difference with respect to EP signal

↓

During science measurement the TM whirl radius r_w must not affect the EP signal detection (through T_{jj}): → $r_w \leq 5 \times 10^{-10}$ m

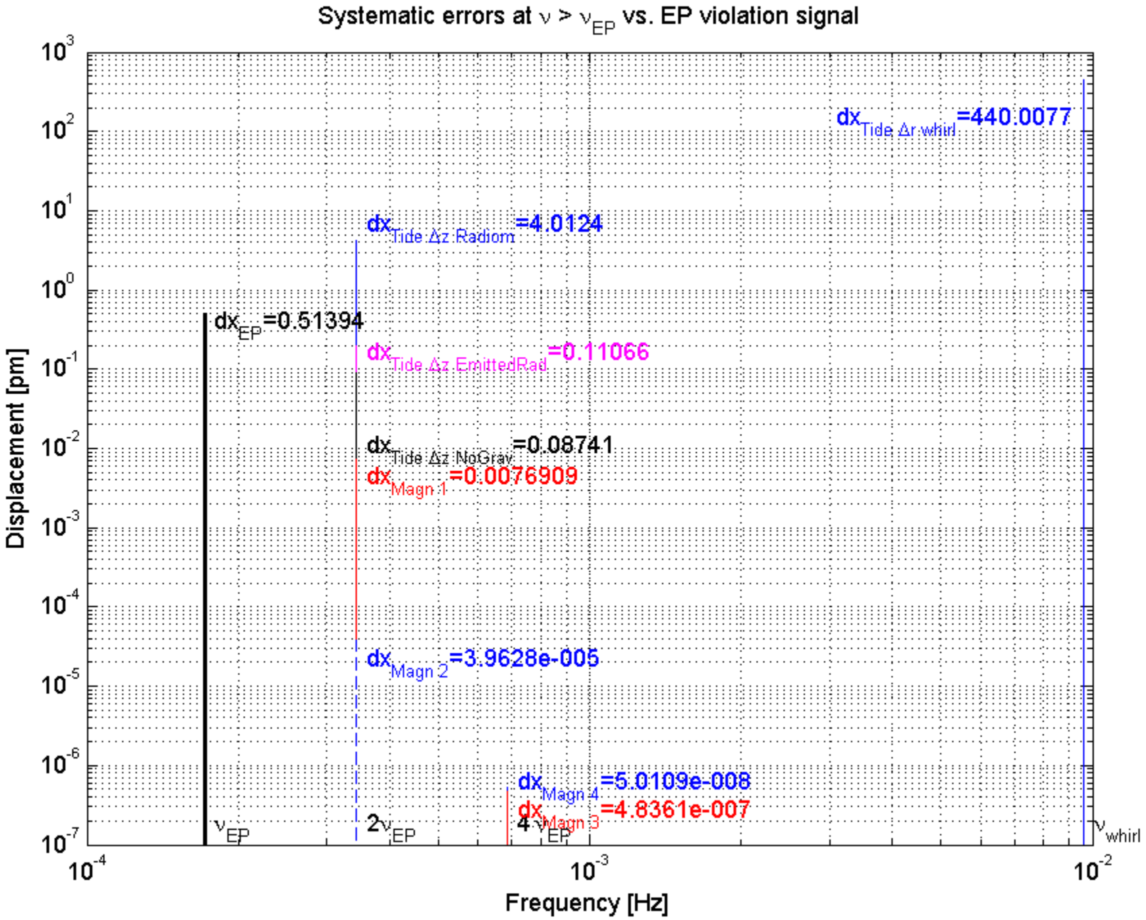
GG Error Budget (according to simulator parameters) (1)

- Amplitude Spectrum of EP signal and disturbing effects (affecting measurements in the XY plane) as observed in the IRF
- Signal and most effective deterministic disturbances (smallest frequency separation
  - Most effecting disturbance at ν_{EP}, well below the signal
  - One week duration of the elementary experiment ensures good frequency separation for all the competing lines, also the first one at $2 \times \nu_{EP}$



GG Error Budget (2)

- Detailed error budget for the first lines of deterministic forces affecting GG.



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GG: error budget

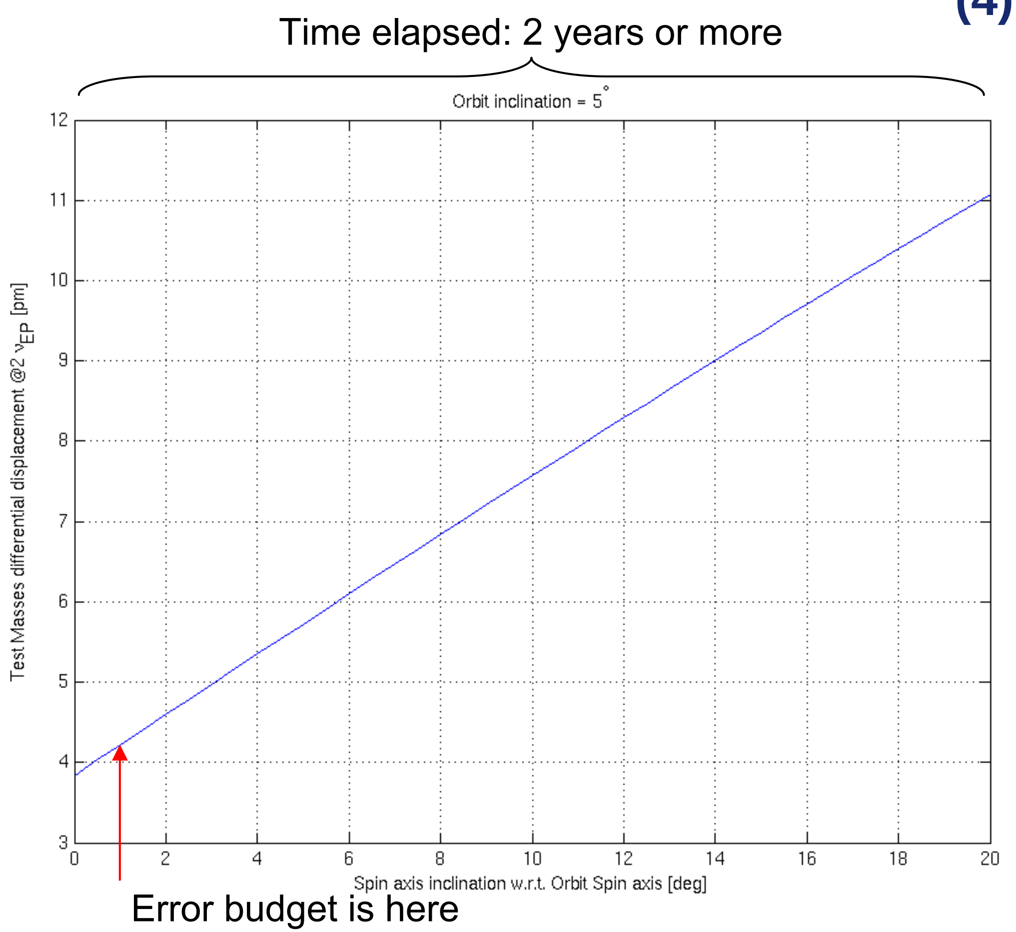
GG Error Budget (3)

Acceleration (transverse plane) due to:	Frequency in IRF (Hz)	Frequency in BF (Hz)	Phase	Differential acceleration (m/s^2)	Differential displacement (pm)
EP signal	ν_{orb}	ν_S (wrt Earth)	X_{LVLH}	$8.116 \cdot 10^{-17}$	0.51
External non gravitational forces	ν_{orb}	ν_S	Mainly along Y_{LVLH}	$1.7 \cdot 10^{-7}$	-
External non gravitational forces after DFC compensation and CMRR	ν_{orb}	ν_S	Mainly along Y_{LVLH}	$3.4 \cdot 10^{-17}$	0.22
Earth coupling with TMs quadrupole moments	ν_{orb}	ν_S	X_{LVLH}	$9 \cdot 10^{-18}$	0.06
Radiometric effect along Z coupled with Earth tide	$2 \cdot \nu_{orb}$	$\nu_S \pm \nu_{orb}$	X_{LVLH}	$6.3 \cdot 10^{-16}$	4.0
Emitted radiation along Z coupled to Earth tide	$2 \cdot \nu_{orb}$	$\nu_S \pm \nu_{orb}$	X_{LVLH}	$4 \cdot 10^{-17}$	0.11
Tide coupled to non grav. acceleration along Z	$2 \cdot \nu_{orb}$	$\nu_S \pm \nu_{orb}$	X_{LVLH}	$1.4 \cdot 10^{-17}$	0.09
TM1 inner magnetic dipole coupled to $B_\oplus$ magnetized TM2	$2 \cdot \nu_{orb}$	$\nu_S \pm \nu_{orb}$	X_{LVLH}	$1 \cdot 10^{-18}$	$8 \cdot 10^{-3}$
TMs inner magnetic dipoles coupled to $B_\oplus$	$2 \cdot \nu_{orb}$	$\nu_S \pm \nu_{orb}$	X_{LVLH}	$6 \cdot 10^{-21}$	$4 \cdot 10^{-5}$
TM1 and TM2 with $B_\oplus$ induced magnetization couple	$4 \cdot \nu_{orb}$	$\nu_S \pm 3 \cdot \nu_{orb}$	X_{LVLH}	$8 \cdot 10^{-23}$	$5 \cdot 10^{-7}$
TM1 with $B_\oplus$ induced magnetization couples with $B_\oplus$	$4 \cdot \nu_{orb}$	$\nu_S \pm 3 \cdot \nu_{orb}$	X_{LVLH}	$8 \cdot 10^{-24}$	$5 \cdot 10^{-8}$
Whirl motion coupled to Earth tide	ν_w, $\nu_w \pm 2 \cdot \nu_{orb}$	$\approx \nu_S \pm \nu_w$ ($\nu_{orb} << \nu_w$)	X_{LVLH}	$6.9 \cdot 10^{-14}$	440
...	Higher frequencies	Frequencies far from ν_S	X_{LVLH}	...	...

GG Error Budget

(4)

- Variation of line @ $2\nu_{EP}$ due to the change of the angle in between spin axis and orbit angular rate
  - Variation very slow in time (signal and line are almost constant during one week)
  - 11 pm can be distinguished very well with one week of continuous data



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GG Error Budget (5)

- Thermal noise due to TMs “spring” dissipation (Q_{TM} = 20000) directly affects the science measurement (it is the main stochastic disturbance):

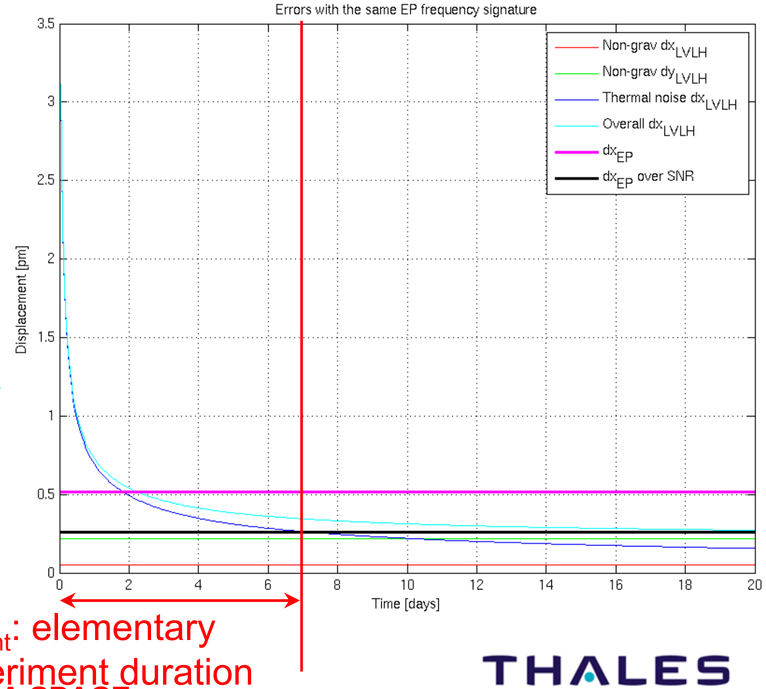
$$SD(\tilde{n}_{TM-th}) = \sqrt{\frac{4K_B T \cdot \omega_{DM}}{m_{TM} \cdot Q_{TM}}}$$

→ $T_{int} \approx$ 1 week

- Overall dx_{LVLH} takes into account deterministic and stochastic contribution

$$SD(\tilde{n}_{TM-th}) = 3.2 \cdot 10^{-14}\ m/s^2/\sqrt{Hz}$$

$$\text{Overall } dx_{LVLH} = \sqrt{(dx_{LVLH})^2 + (dy_{LVLH})^2 + \frac{SD^2(\tilde{n}_{TM-th})}{T_{int} \cdot \omega_{DM}^4}}$$

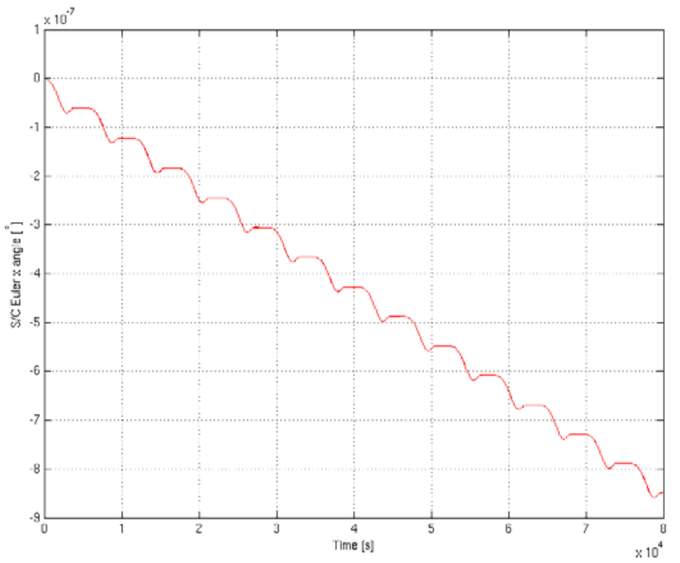


Simulator for GG spinning @1 Hz (1)

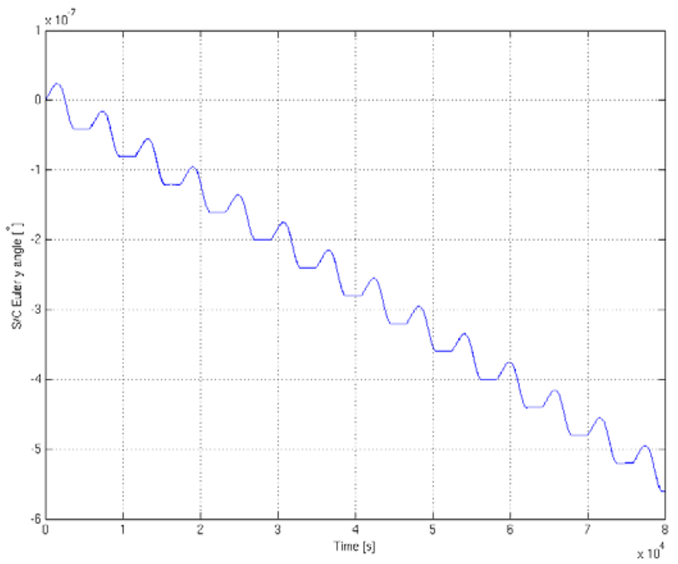
- Spacecraft shell, PGB, TMi, TMo, dummy body for not solving the orbit motion in a rapidly spinning reference frame: 27 DoFs
- Gravity and gravity gradient are "on"
- Current mass/inertia properties for all bodies (included proof masses quadrupole moment)
- Orbit altitude h = 630 km to match the reference 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 simulations are carried out in order to predict science performance of the mission

Simulator for GG spinning @1 Hz (2)

- DFC, AOCS and PGB-s/c control in open loop
- PGB and TMs whirl control in closed loop



s/c to LVLH hinge attitude angle x
time series



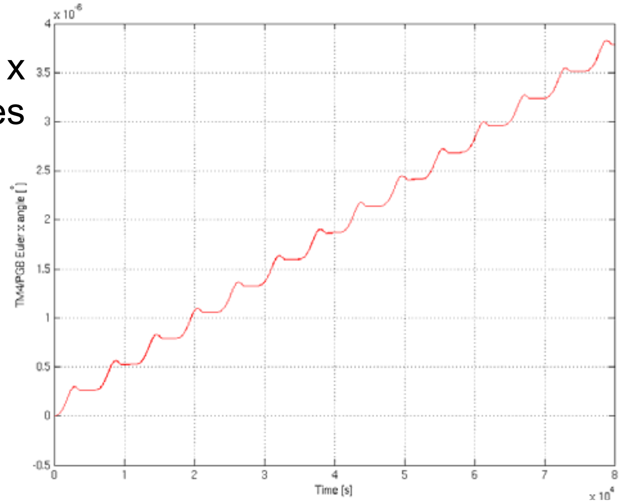
s/c to LVLH hinge attitude angle y
time series

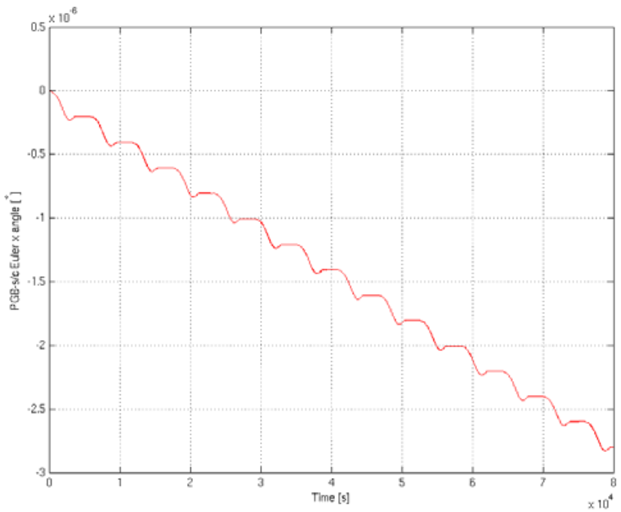
s/c to LVLH hinge attitude angle z
time series is ωt

GG: Simulated Performance

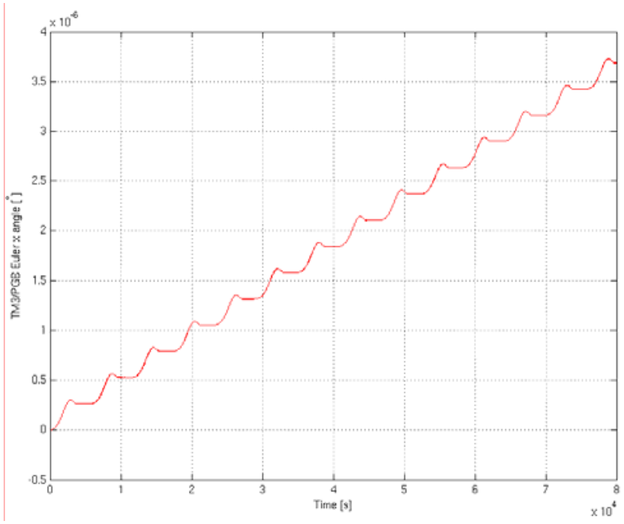
Simulator for GG spinning @1 Hz (3)

TM4-PGB hinge attitude angle x time series

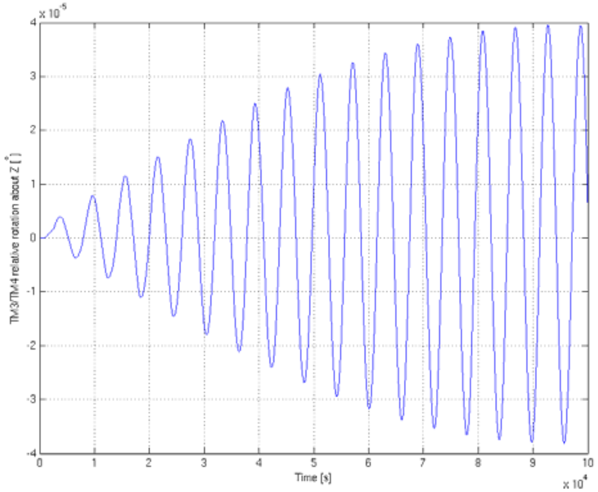




PGB-s/c hinge attitude angle x time series



TM3-PGB hinge attitude angle x time series



TM3-TM4 differential angle z time series

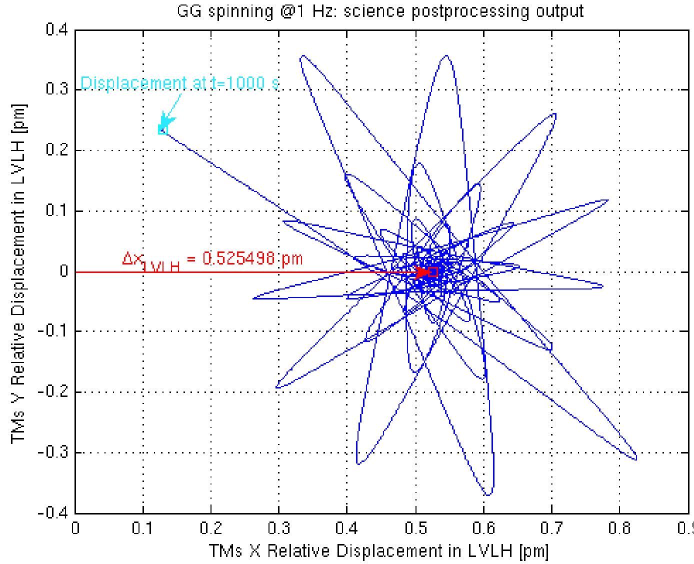
GG: Simulated Performance

Simulator for GG spinning @1 Hz (4)

- 1 Hz is better for the simulator… CPU time is reduced by a factor 2
- Changing spin frequency modifies dynamics, changing η modifies F_{EP} strength… but

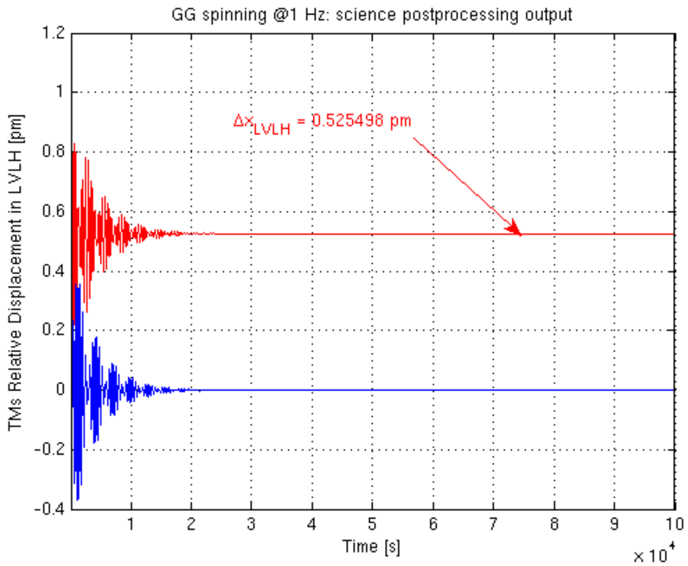
Predicted value: $\Delta x_{LVLH} = \dfrac{F_{EP}}{m_{TM}\cdot\left(\omega_{DM}^2 - 3\cdot\dfrac{GM_\oplus}{(R_\oplus + h)^3}\right)} = 5.25501\cdot 10^{-13}\,\mathrm{m}$

"Measured" value: $\Delta x_{LVLH} = 5.25498 \cdot 10^{-13}$ m !!



Polar plot of the TMs differential displacement in the LVLH Reference Frame

After a transient the TMs relative position has almost null mean value along Y_{LVLH} and 0.525 pm mean value along X_{LVLH}



Time series of the TMs differential displacement in the LVLH Reference Frame