lisa pathfinder

LISA Pathfinder:
Sub-femto-g differential accelerometry for gravitational wave observation from space

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for the LISA Pathfinder Collaboration

Amaldi Meeting
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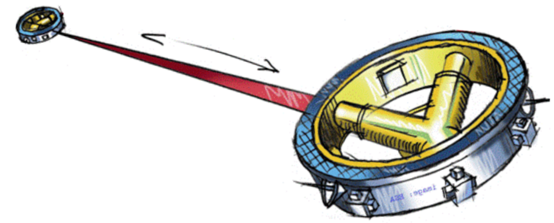
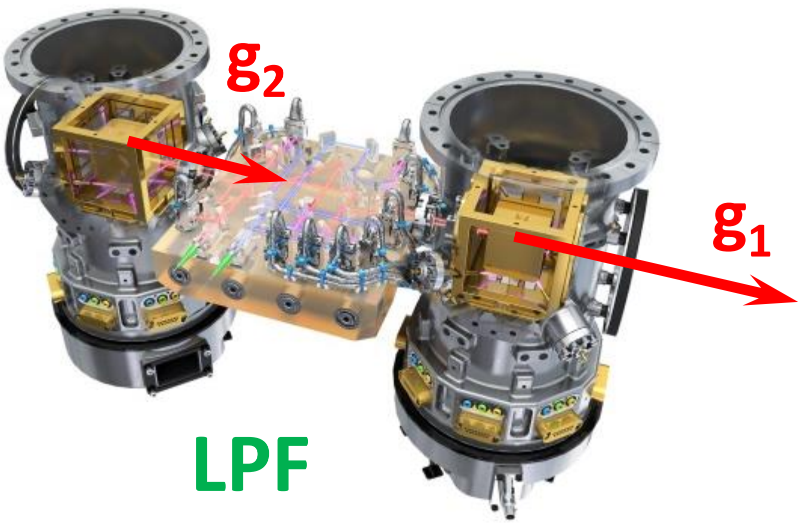
UNIVERSITÀ DEGLI STUDI DI TRENTO

TIFPA Trento Institute for Fundamental Physics and Applications

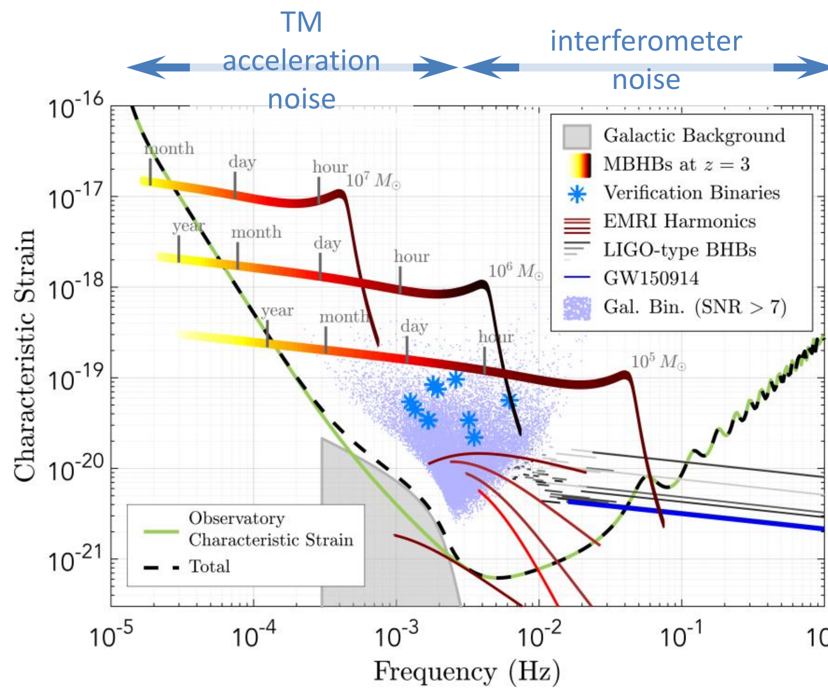
Measuring sub-femto-g/Hz$^{1/2}$ differential acceleration

- LPF: gravity gradiometer 2 TM with 37.6 cm baseline in drag-free spacecraft at L1





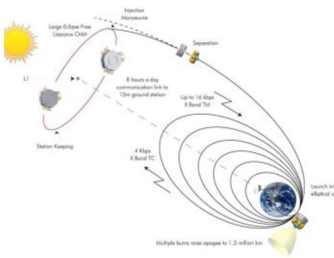
$$\Delta g \equiv g_2 - g_1$$



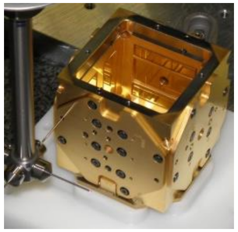
Measuring sub-femto-g/Hz$^{1/2}$ differential acceleration

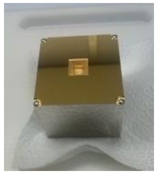
- LPF: gravity gradiometer 2 TM with 37.6 cm baseline in drag-free spacecraft at L1

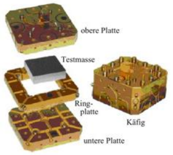
- Similar to 1 component of GOCE geodesy mission

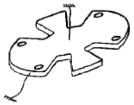


Actuation force noise «accelerometer range»	LEO μm/s²(Terrestrial) residual atmosphere	L1 nm/s² (spacecraft **g**) → **0 for eLISA !!** deep space
GRS surface force noise	300 gm TM 100 μm gaps discharge wire	2 kg TM 3-4 mm gaps no contacts









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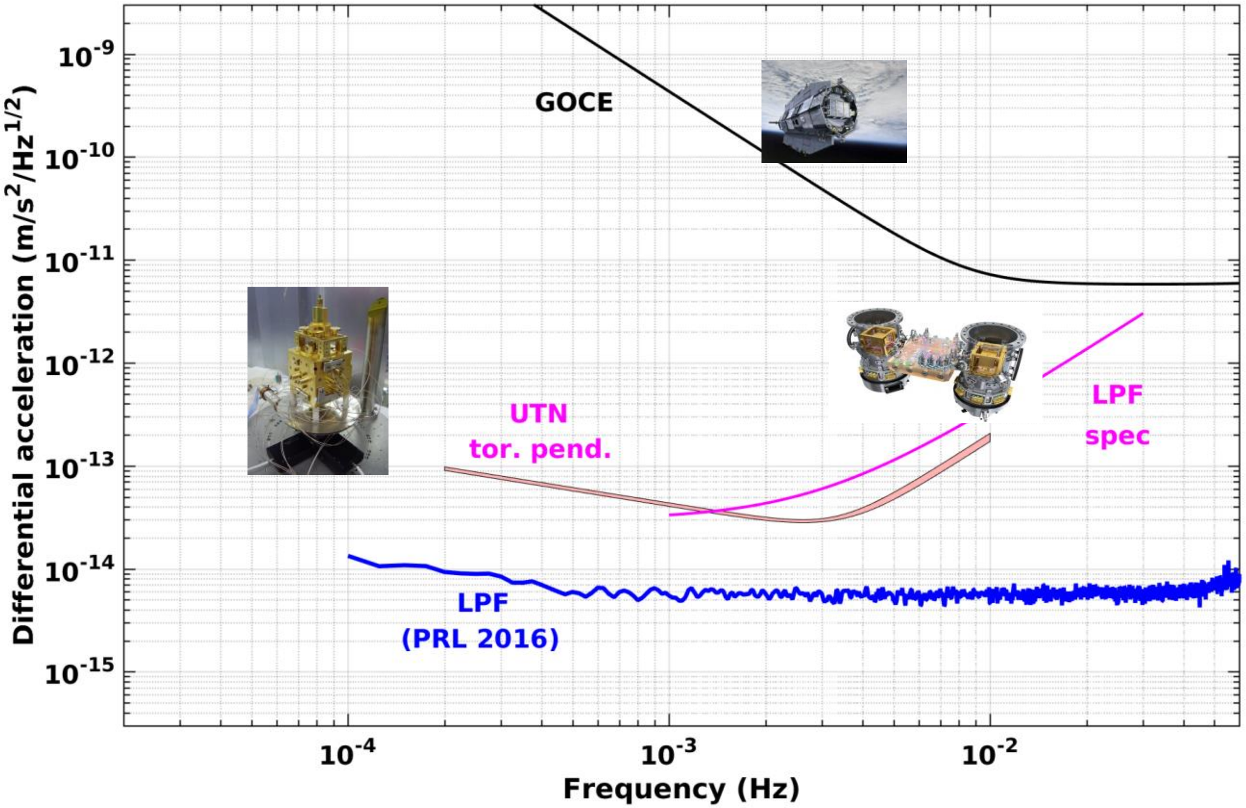
Free-falling test masses as sub-femto-g geodesic references: pre-LPF knowledge



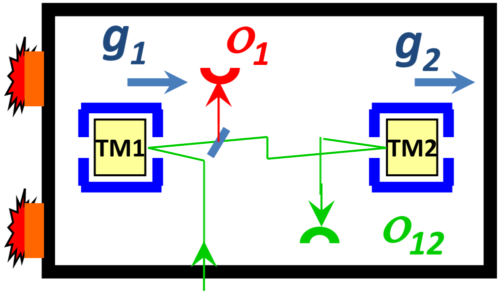
Pre-flight torsion pendulum tests retired some GRS force risks

- Not representative of all forces (or full free-fall + control)
- Not quite to LPF specs (far from true space performance)

LISA Pathfinder as a differential accelerometer

$$\Delta g \equiv g_2 - g_1$$

«gravitational observable»
differential force per unit mass



Control:

- Thrust SC to follow TM1
- Electrostatically force TM2 to follow TM1

Newton's Laws:

$$\ddot{x}_1 = g_1 - \omega_{1p}^2 (x_1 - x_{SC})$$

$$\ddot{x}_2 = g_2 - \omega_{2p}^2 (x_2 - x_{SC}) + \frac{F_{ES}}{m}$$

IFO Readouts :

$$o_{12} = x_2 - x_1 + n_{12}$$

$$o_1 = x_1 - x_{SC} + n_1$$

$$\Delta g = \ddot{o}_{12} - \frac{F_{ES}}{m} + (\omega_{2p}^2 - \omega_{1p}^2) o_1 + \omega_{2p}^2 o_{12} - \ddot{n}_{12} - (\omega_{2p}^2 - \omega_{1p}^2) n_1 - \omega_{2p}^2 n_{12}$$

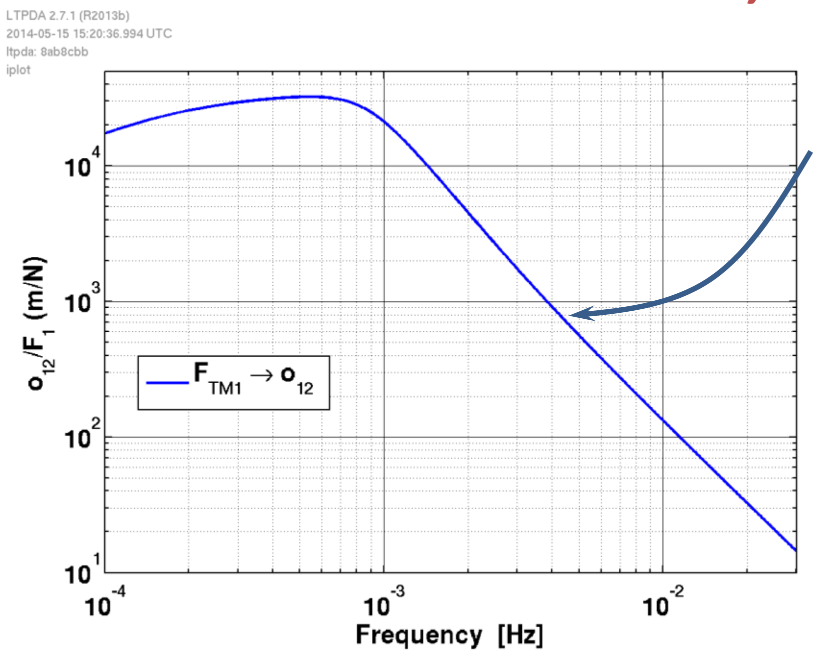
$$\Delta \hat{g}$$

Differential acceleration time series

$$-\Delta g_{IFO}$$

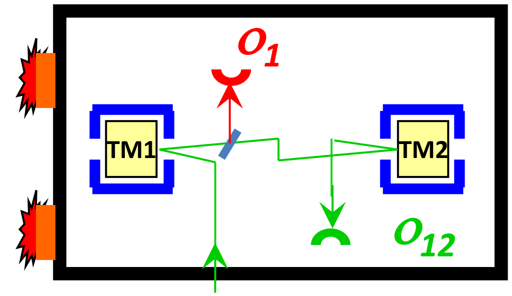
IFO Noise

LISA Pathfinder control, displacement and acceleration

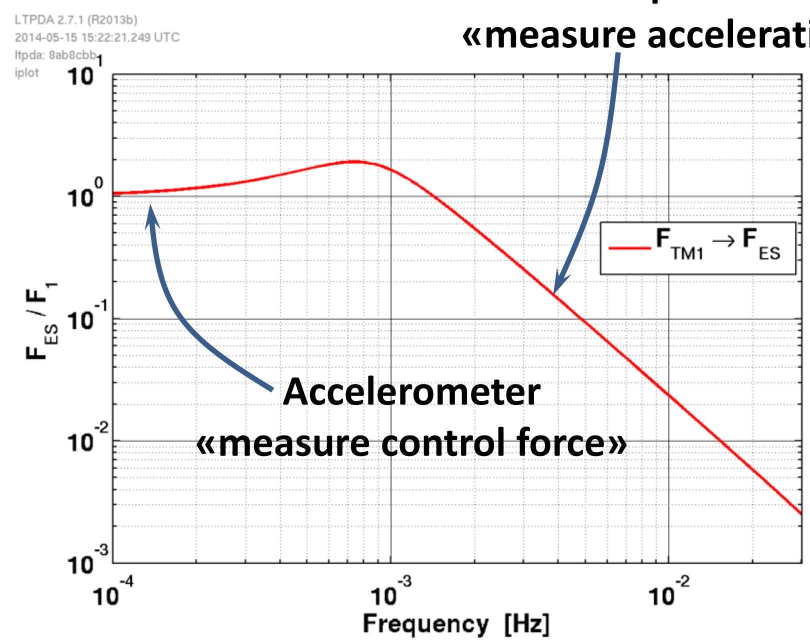


Free particle

$$\Delta x \approx \frac{\Delta F}{m\omega^2}$$



Free particle
«measure acceleration»

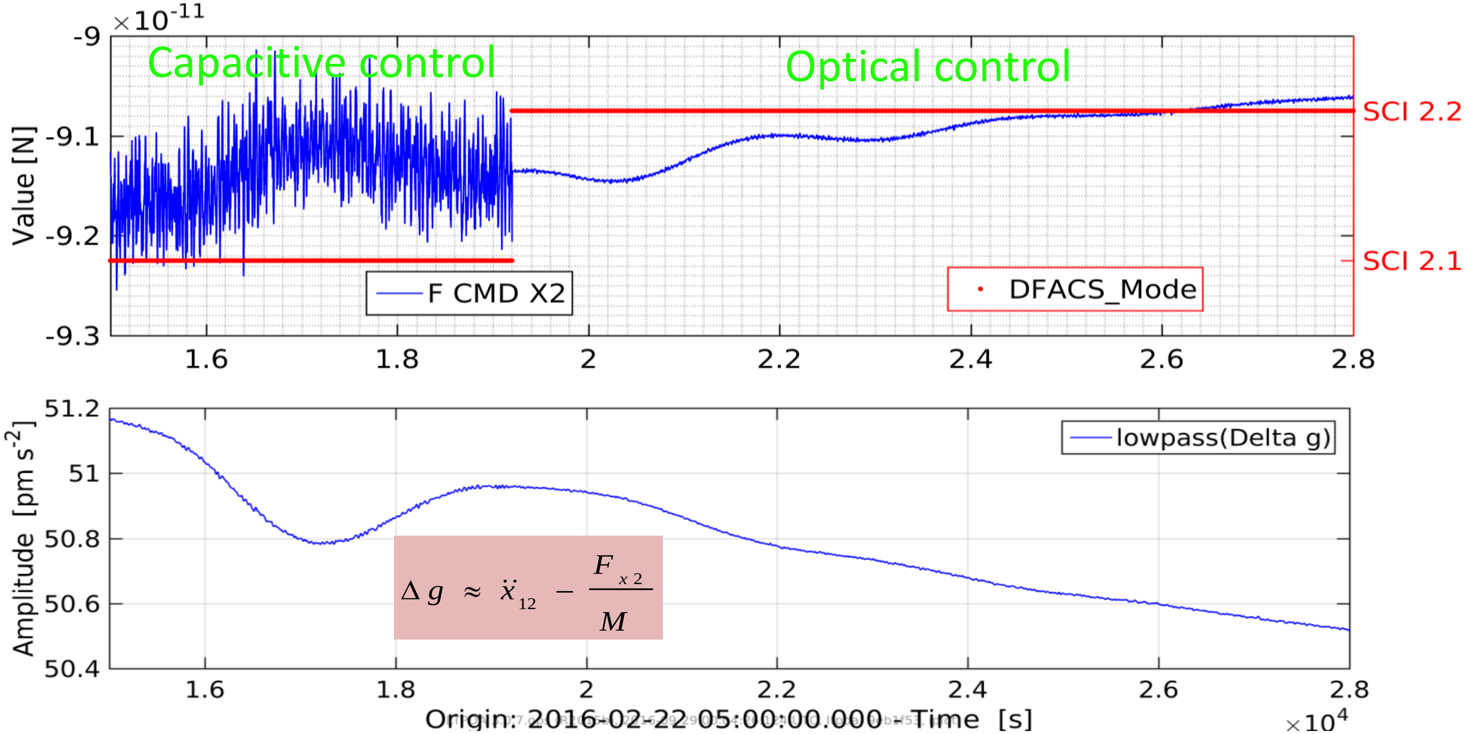


Accelerometer
«measure control force»

$$\Delta \hat{g} = \ddot{o}_{12} - \lambda \frac{F_{ES}}{m} + \left(\omega_{2p}^2 - \omega_{1p}^2\right) o_1 + \omega_{2p}^2 o_{12}$$

Need to calibrate actuator and SC coupling (stiffness)

Quieting down ... Applied TM2 force across mode changes



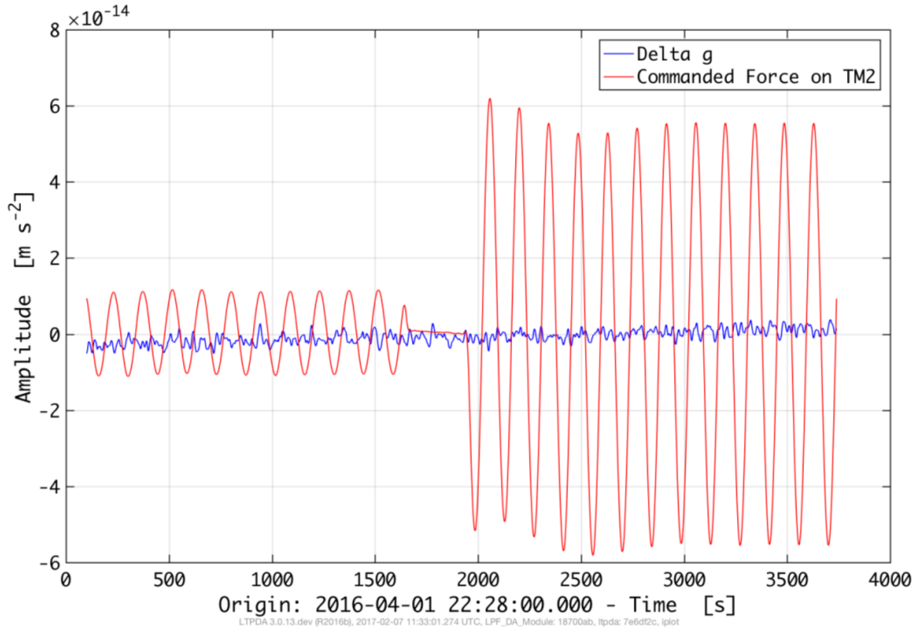
Good news! Δg < 50 pm/s^2 (and decreasing)

- Well below specs (650 pm/s^2) → less actuation → less noise!
- Start to see our science signal ... Sub-mHz fluctuations in Δg

- Drift ... initially 5 pm/s^2/day (residual gas TM)
- 1 year later order 0.3 pm/s^2/day (gravity from cold gas)

Δg calibration tone: extra known forces disappear

$$\Delta \hat{g} = \ddot{o}_{12} - \frac{F_{ES}}{m} + \left(\omega_{2p}^{2} - \omega_{1p}^{2}\right) o_{1} + \omega_{2p}^{2} o_{12}$$



- Injection of a 20 fN or 100 fN «out-of-loop» force accurately removed in Δg calculation → down to femto-Newton level

- Acceleration observable → analysis immune to initial conditions
  - Control transients irrelevant

Centrifugal force correction Δg

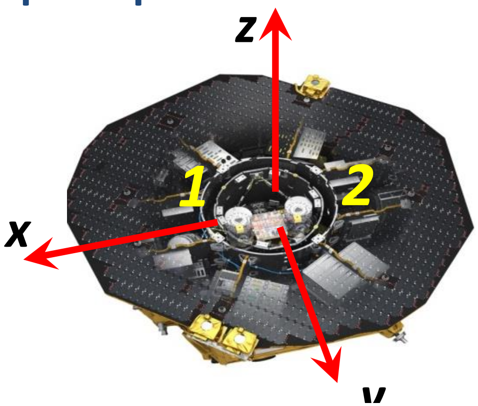
- SC rotates to point at earth/sun
- TM forced to rotate with SC
- SC low freq attitude noise from noisy star trackers
- **1st principles subtraction**

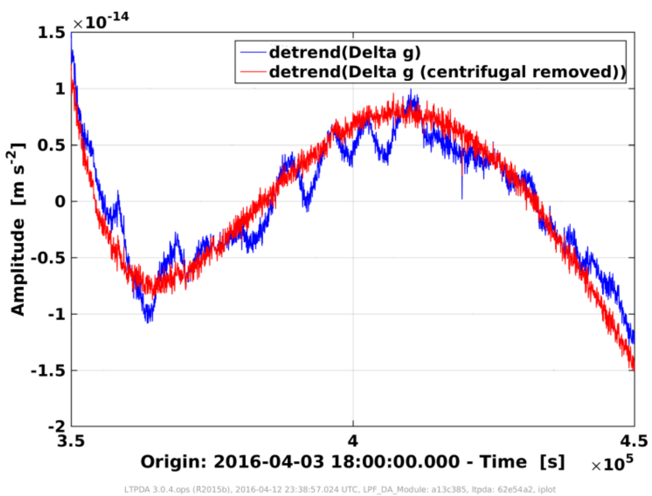
$$\Delta \hat{g}_{CENT} = -L\left(\dot{\phi}_{SC}^{2} + \dot{\eta}_{SC}^{2}\right)$$

$$\left(\dot{\phi}_{"DC"} + \dot{\phi}(t)\right)^{2}$$

Quasi-DC from star tracker angular rates

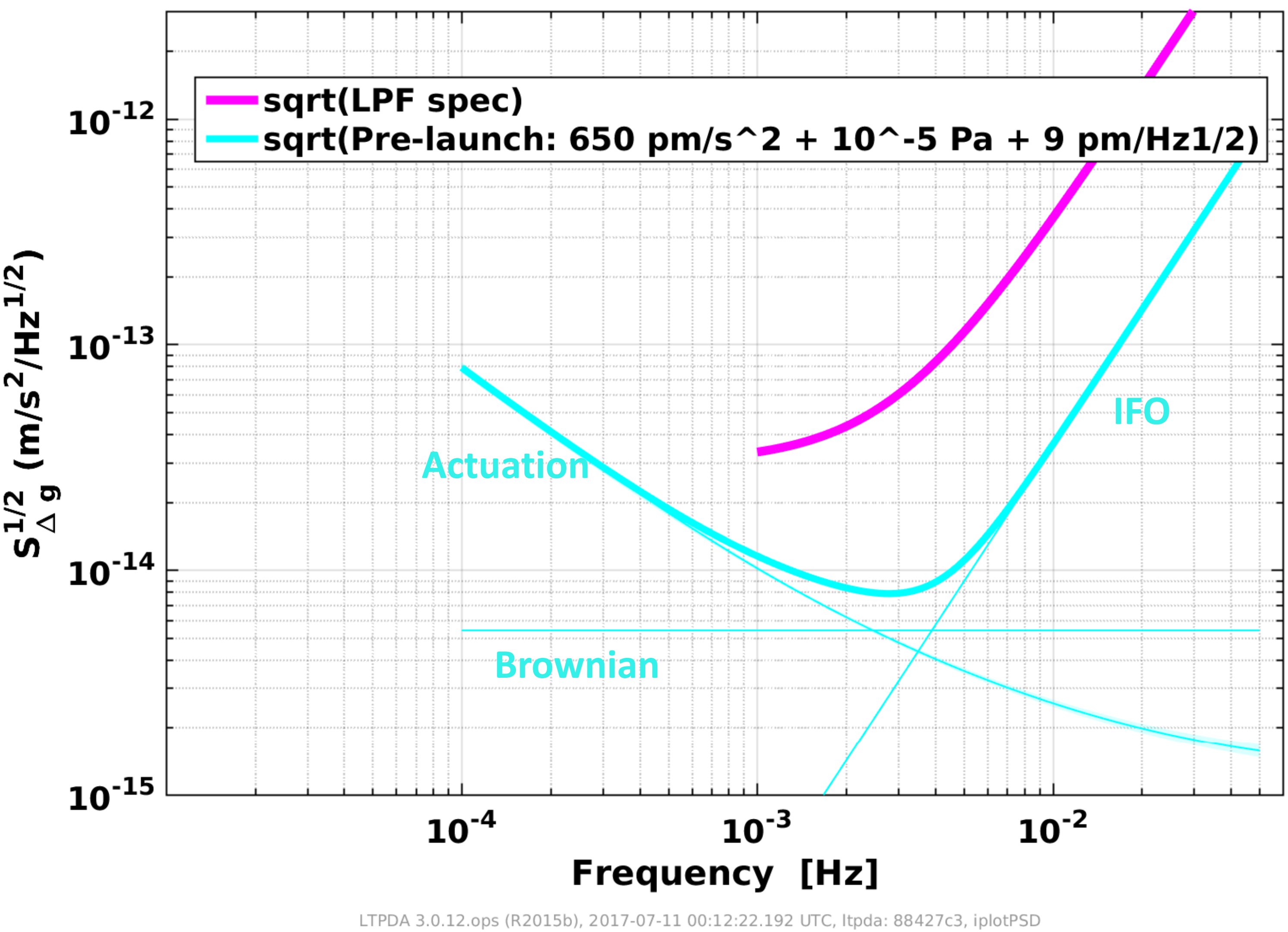
In-band (0.1-1 mHz) using 2 TM as gyroscope (applied torques)



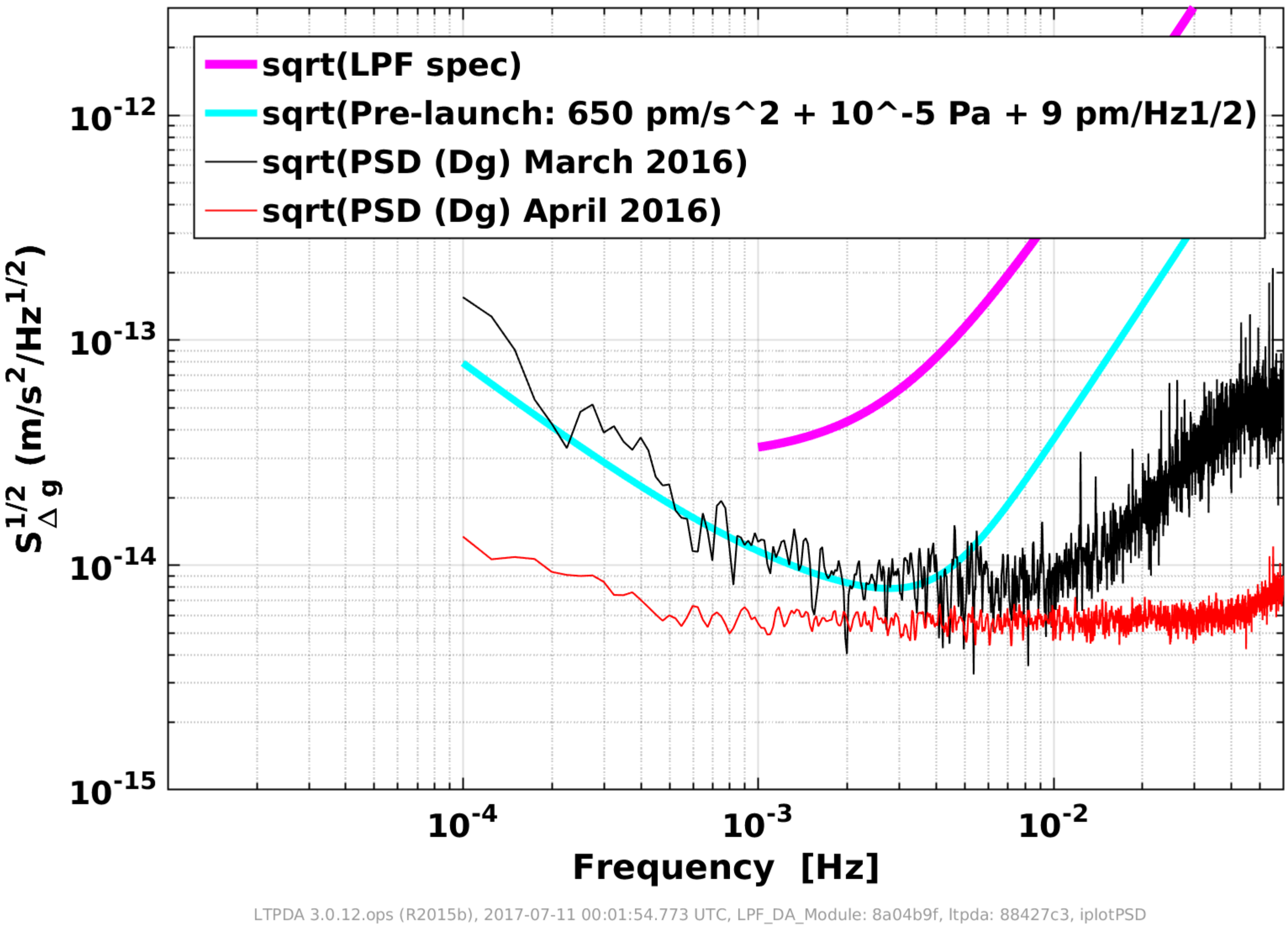


- Additional inertial correction due to angular acceleration (and TM lateral offset)

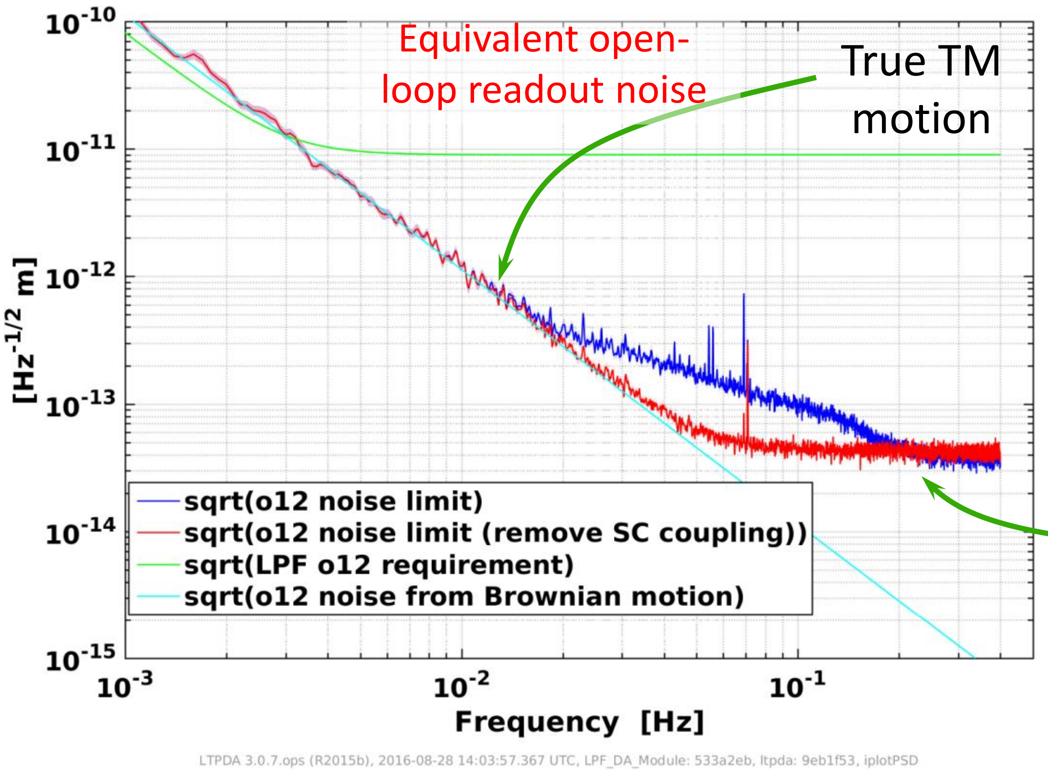
LISA Pathfinder differential acceleration noise

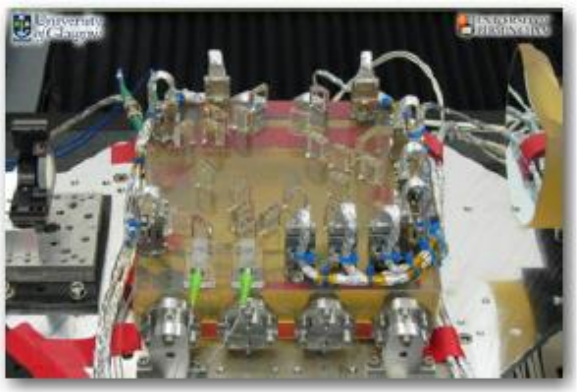


LISA Pathfinder differential acceleration noise



LISA Pathfinder instrument performance: interferometer

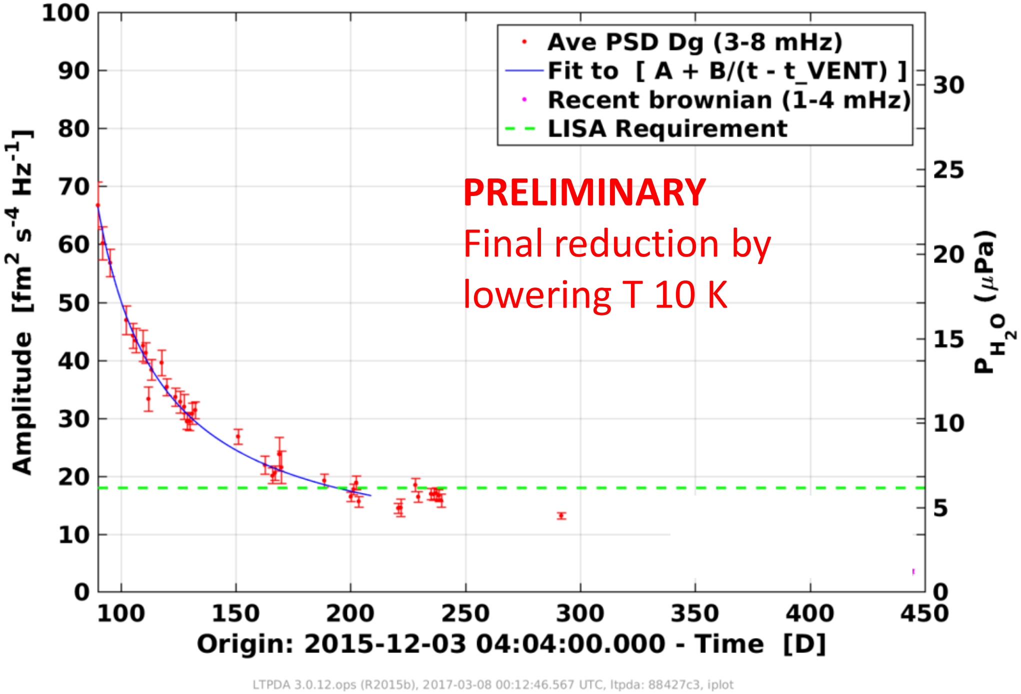




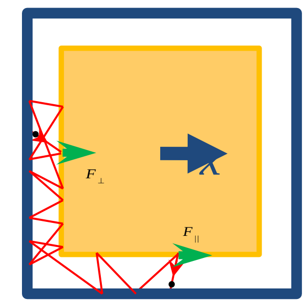
35 fm/Hz$^{1/2}$ noise floor

- Dominated by (mostly understood) phase meter noise
- Visible coupling to SC motion → removal by alignment / software
- Allows measurement of true TM motion (brownian) below 50 mHz
- **Demonstration of an (overachieving) local IFO in space**

Brownian motion from residual gas impacts



Brownian motion
from gas impacts limit
in 1 – 10 mHz band

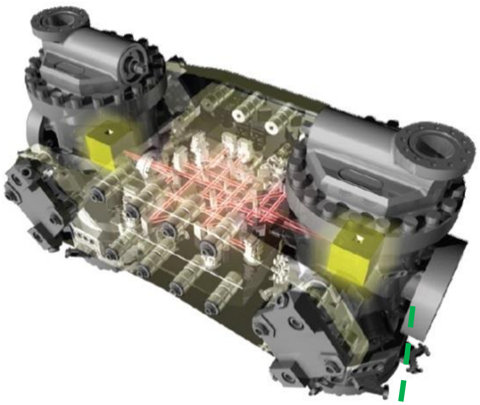


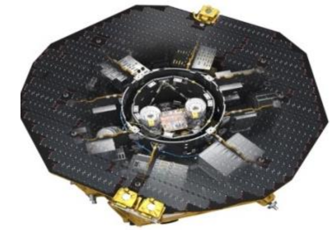
Increased inside (tight) GRS
due to correlated collisions

- Rough t^{-1} dependence of white noise level over time –
  - → young vacuum system: launch Dec 2015, vented to space Feb 2016
  - → outgassing diminishing over time

- Dependence on temperature (T)
  - →roughly factor 2 (power) with 10 K
  - → exp $-\Theta/T$ dependence of adsorption

LPF Noise: actuation gain fluctuations





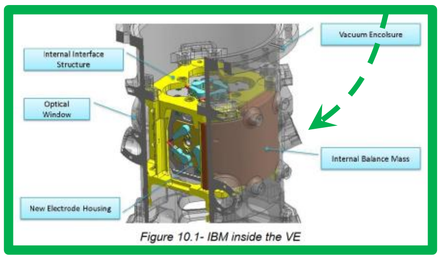


Figure 10.1- IBM inside the VE

«accelerometer dynamic range» problem

Noise in "DC" force applied to compensate local Δg

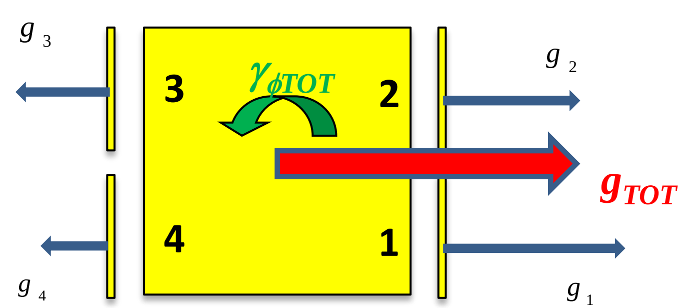
→ in LISA (no x-axis applied force)

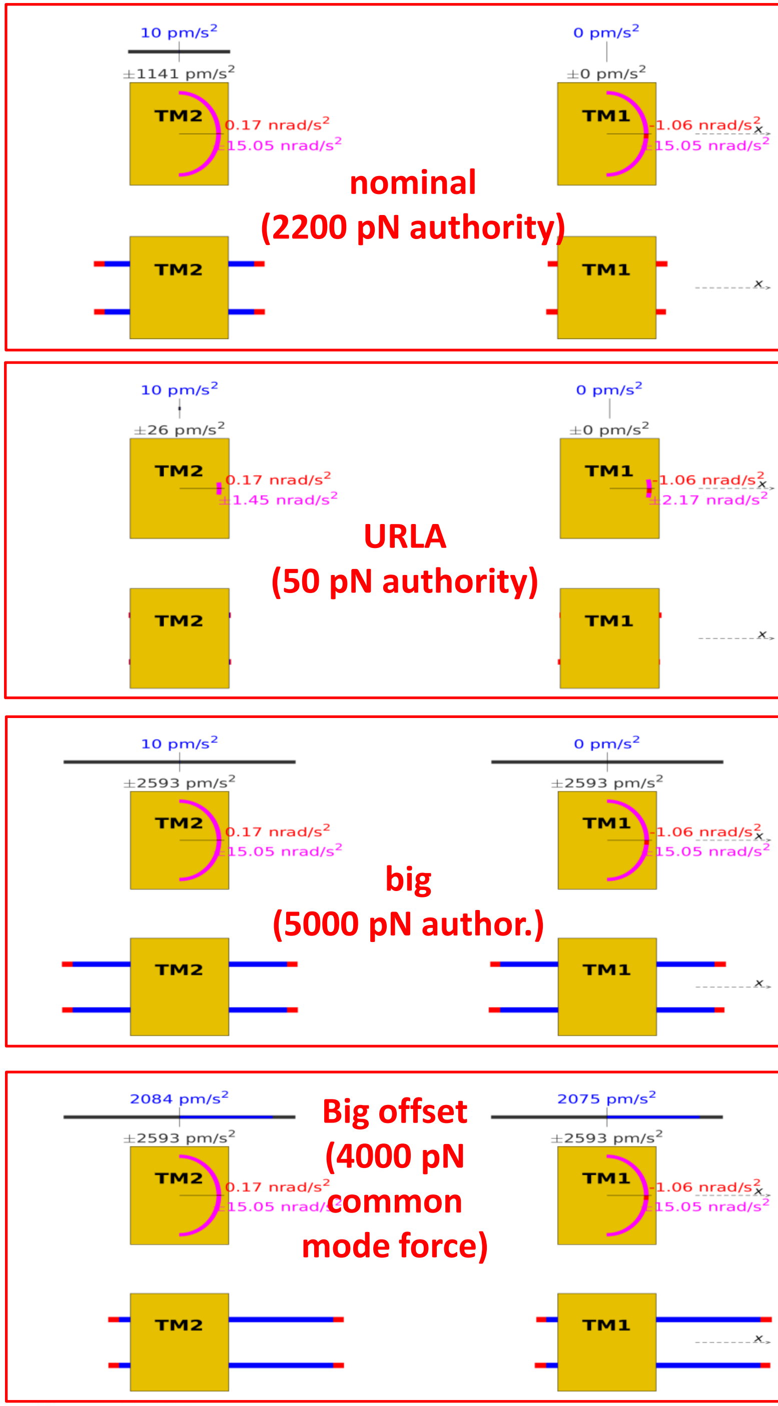
$$F \propto V_{ACT}^{2} \qquad \rightarrow \qquad S_F^{1/2} \approx 2\,F\,S_{\delta V/V}^{1/2}$$

- Force noise scales with applied forces, summed over all electrodes
- Same electrodes apply ϕ torque and x forces

- Voltage stability 3-8 ppm/Hz$^{1/2}$ at 1 mHz

Gravitational balance:
- LPF designed for Δg 650 pm/s^2
- LPF in-flight Δg < 50 pm/s^2

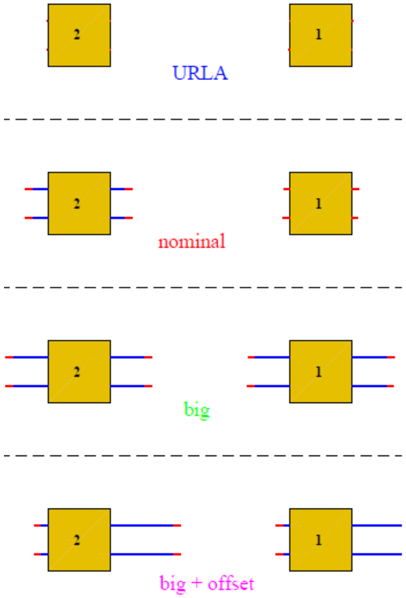


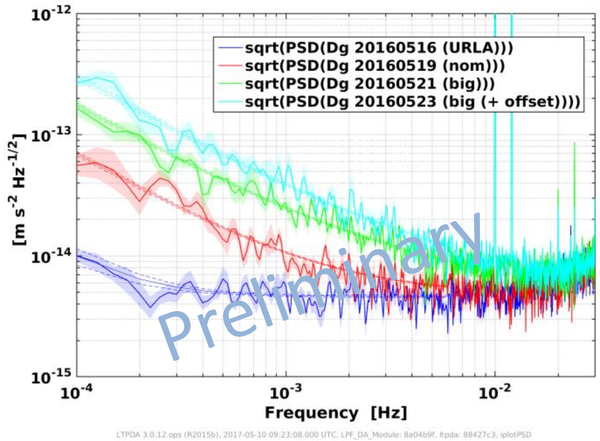


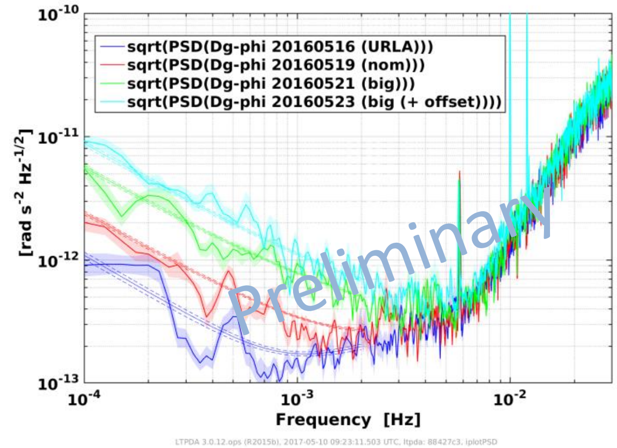
Quantifying actuation noise

- Increase actuation forces (without letting TM hit SC) to exxagerate force noise
- Measure both force and torque noise
- Parametric model to «extract» intrinsic voltage fluctuations from combinations of electrodes
- Distinguish correlated fluctuations from uncorrelated fluctuations
- Distinguish +X actuators from -X

Actuation noise test campaign: results







Noise in Δg, $\Delta\gamma_{\phi}$ increases with larger authoritities and same net forces / torques

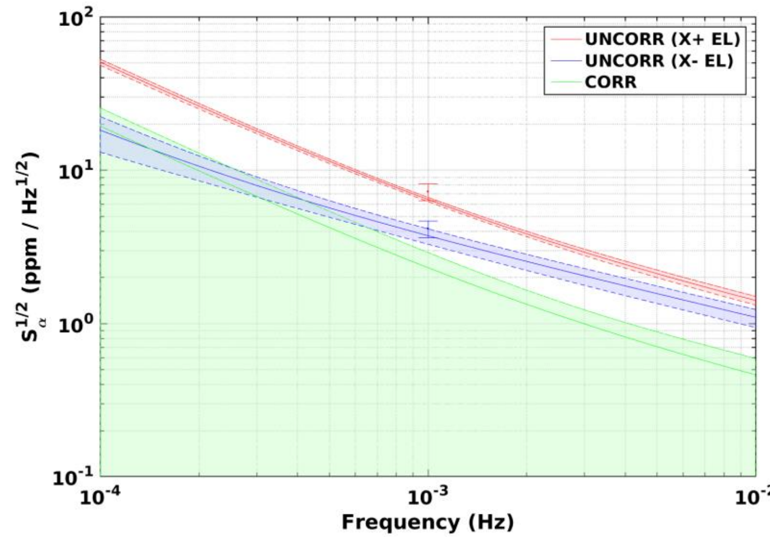
→ Uncorrelated gain fluctuations

Noise increase with large applied +X force

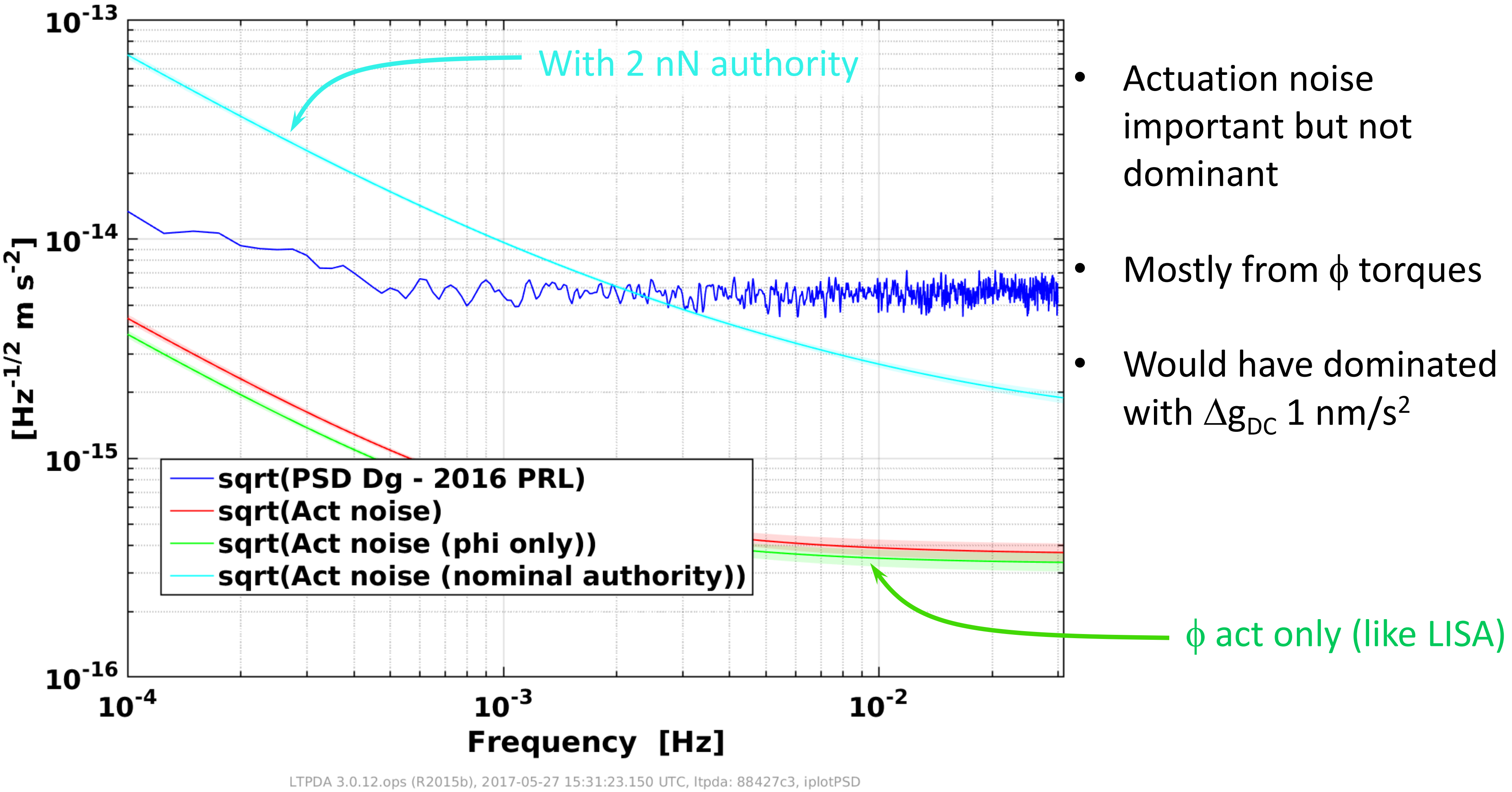
→ X+ actuators worse!

→ In agreement with ground tests!

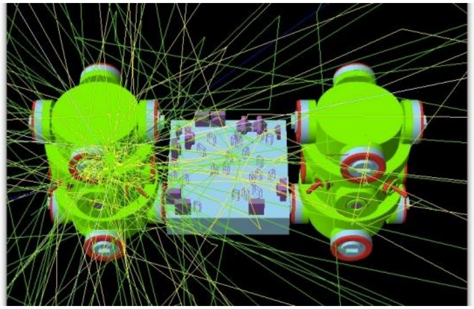
No correlated (voltage reference) noise



Actuation noise projection

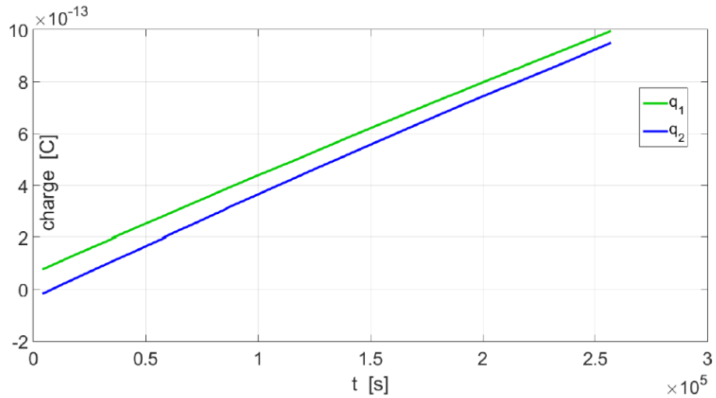


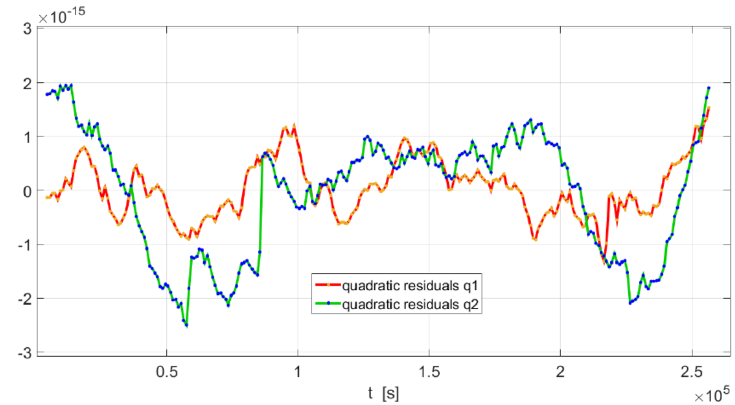
- Actuation noise important but not dominant
- Mostly from ϕ torques
- Would have dominated with Δg_{DC} 1 nm/s^2



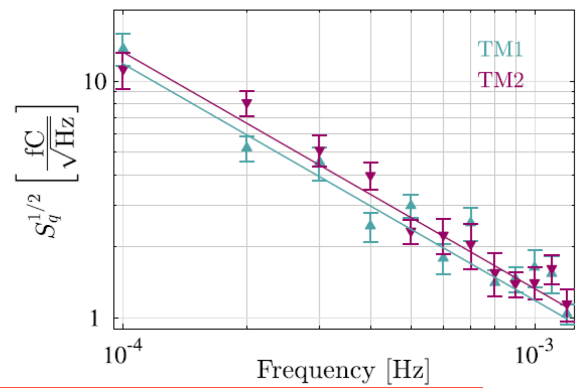
TM charging: steady and stochastic

- Cosmic ray + solar particle events accumulate TM charge
- Mix with stray electrostatic fields to give forces (and noise)





Net charge rate:	+25 e/s
Effective shot noise rate:	1200 e/s



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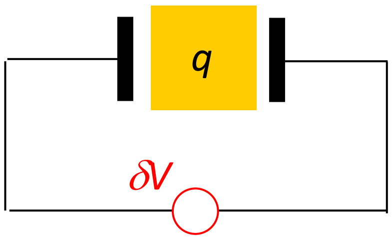
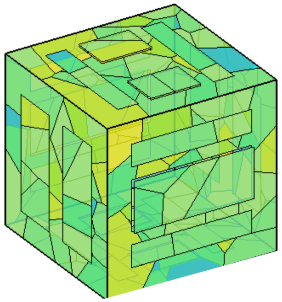
Charge-Induced Force Noise on Free-Falling Test Masses: Results from LISA Pathfinder

TM charging and stray electrostatic fields

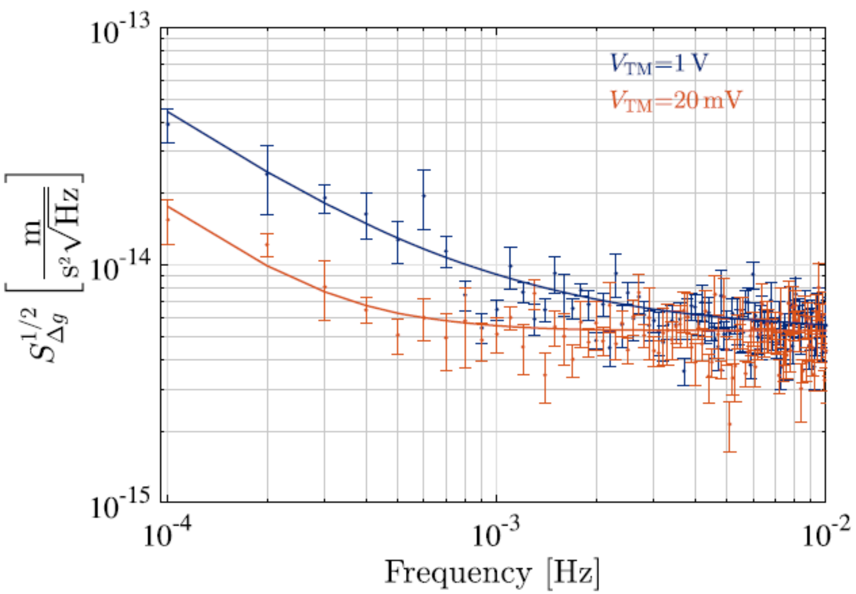




TM charge

$$F = -\frac{q}{C_{TOT}}\left|\frac{\partial C_x}{\partial x}\right|\Delta_x$$

Stray E-field (equiv. ΔV on 1 electrode)



Charge fluctuations

→ measure 10 aA/Hz$^{1/2}$

→ need to limit stray DC field (Δ_x < 10 mV)

Stray field fluctuations

→ measure $S_{\Delta X}^{1/2}$ 200 μV/Hz1/2 at 100 μHz

→ consistent with actuation voltage noise

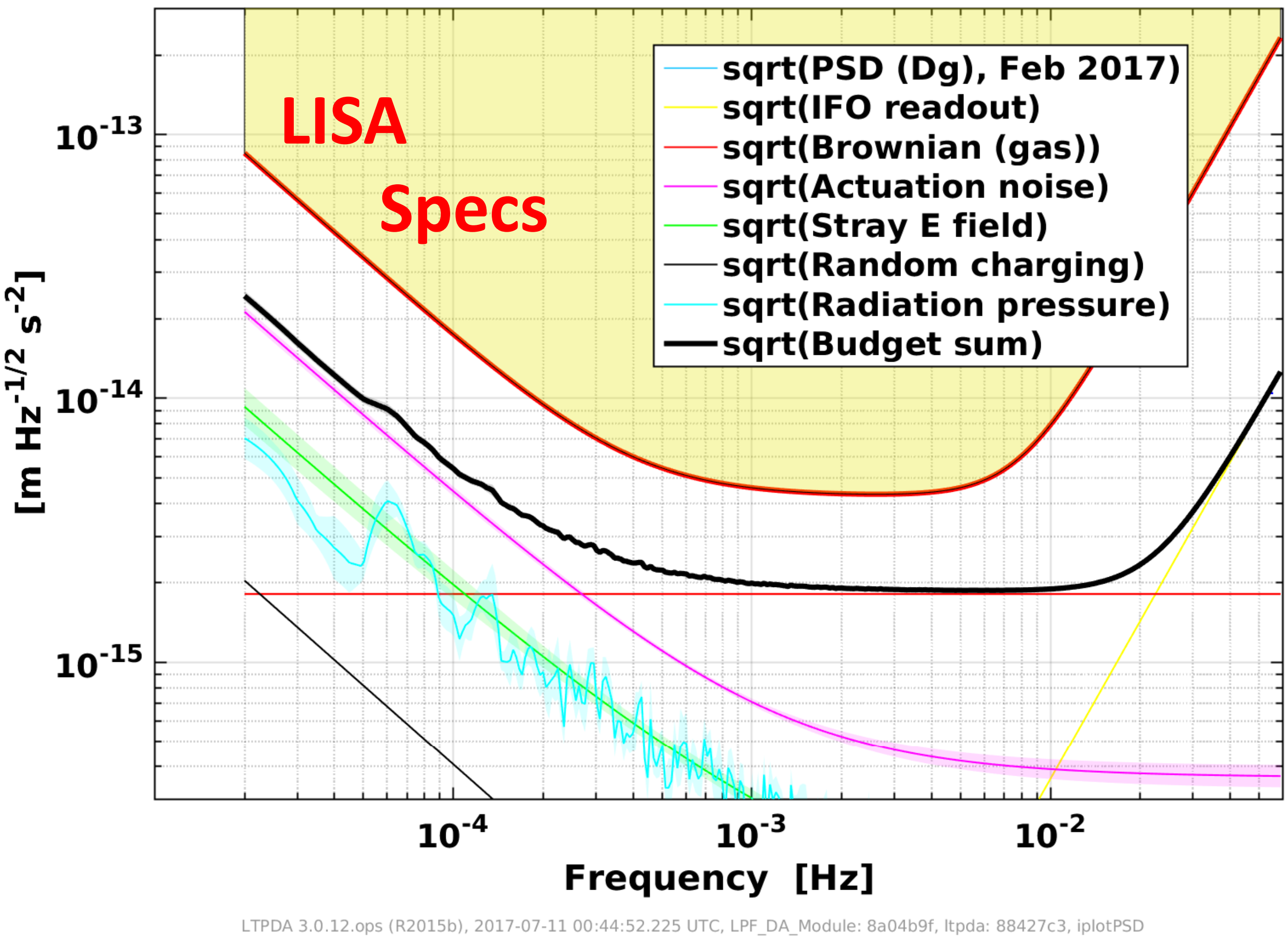
→ need to keep TM charge < 10^7 e (50 mV)

→ OK for 2 weeks between discharge

→ continuous discharge better, eliminates interuptions

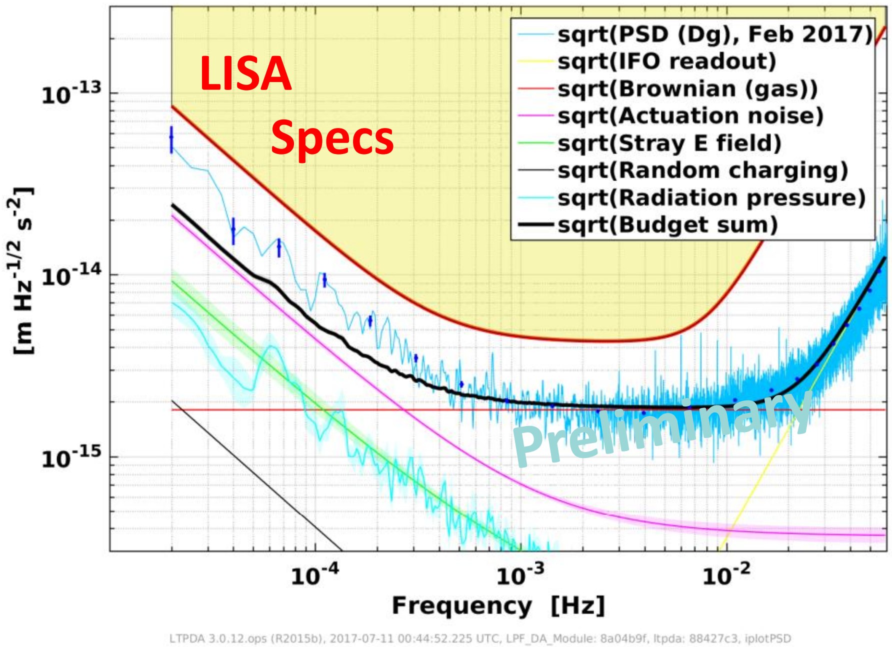
→ also demonstrated on LPF!

LISA Pathfinder Δg noise budget (February 2017)



Work ongoing for low freq sources (thermal, inertial, magnetic ...)

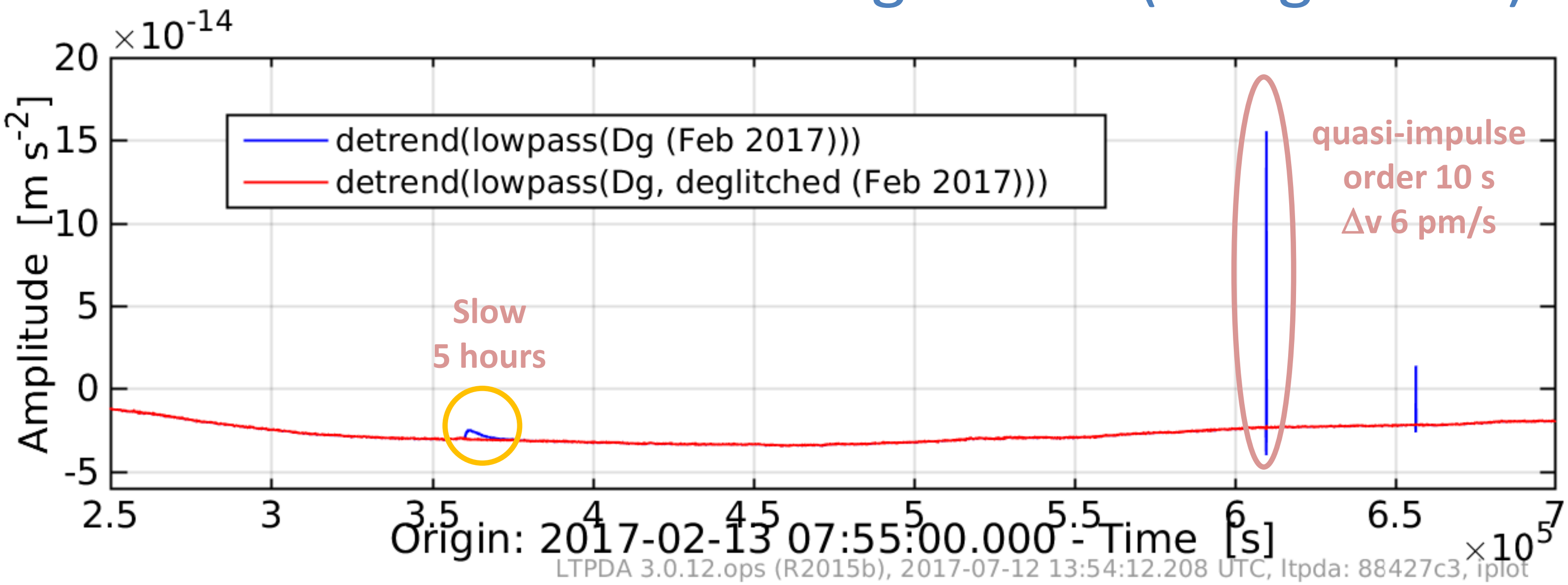
LISA Pathfinder Δg noise budget (February 2017)



- LPF acceleration noise below LISA requirement at all frequencies

- Noise budget (conservative) explains less than half noise (power) at low frequencies
  - Work ongoing for low freq sources (gravitational, thermal, inertial, magnetic ...)
  - Need to understand, test, and reproduce with LISA

Transient non-Gaussian Δg events (aka glitches)



- Mostly fast (10’s seconds), up to of order 1/day
- (as yet) cause unidentified

- Fit with «simple» phenomenological model (4-8 params)

- Need to handle these in LISA data analysis?
  - Ideally discriminated at instrument / SC level (correlation with a disturbance)
  - Sagnac (less sensitive to GW) discrimination?
  - Population of unmodelled gravitational wave sources?

Thank you!