lisa pathfinder

Physical model of the LISA Pathfinder differential acceleration measurement and its application to LISA

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for the LPF science collaboration

LISA Symposium
5 September 2016, Zurich

UNIVERSITÀ DEGLI STUDI DI TRENTO

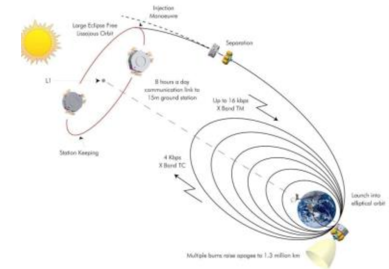
TIFPA
Trento Institute for Fundamental Physics and Applications

LISA Pathfinder acceleration noise budget

- Evidence for main noise sources
  - actuation and brownian noise
- «Known» noise budget and open questions for known noise sources
- Remaining challenges
  - Actuation calibration error
  - Low frequency noise
  - Glitches
- Application to LISA

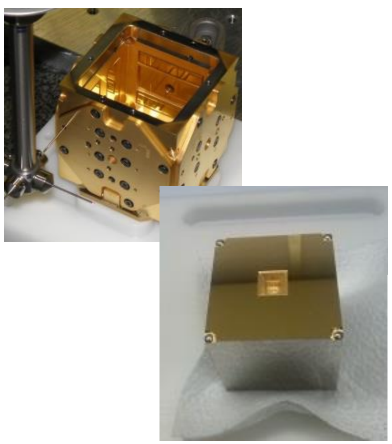
LPF: Testing jump from pico-g/Hz$^{1/2}$ to sub-femto-g/Hz$^{1/2}$:

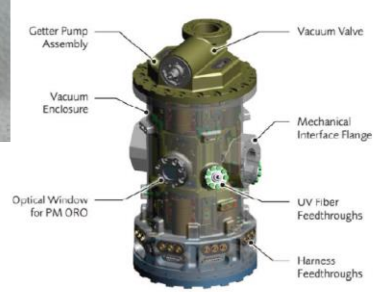
Geodesy in low earth orbit
(μm/s^2)



LPF at L1
nm/s^2

Are surface forces low enough to allow this jump?

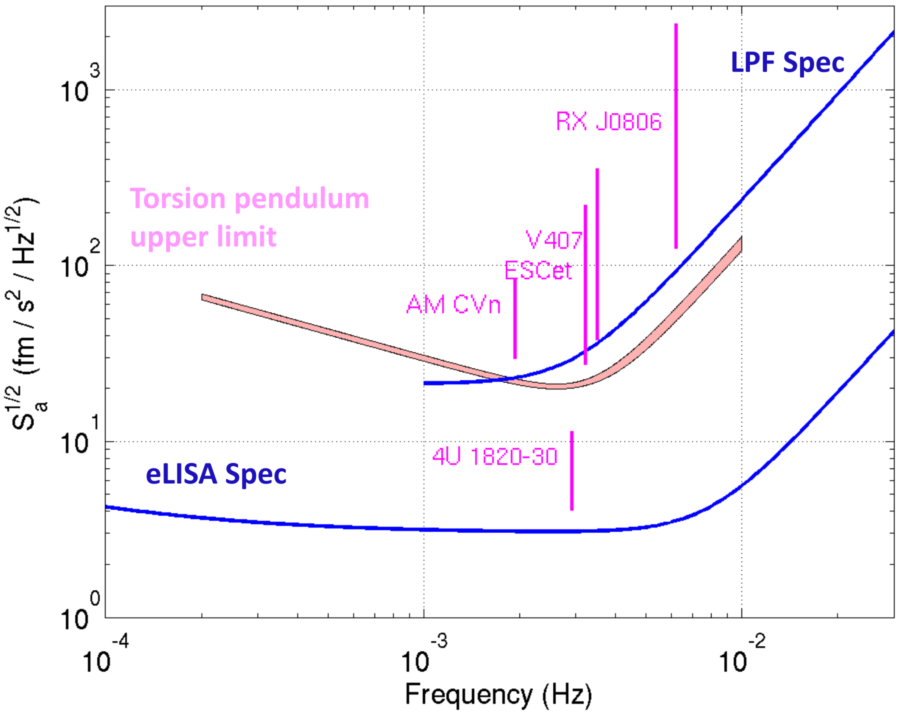


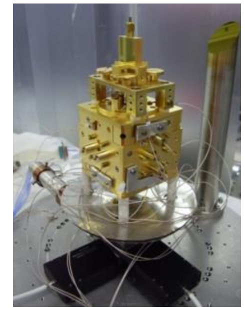


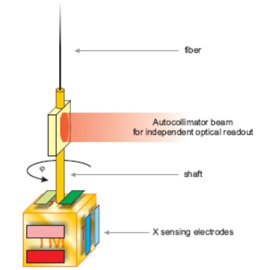
- Heavy TM, 2 kg Au-Pt
- 3-4 mm gaps
- no contacts (no discharge wire)
- AC-carrier force actuation
- Vent to space (< 10 μPa)

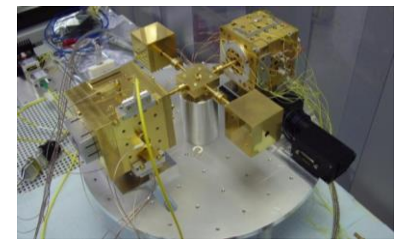
- tough caging
- UV discharge
- **need IFO**

LPF small force test: pre-launch data







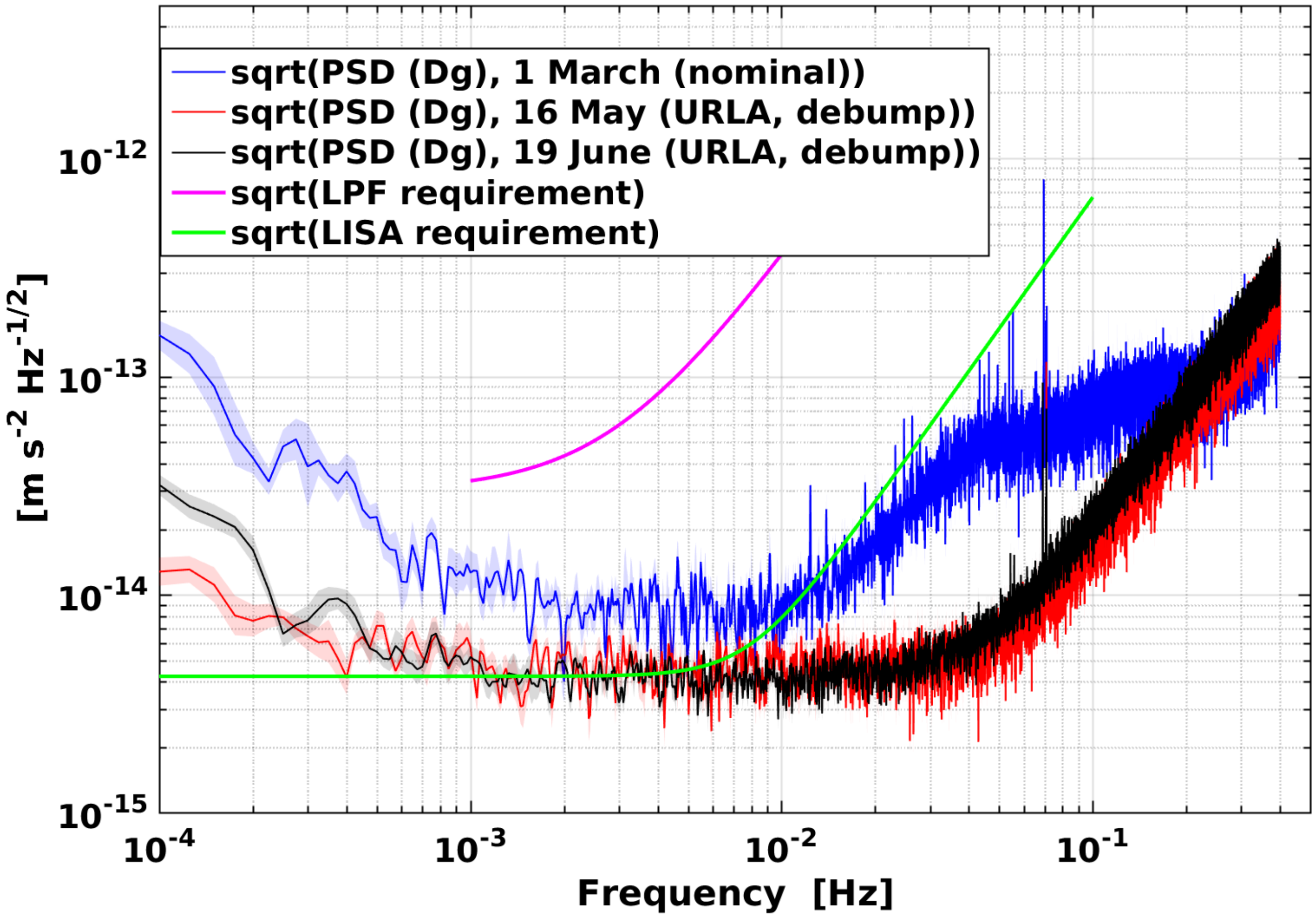


Torsion pendulum ground testing

- Surface forces: factor 2 of LPF goal at 1 mHz
- Individual noise sources even better

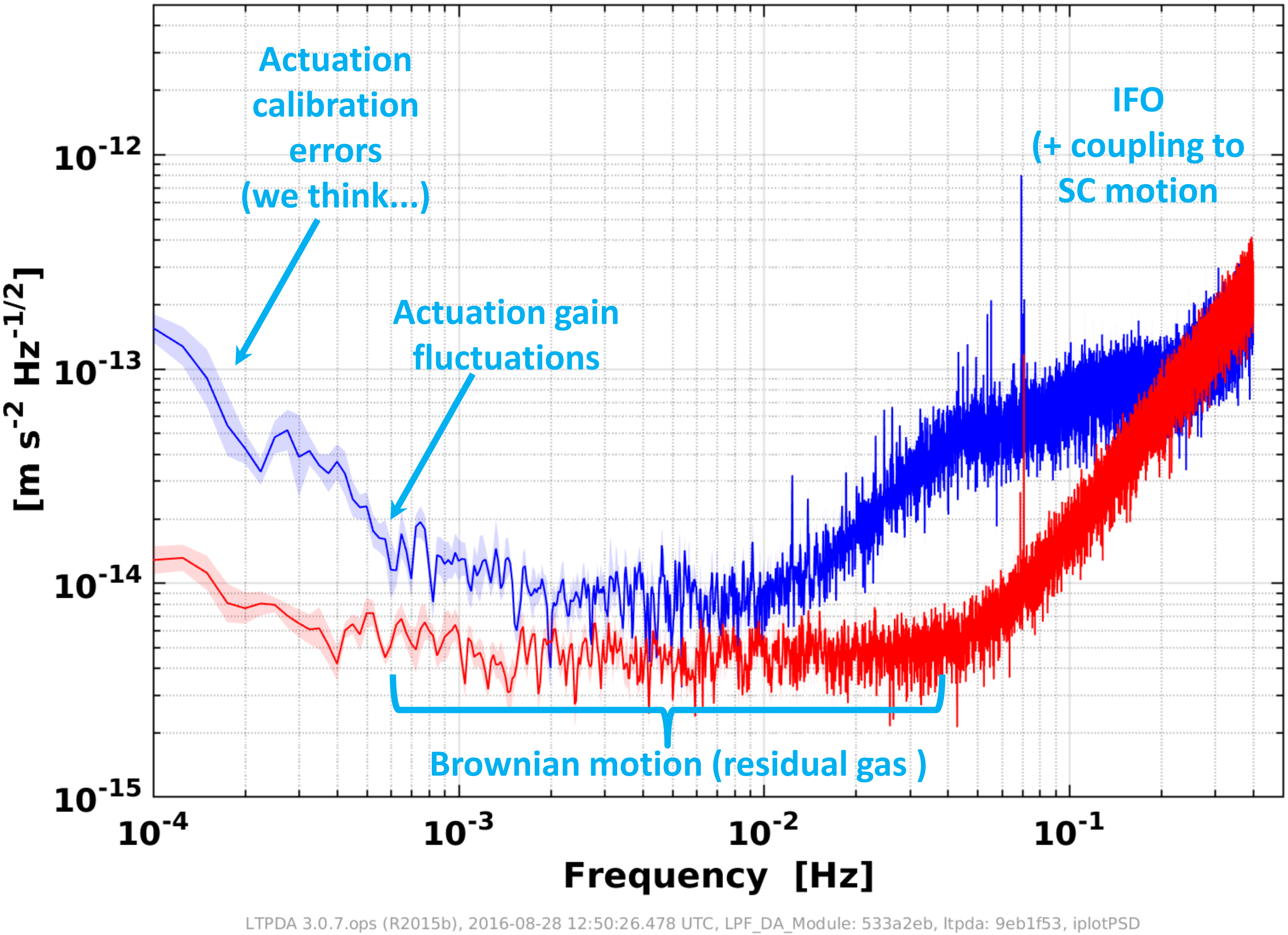
- Not sensitive to all forces
- No 6+ DOF control
- Not final environment
- Not end-to-end

LPF differential acceleration (Δg) noise floor

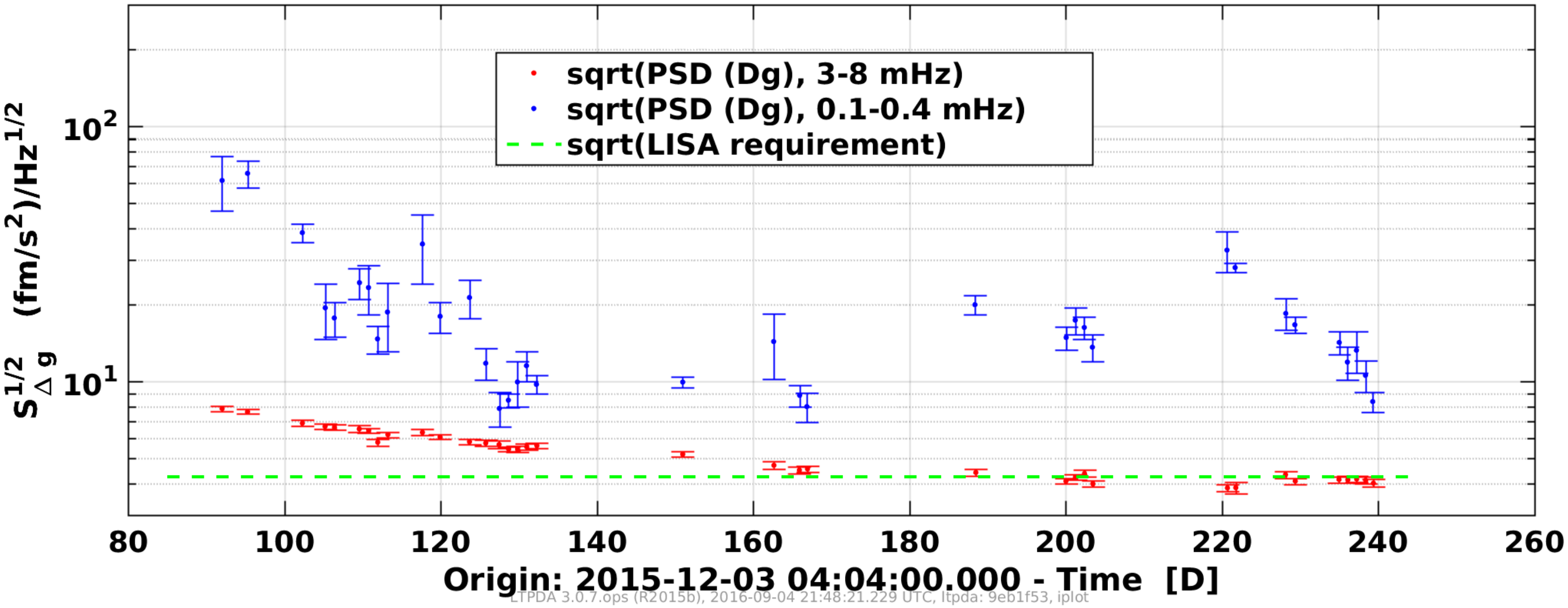


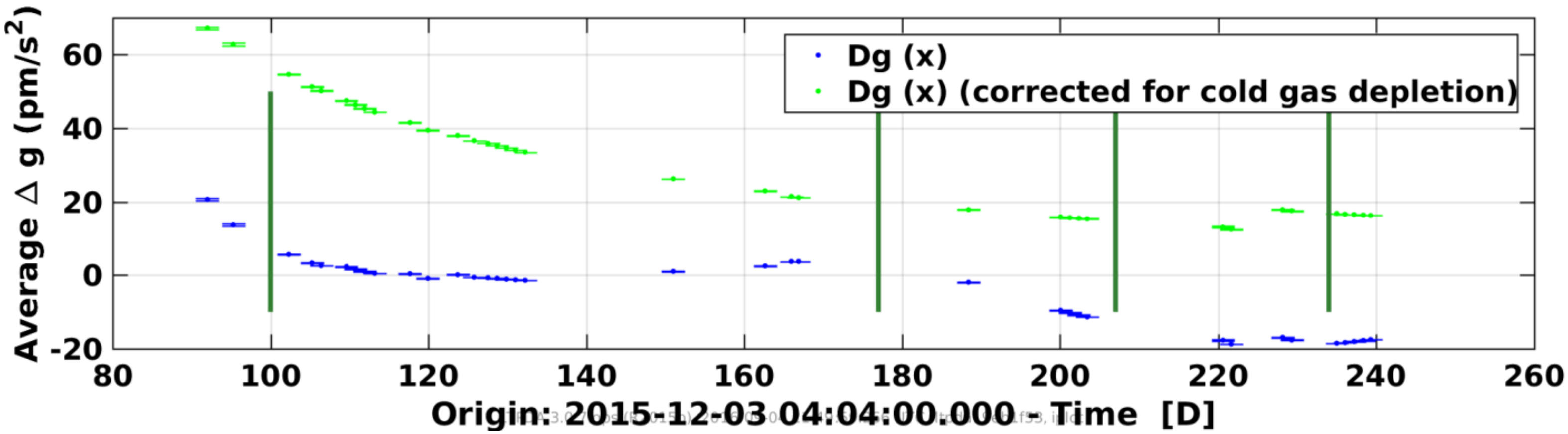
- Noise non-stationary ... improving!
- How much do we understand? Can we reproduce?
- Things could get worse

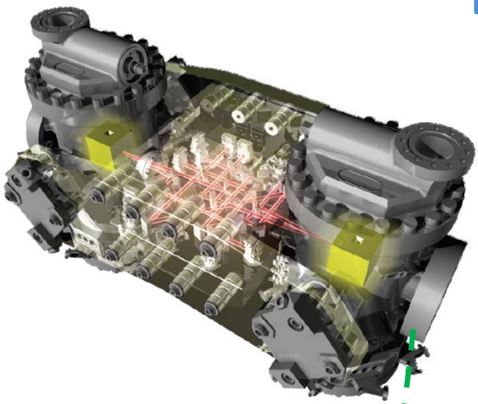
LPF differential acceleration (Δg) noise floor



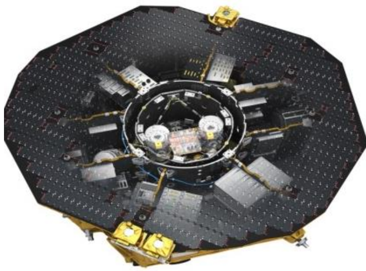
Evolution of noise and «quasi-DC» Δg







LPF Noise: gravitational balance and actuation gain fluctuations



«accelerometer dynamic range» problem

Noise in "DC" force applied to compensate local Δg

$$F \propto V_{ACT}^{2} \quad \rightarrow \quad S_a^{1/2} \approx 2\,\Delta g\, S_{\delta V/V}^{1/2}$$

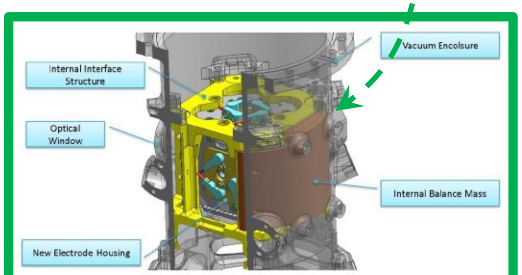


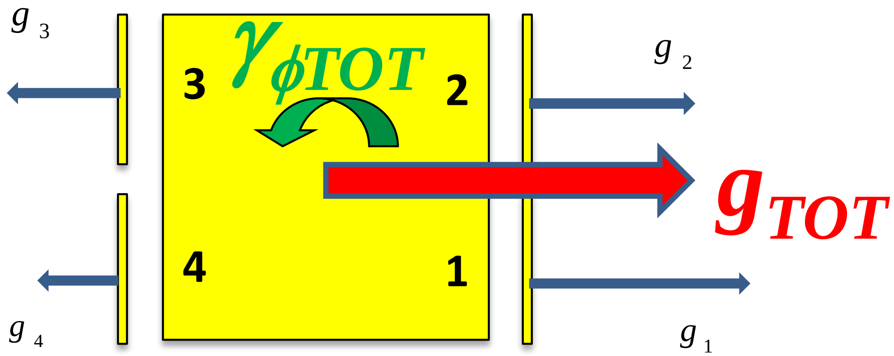
Figure 10.1- IBM inside the VE

- FEE actuators:
  Measured stability 3-8 ppm/$Hz^{1/2}$
- **LPF designed for Δg 650 pm/s^2**
  - **Budget: 10 fm/s^2/$Hz^{1/2}$ at 1 mHz**
- **LPF in-flight Δg < 50 pm/s^2**

→ Excellent gravitational balancing

See: talk Trenkel and poster Ferroni

Acceleration noise from actuation gain fluctuations



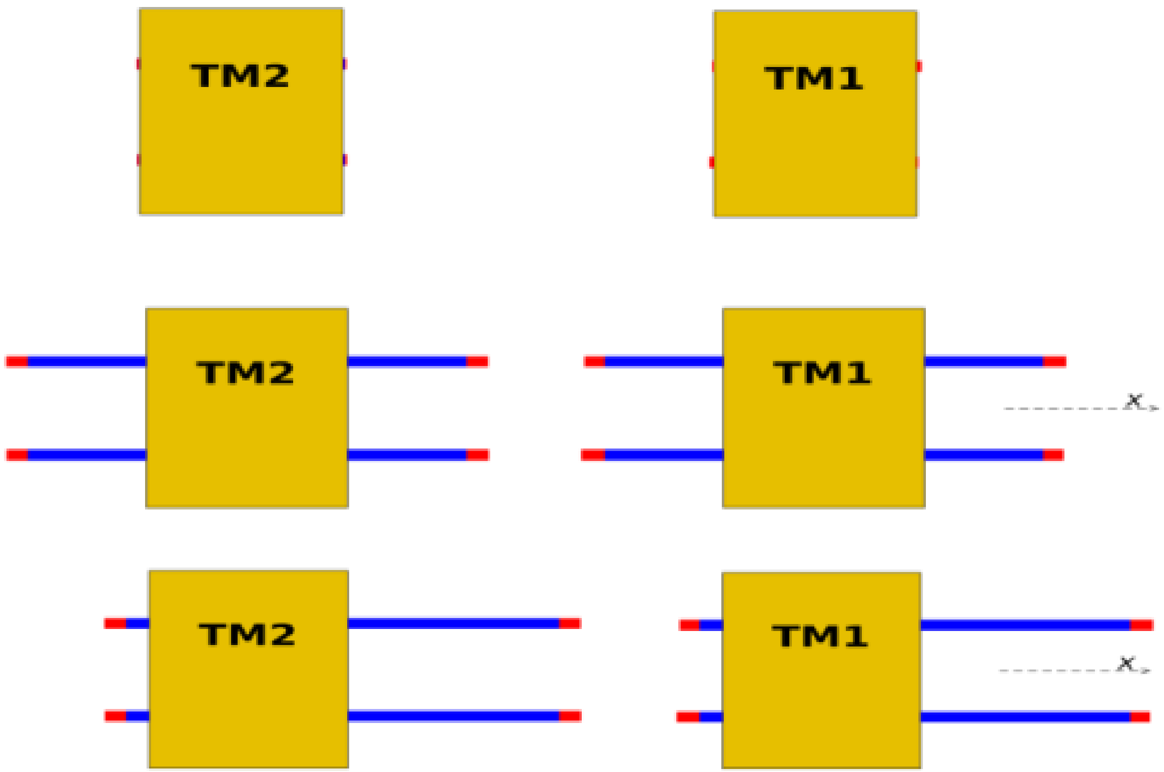
- Same electrodes used to apply both force and torque
- Constant stiffness → pull on both sides of TM
- (mostly) uncorrelated fluctuations between electrodes

Gain fluctuations in 4 electrode actuators

$$\delta g = 2\left(g_1\alpha_1 + g_2\alpha_2 + g_3\alpha_3 + g_4\alpha_4\right)$$

Modeling, measuring and projecting actuation gain noise

Apply large actuation forces (without crashing TM into SC) to accentuate effect of actuation noise in Δg measurement



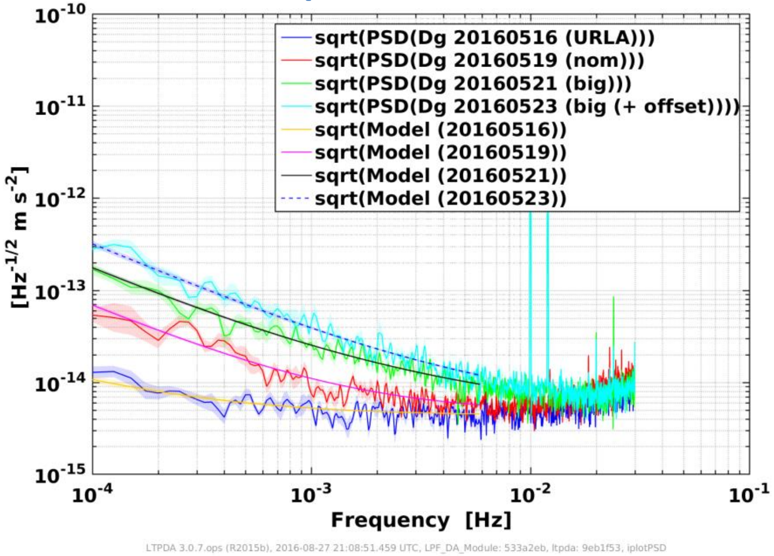
Standard «URLA» 50 pN authority (10 pN net force TM2)

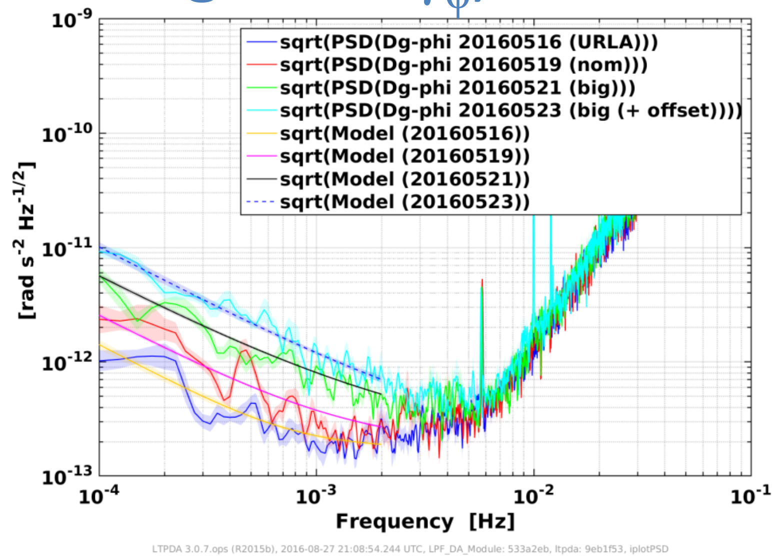
Big (5 nN) force authority

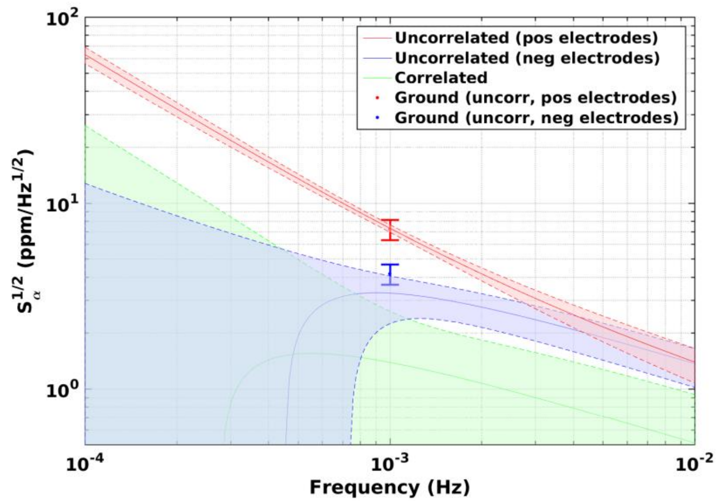
Big (4 nN) common mode force

Blue bars: electrode force vectors for force
Red bars: electrode force vectors for torque

Actuation measurement campaign: results (fit of model to both noise in Δg and $\Delta\gamma_\phi$)





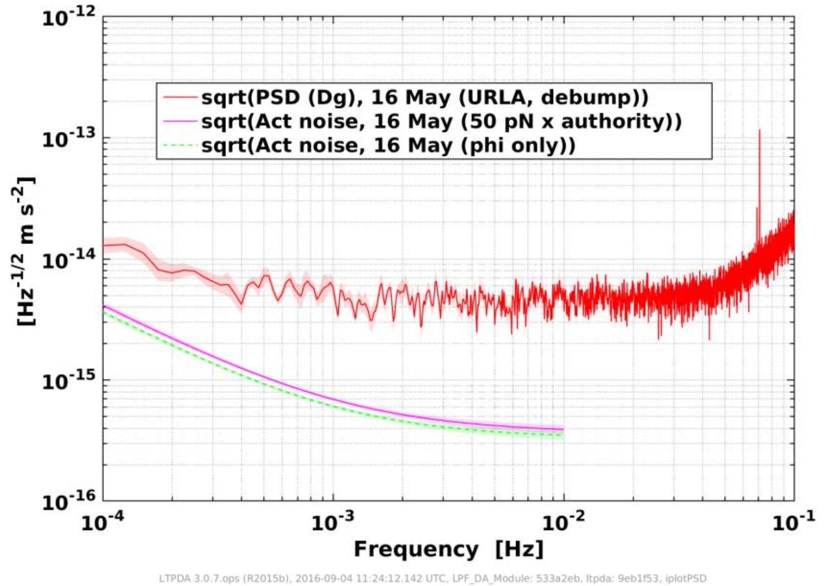


- Detect actuation gain noise
- Dominated by uncorrelated gain fluctuations

- Agreement with ground testing

→ **Noisier amps (positive forces) on ground are noisier in space!!!**

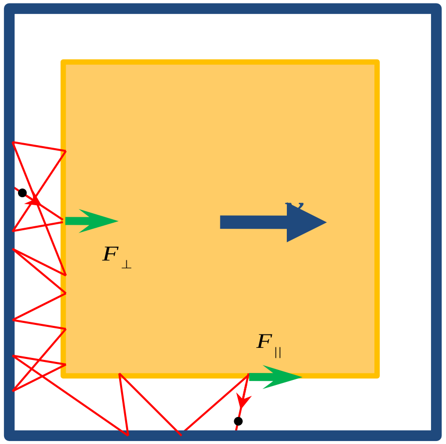
Actuation gain fluctuations: projection to noise in Δg

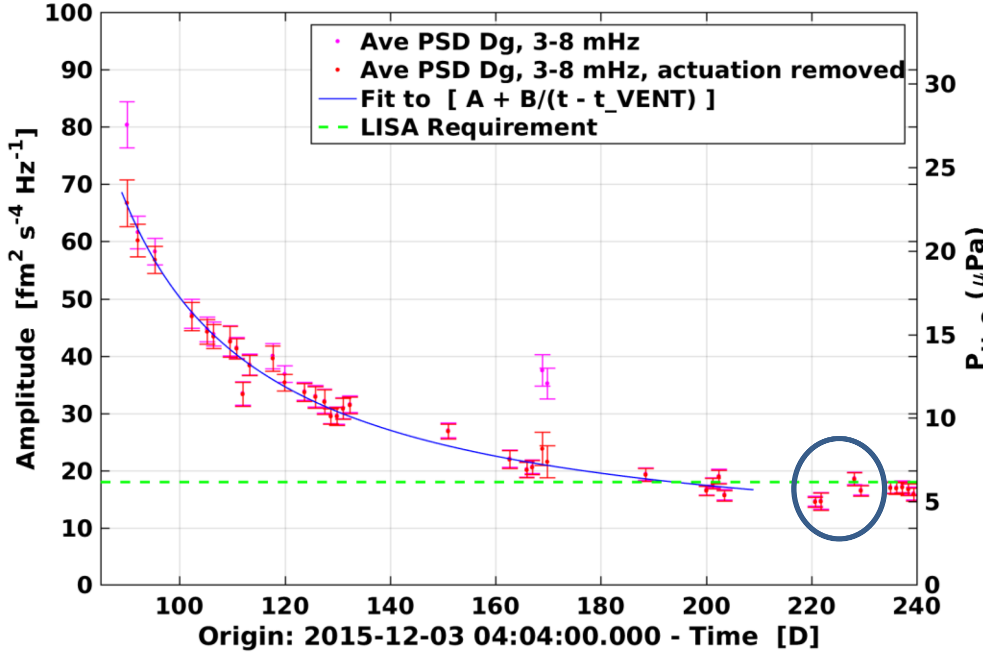


- Actuation gain noise not dominant in lowest actuation authority (URLA)
  - Typically 4 fm/s^2/Hz$^{1/2}$ at 0.1 mHz
  - Dominated by uncorrelated fluctuations and applied ϕ torques
- Agreement with ground model
  - FEE actuation noise as expected
  - LPF low noise → thanks to LPF gravitational balancing

See: talk Ferraioli (FEE performance), poster Mance (FEE for LISA)

White noise 3-8 mHz: Brownian motion from residual gas





Evidence for Brownian noise:

- 1/t-t0 fit with t0 = 3 Feb 2016 (venting day)
- roughly compatible with radiometric pressure
- Increases with temperature

  → «event» around 225 days after launch (NASA thruster turn on)

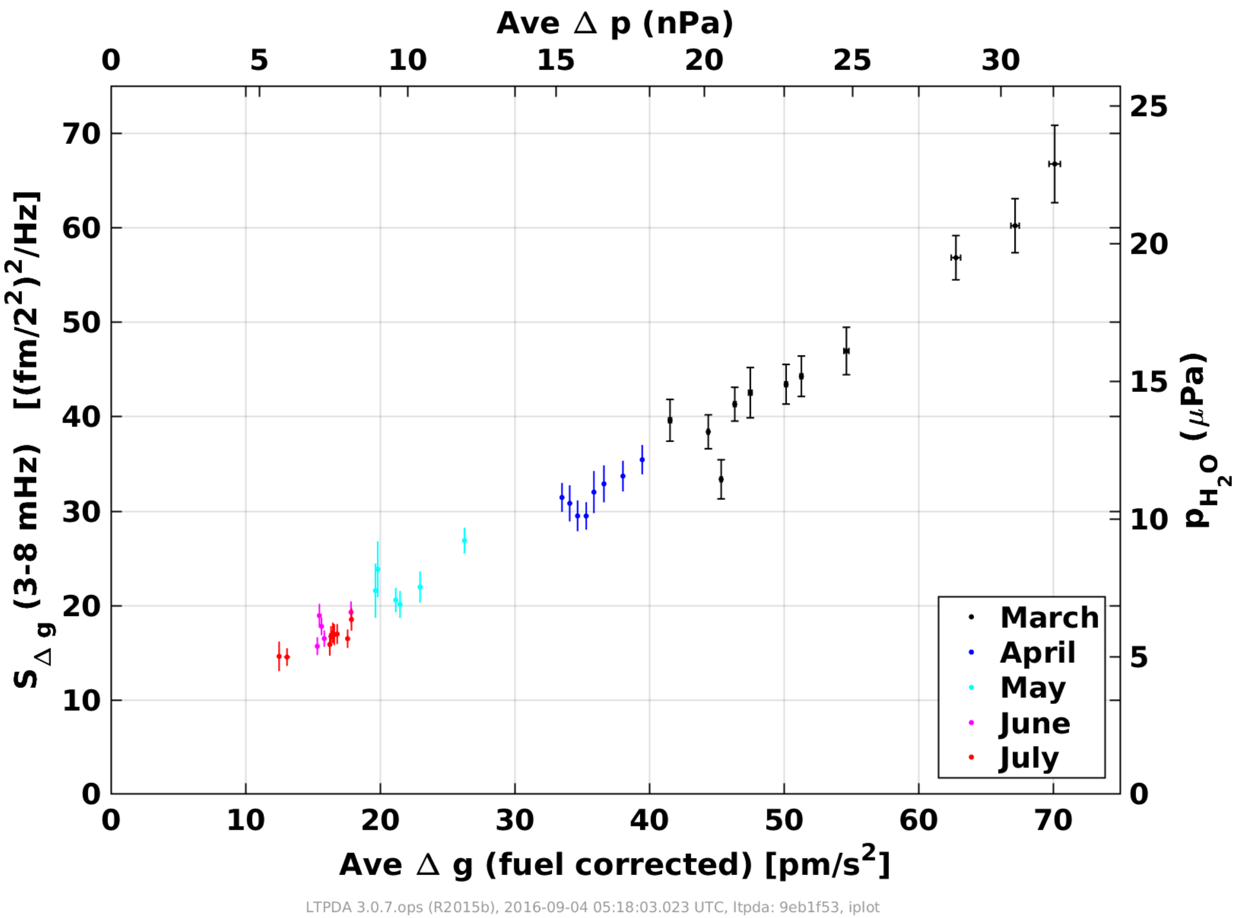
See talk: Rita Dolesi

- **Now below LISA spec ... will it continue to decrease?**

  → Fit «saturates» at 2 fm/s^2/Hz$^{1/2}$ ...

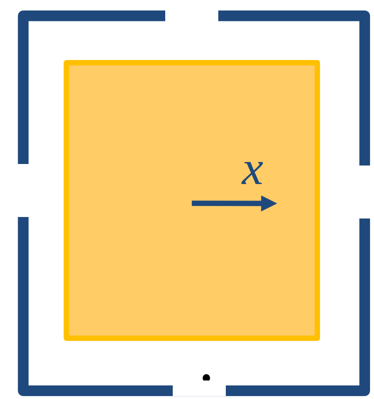
Correlation between Brownian noise and «quasi-DC» Δg

Δg → average Δp across TM



Possible link between quasi-DC force and Brownian pressure

- similar time, temperature response
- Implies 1 per 1000 imbalance in outgassing / conductance across TM



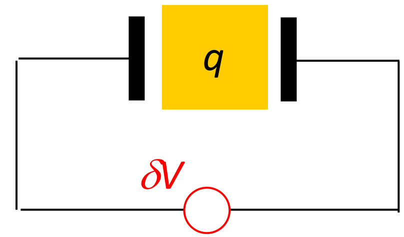
LPF noise budget: stray electrostatic forces

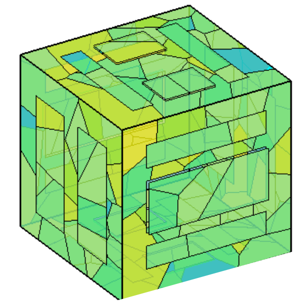
Interaction between TM charge and stray electrostatic fields

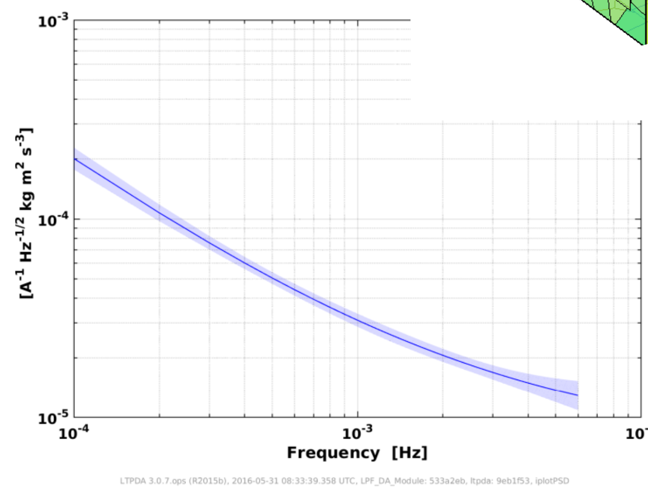
- **Measured DC stray fields**
  - → dF/dq with UV charge burst
  - → Order 10's mV (as on ground)
  - → Compensated with applied voltages

- **Measured stray field fluctuations**
  - → noise with charged TM
  - → Similar to ground upper limits

- **Measured TM charge fluctuations**
  - → noise with large DC E field
  - → Dedicated long term charge measurement

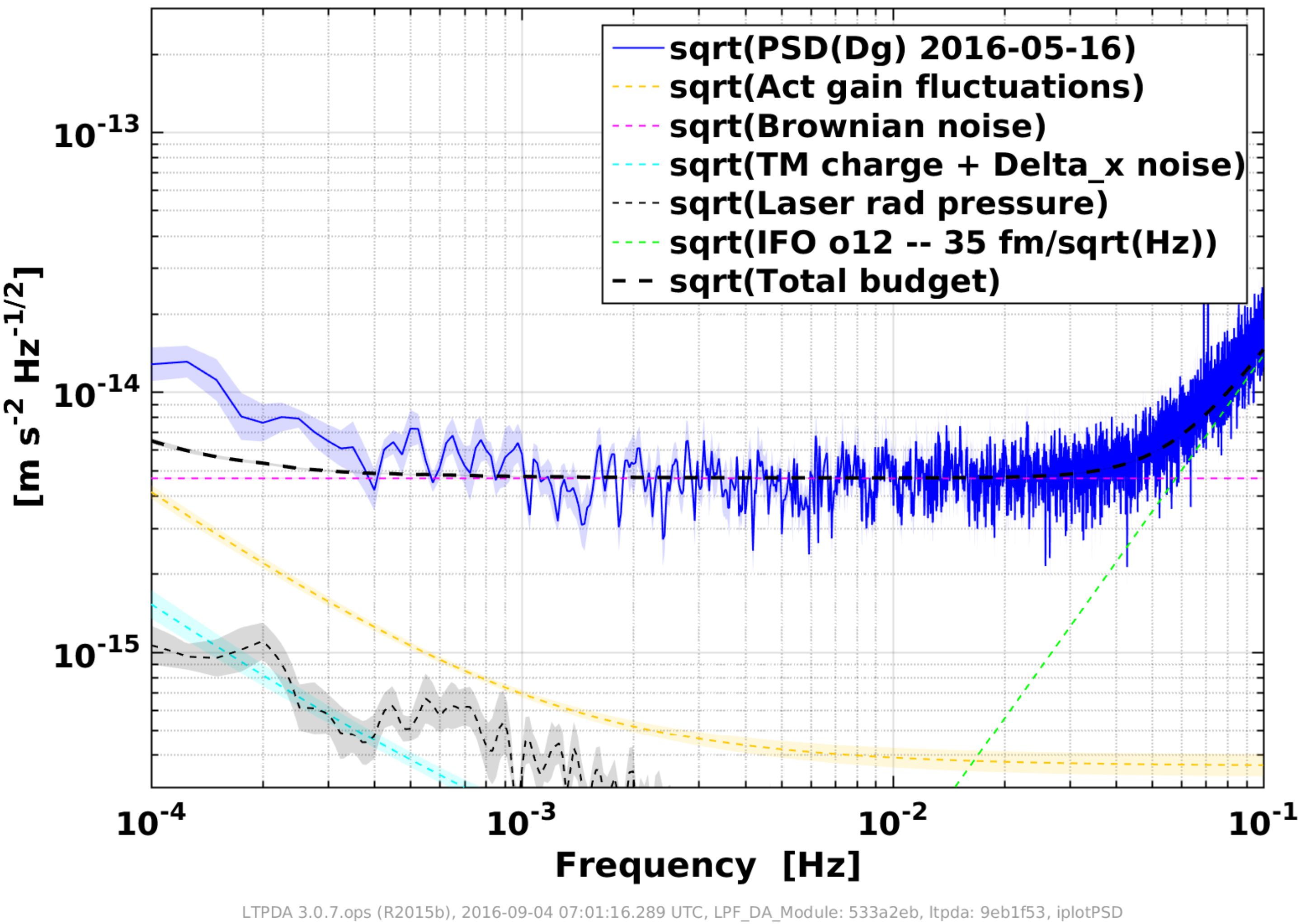






See talk Peter Wass

LPF noise budget: «explained» noise, 16 May 2016



NB: Charge noise interaction with DC bias off the chart small (compensation)

LPF noise budget: what's missing here

- Noise budget curve only shows consolidated sources
- Avoid overestimating «known» noise where we have (only) upper limits

- **Magnetic noise**

Measured susceptibility, B noise
Working on DC gradients

Talk Miquel Nofrarias

- **Thermal gradient noise**

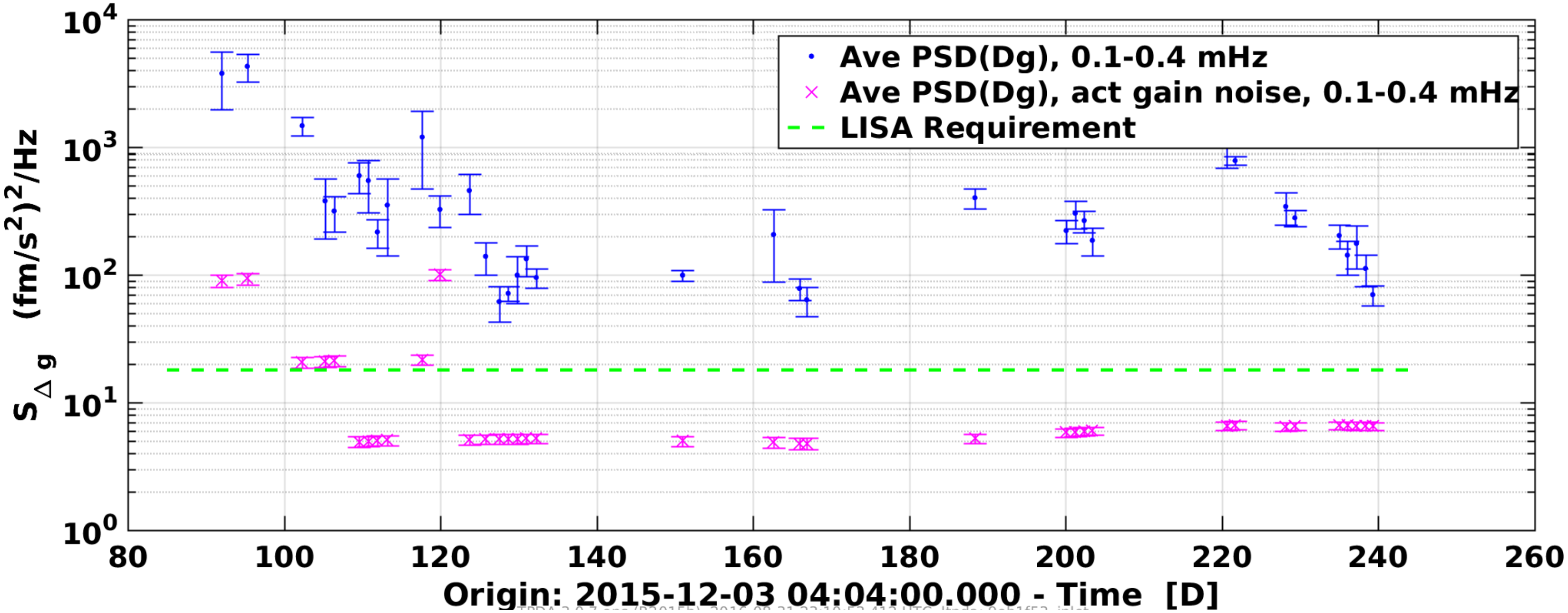
Measured $dF/d\Delta T$
Working on noise in ΔT

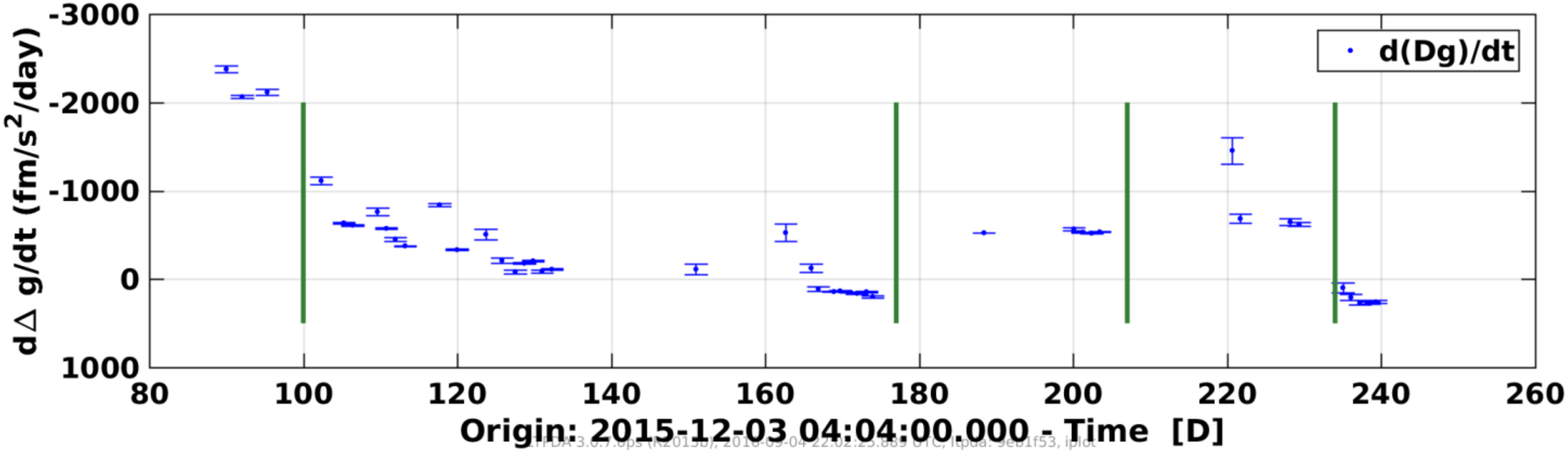
Talk Rita Dolesi,
poster Ferran Gibert

- **Crosstalk**

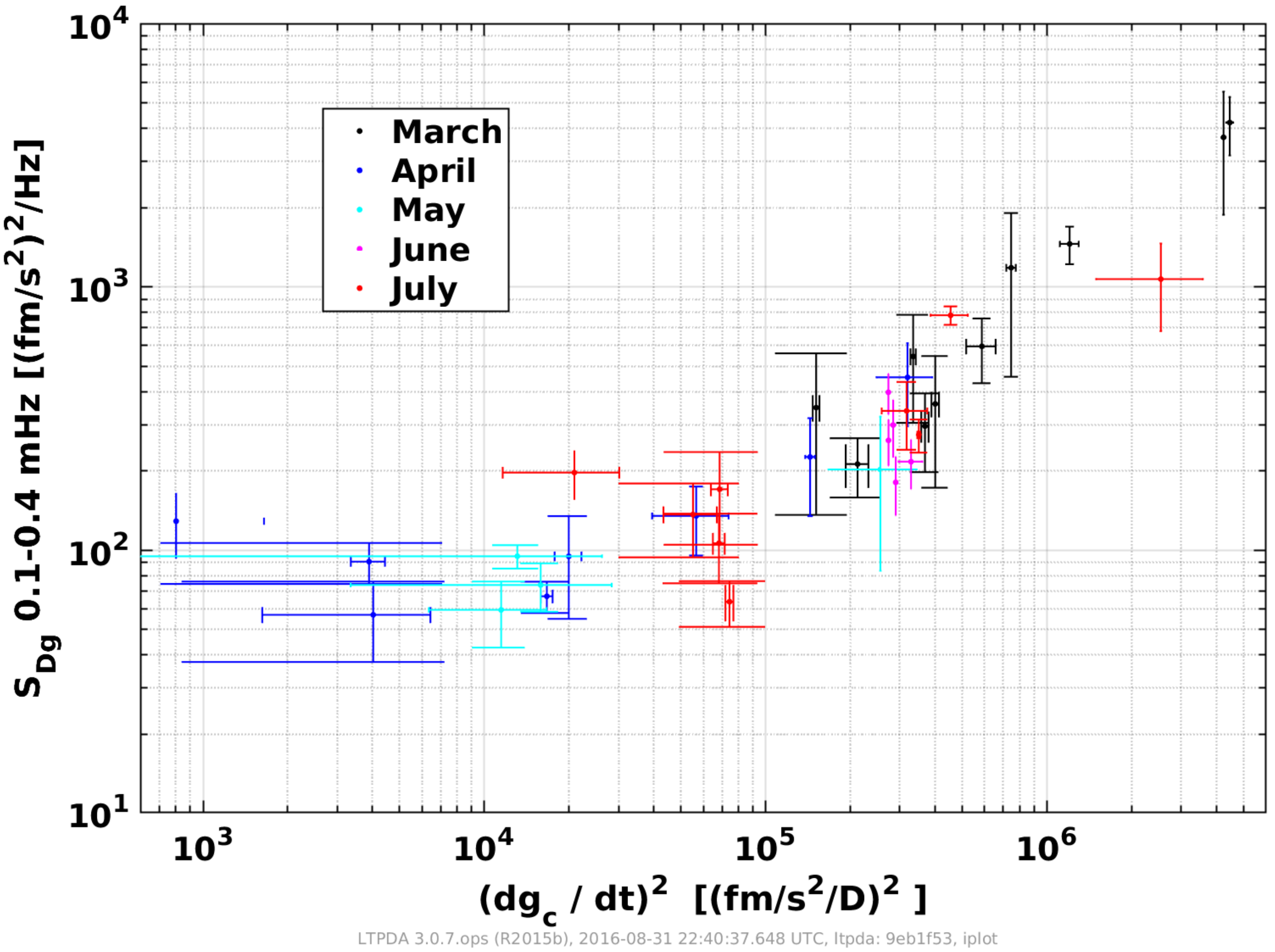
IFO (debump) + cross-stiffness
Actuation to be revisited

Evolution of low frequency noise and slope dΔg/dt





Observed correlation between dΔg/dt and low frequency noise



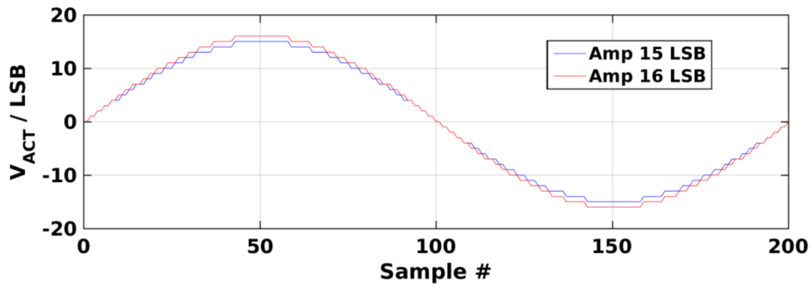
NB: noise from actuation gain fluctuations removed

LPF low frequency noise and drifting Δg: actuation?

- Observed correlation between $d\Delta g/dt$ and $S_{\Delta g}$ at low frequencies
- Need to accurately subtract changing actuation force:

$$\delta(\Delta g) = \frac{1}{M}\left(F_{x2}^{CMD} - F_{x2}^{ACT}\right)$$

- Actuation «LSB» – 153 μV in Volts → roughly 10 fm/s^2 in Δg
- Typical (big) drifts: 500 fm/s^2 / day → 1-2 bits / hour
  - Accurate digitization «smoothed» by high-f Σ–Δ dither (force CMD)
  - inaccurate digitization – even if stable – gives low frequency force noise



- Peak output changes by 1 LSB
- Analog output amplitude changes by 0.85 – 1.15 LSB
- FPGA «double digitization»

LPF low frequency noise and drifting Δg: actuation?

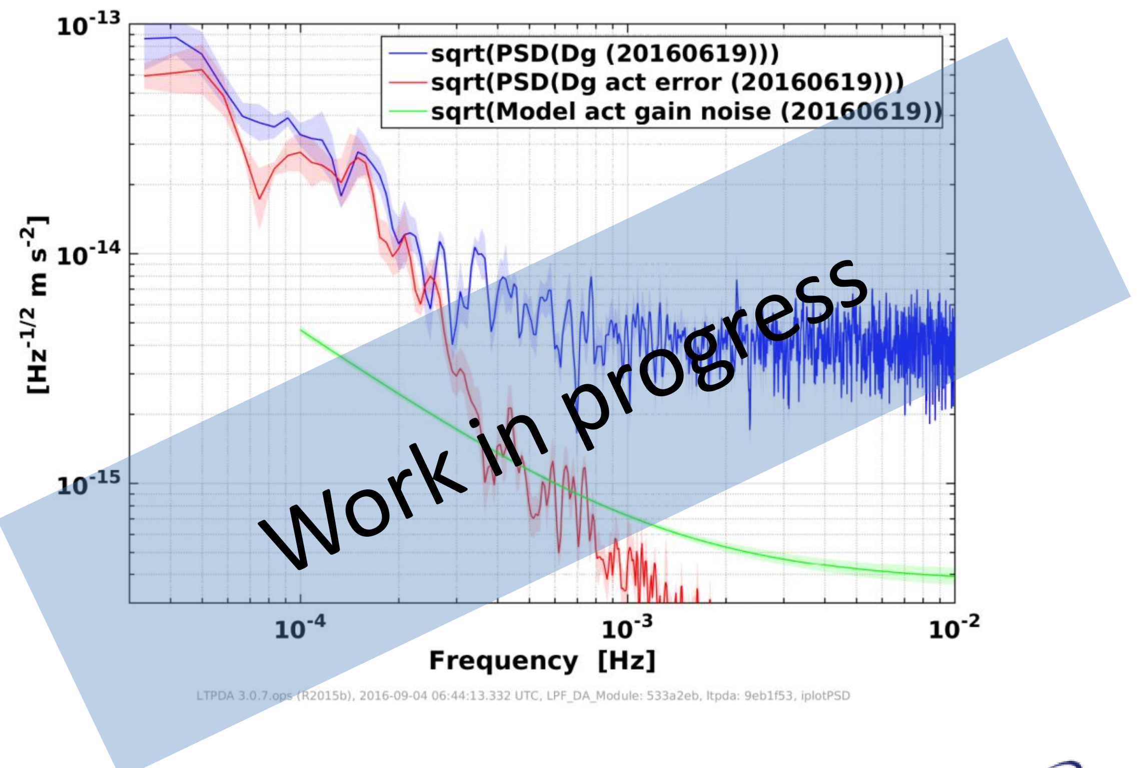
- 1 LSB change in peak amplitude produces 0.85-1.15 LSB change in effective amplitude (typical 10 μV errors)
- Observed in lab (prototype FEE) and by simplified analysis

- **Could explain our low frequency noise increase with drift**

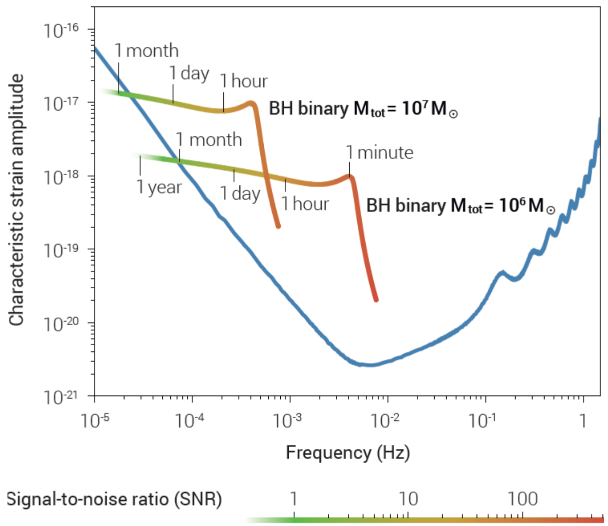
One possible actuation scheme

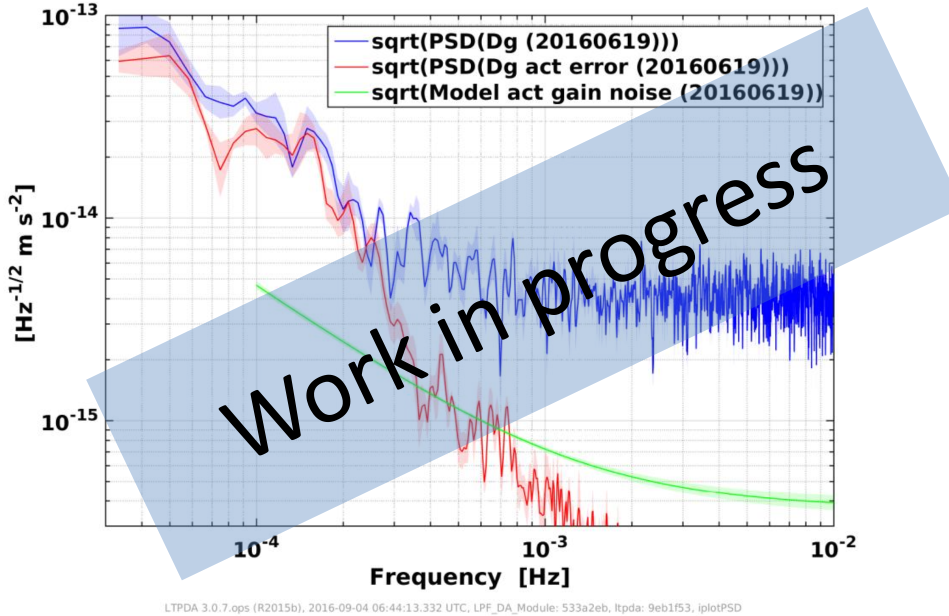
Need to find true code:

$$V_x^{CMD} \rightarrow V_x^{ACT}$$



Low frequency noise (10-100 μHz)
Very interesting for LISA (last year of mergers)



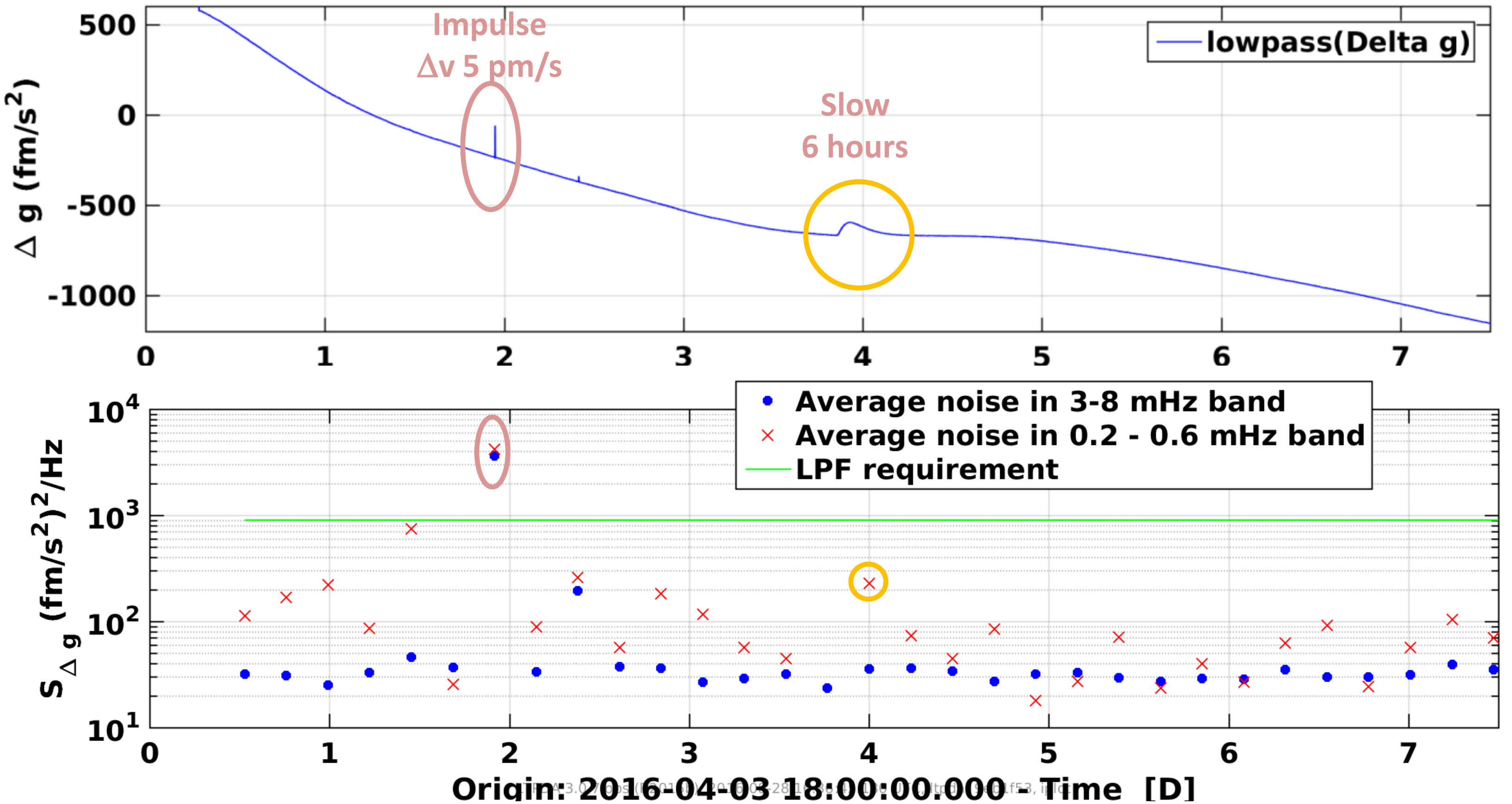


Studying this with LPF requires:

Subtraction accuracy

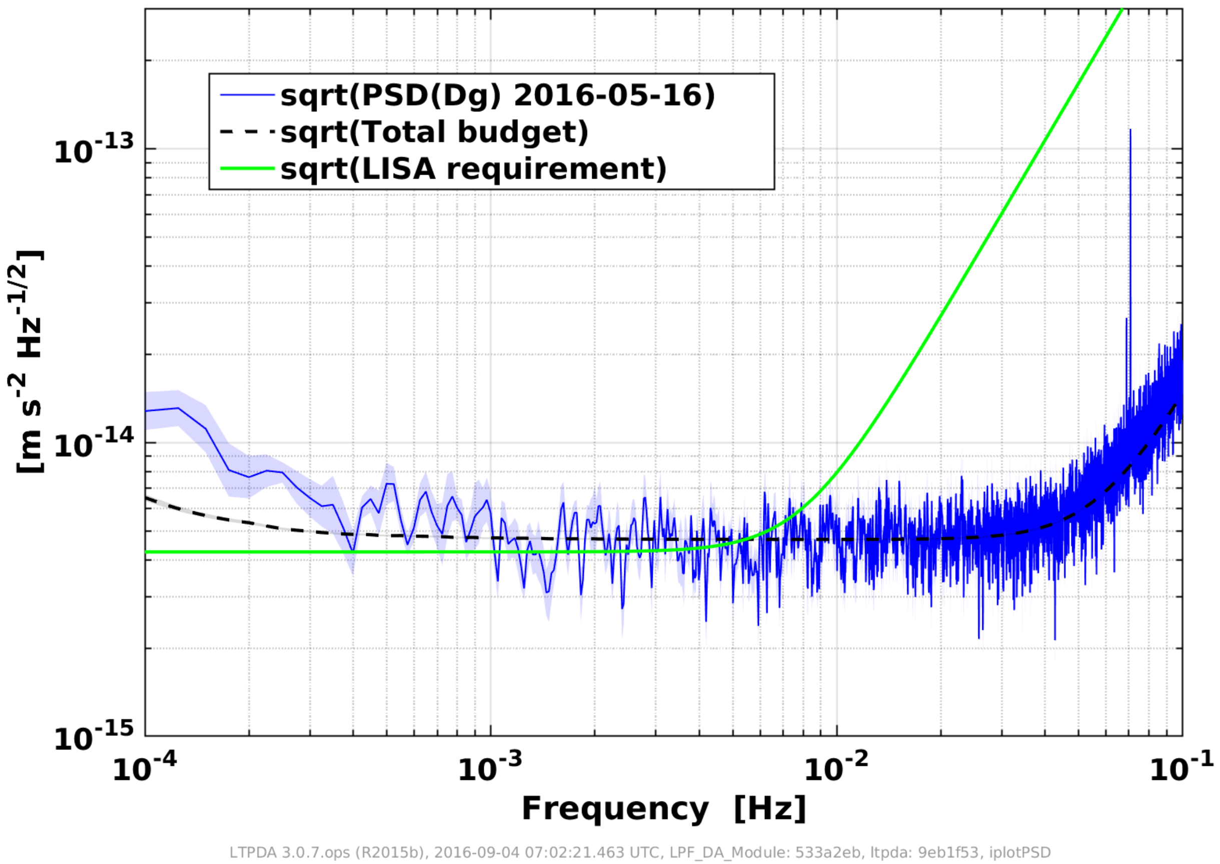
- Centrifugal
- Actuation (digitization)
- Charge and thermal
- Other?

LPF challenges: glitches



- Roughly 1-2 dozen unexplained events in Δg in 2 month noise dataset
- Most fast (minutes), a few long (hours)
- Under investigation ... for observatory, want to discriminate!

Physical model of the LISA Pathfinder differential acceleration measurement

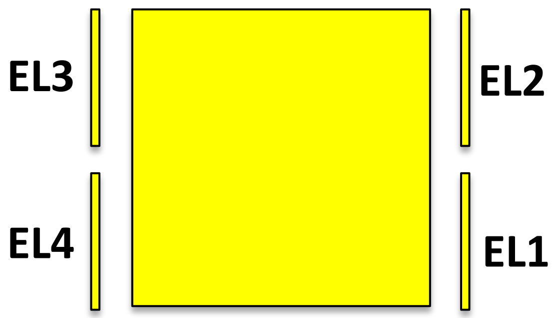


- Meeting LISA goal down to 1 mHz
- Most of noise in most of LISA bandwidth understood
- Low frequency tail (and time evolution) under study

Extra

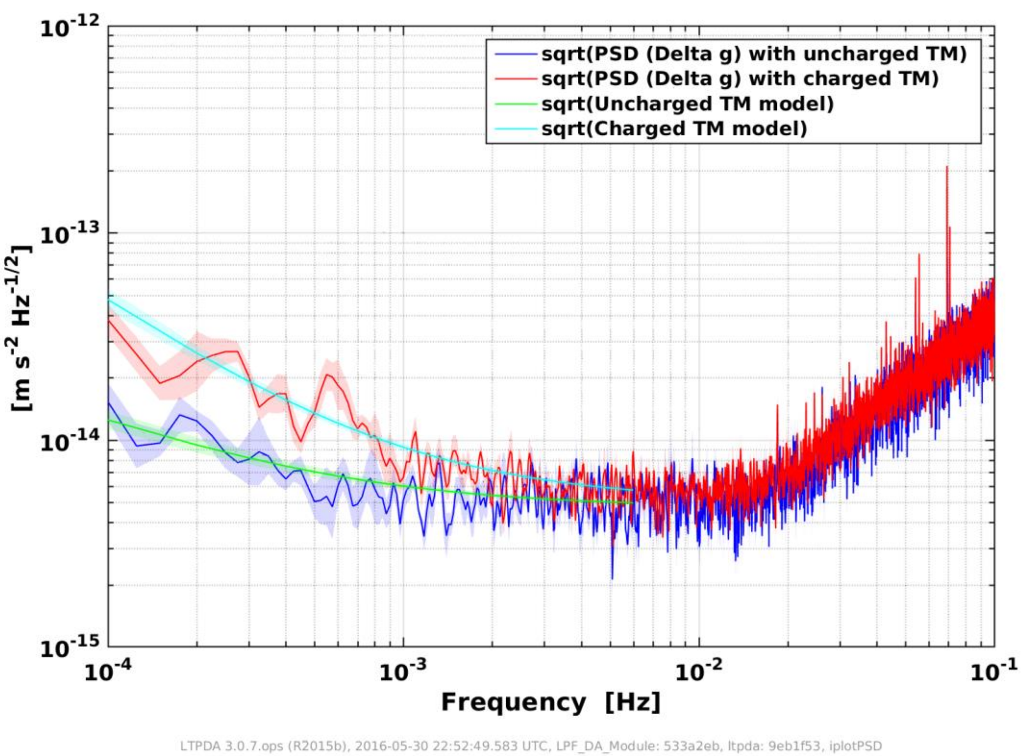
(section 4D)

Actuation contribution to noise in Δ_x
Measurements with charged TM (1-4 May 2016)



- Coupling of stray fields (Δ_x) to TM potential:

$$F_x = -\Delta_x \left| \frac{\partial C_x}{\partial x} \right| V_{TM}$$



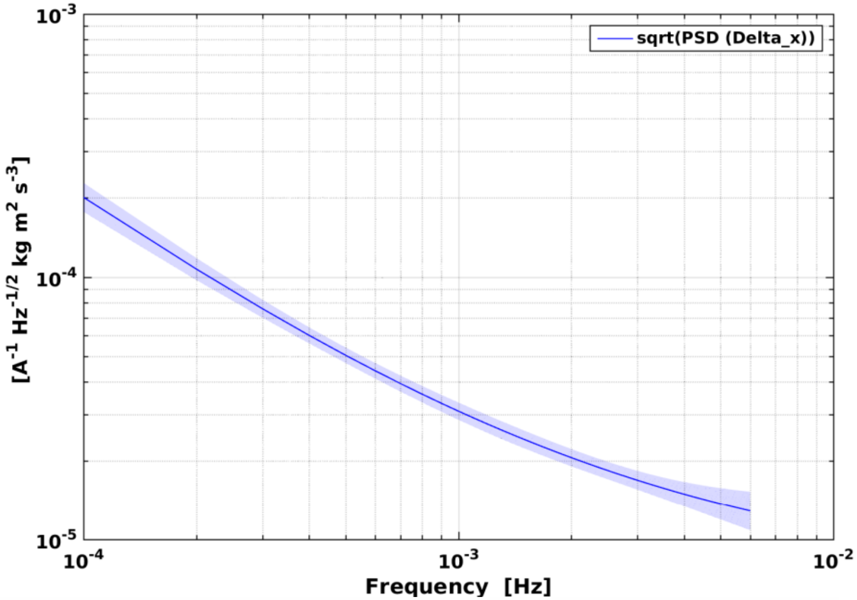
- Contribution of actuation voltages to Δ_x:

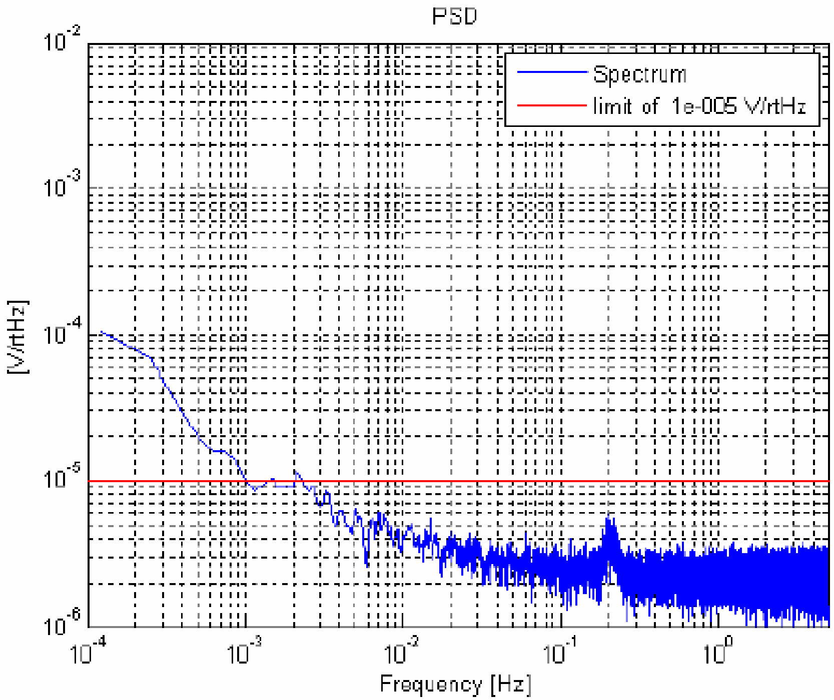
$$\Delta_x^{ACT} = V_{EL\,1} + V_{EL\,2} - V_{EL\,3} - V_{EL\,4}$$

- Noise in Δg as function of TM potential allows measurement of noise in Δ_x

Measured noise in Δ_x looks compatible with actuation noise from FEE

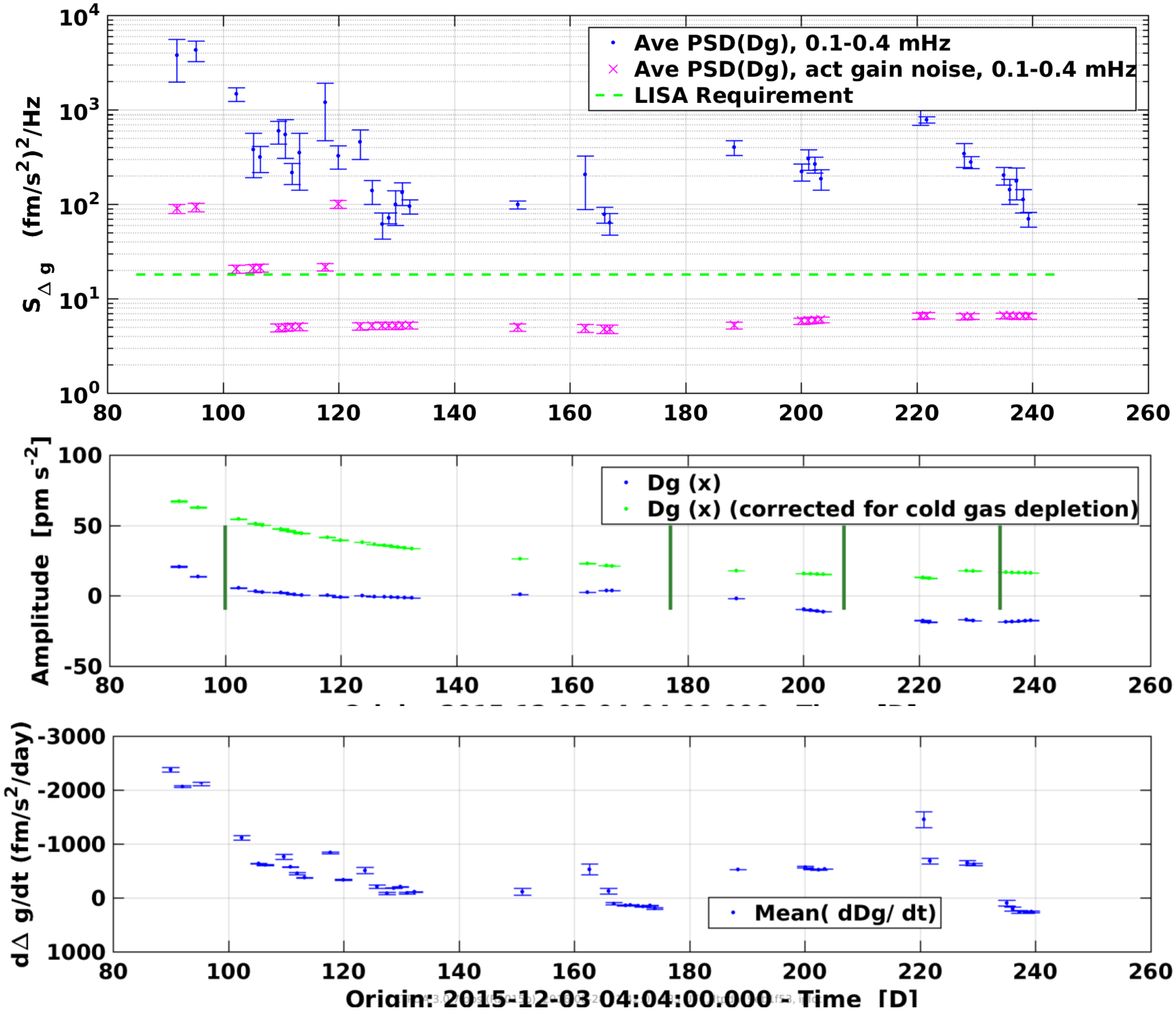
- NB 4 electrodes contribute, assumed here to sum incoherently
- Important for surface electrostatics fluctuations (compatible with zero)
- Reference is breadboard level testing, S2-HEV-RP-3042, page 43





Channel 1+

Evolution of low frequency noise and «quasi-DC» Δg



Weber – LISA Symp – 5 September 2016

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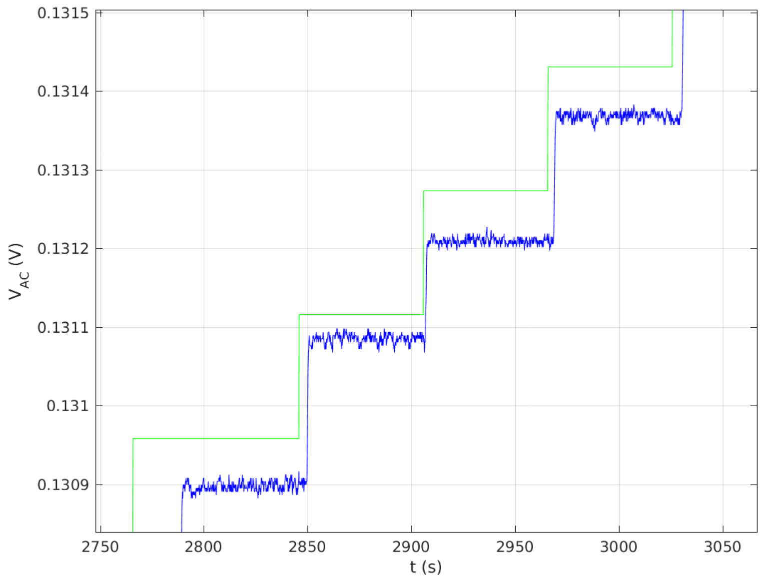
Actuation voltage inaccuracies: ELM-light test



Scanning 60 Hz VAC-x1 actuation command

- 50 μV step every 20 s

Green: 152.588 μV staircase

Blue: lock-in measurement of demodulated 60 Hz x VAC

Observation: not all LSB jumps are same size (120-180 μV)

- Repeatable on same electrode
- **Repeatable also on other +X electrode**
  - → **big and small jumps occur for same voltage commands**
  - → **systematic digitization issue**

Is 10 μV RMS error to be expected? Actuation waveform generation

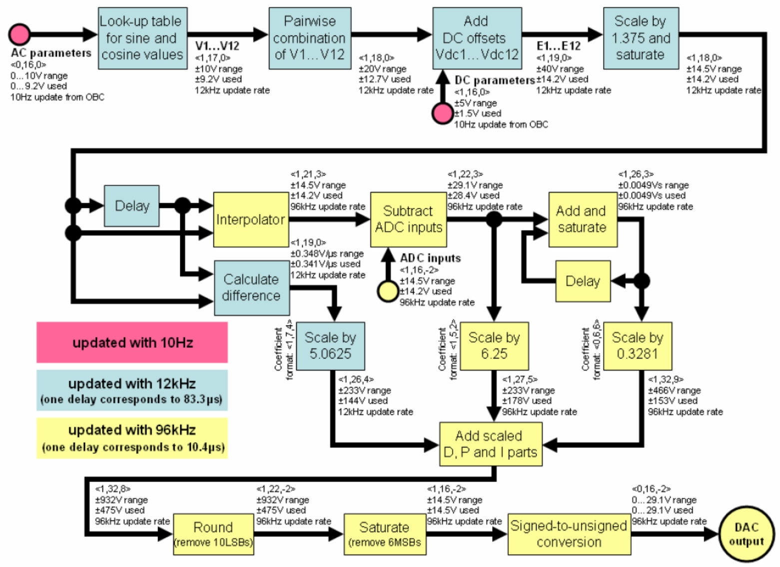


Figure 4-1: Actuation waveform calculation in the HR mode.

Actuation Waveform Generation
S2-CSA-TN-3020

First digitization steps:

1. 16-bit digitization (153 μV) of actuation peak amplitude (10 Hz)
2. Multiplication by 16-bit sine look-up table and truncation
   - 153 μV, 16-bit + sign
   - 12 kHz sampling (x waveform at 60 Hz, 200 pts / cycle)

What happens in first two steps?

3. Summing with ϕ waveform and DC voltages
4. Rescaling of bits to match feedback ADC
5. Interpolation to 96 kHz (adds 3 bits between 16 bit levels)

Simplified calculation for first two digitization steps

Digitize peak amplitude

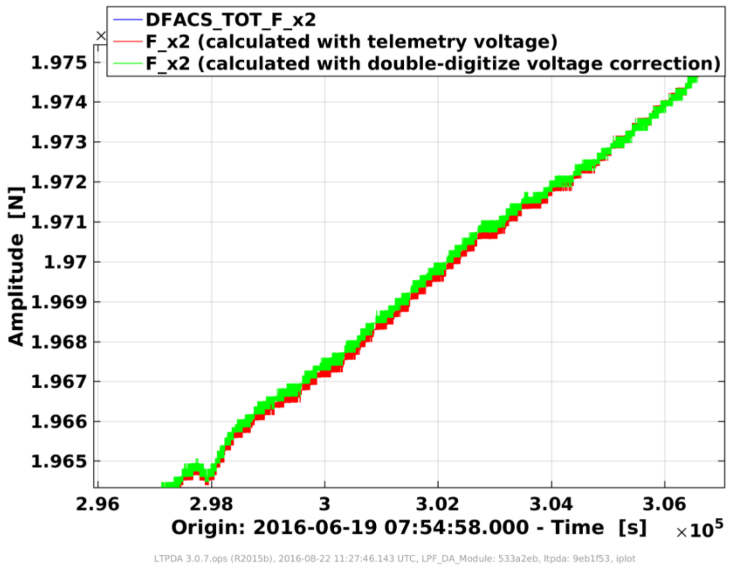
16-bit sine LUT

$$n_{LSBj} = ROUND\left(\frac{ROUND\left(\frac{V_x}{LSB}\right) \times ROUND\left(2^{16} \sin \omega_x t_j\right)}{2^{16}}\right)$$

Truncation to 153 μV LSB

NB: it does not do this: $n_{LSBj} \neq ROUND\left(\frac{V_x \sin \omega_x t_j}{LSB}\right)$

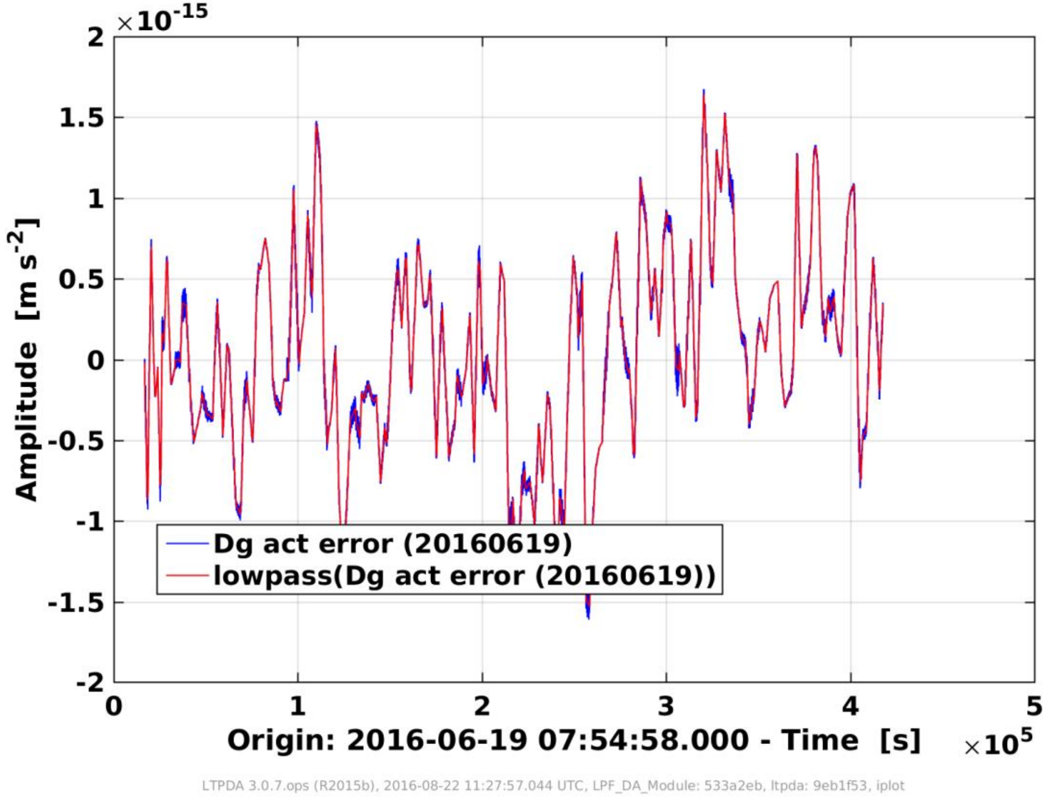
- Simple calculation implemented with matlab
  Input peak amplitude→ target waveform→ effective amplitude
  - Some uncertainty (use of «round» or «floor»)
  - Further stages (including interpolation) can change ***but not improve*** non-uniformity of effective force LSB



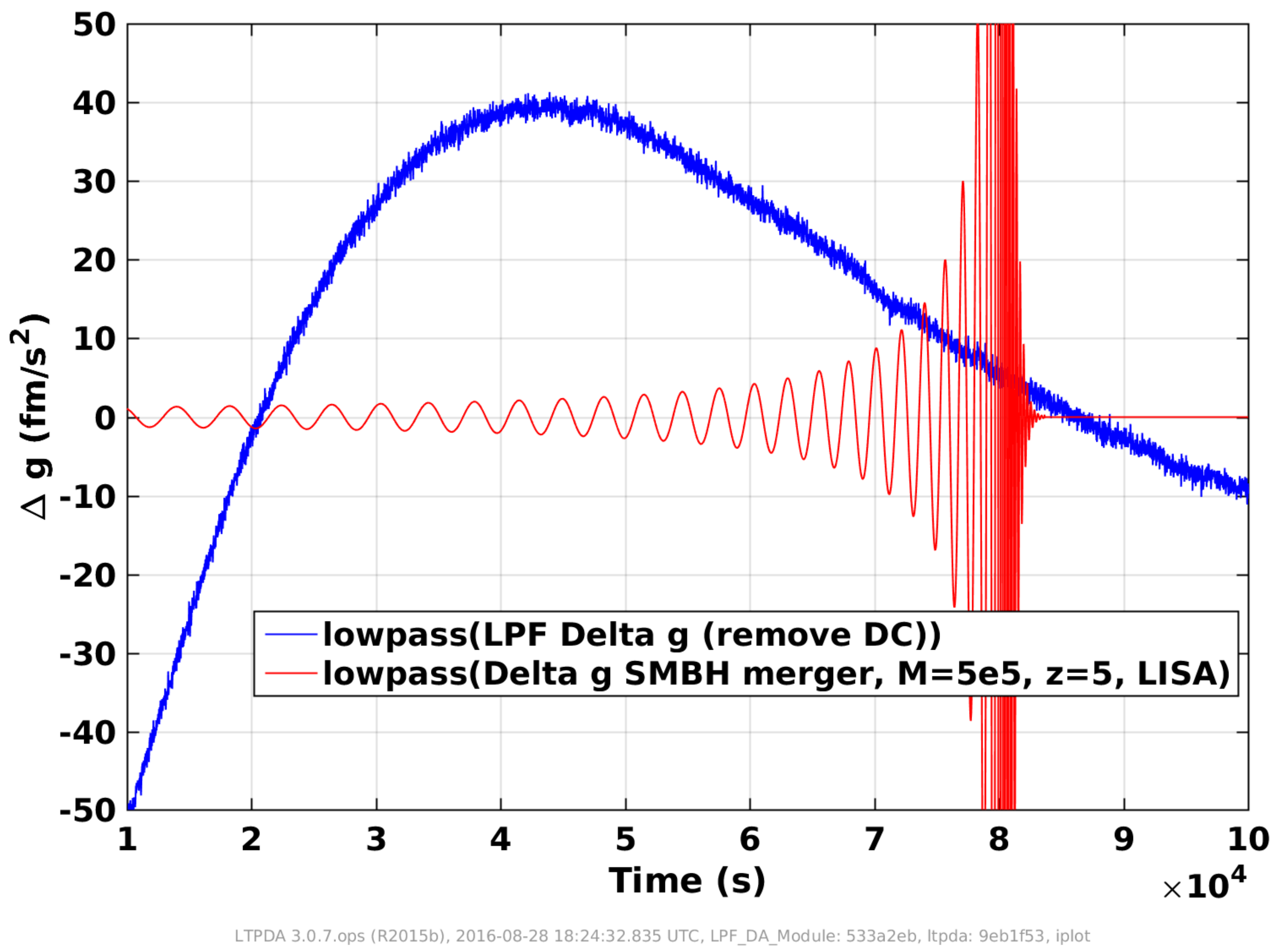
«Corrected» data, 19 June 2016

5 day measurement with roughly -0.5 pm/s^2/day

Visible error of order fm/s^2, changing as expected on 2000-5000 s time scales



Typical LPF Δg time series: comparison with SMBH merger



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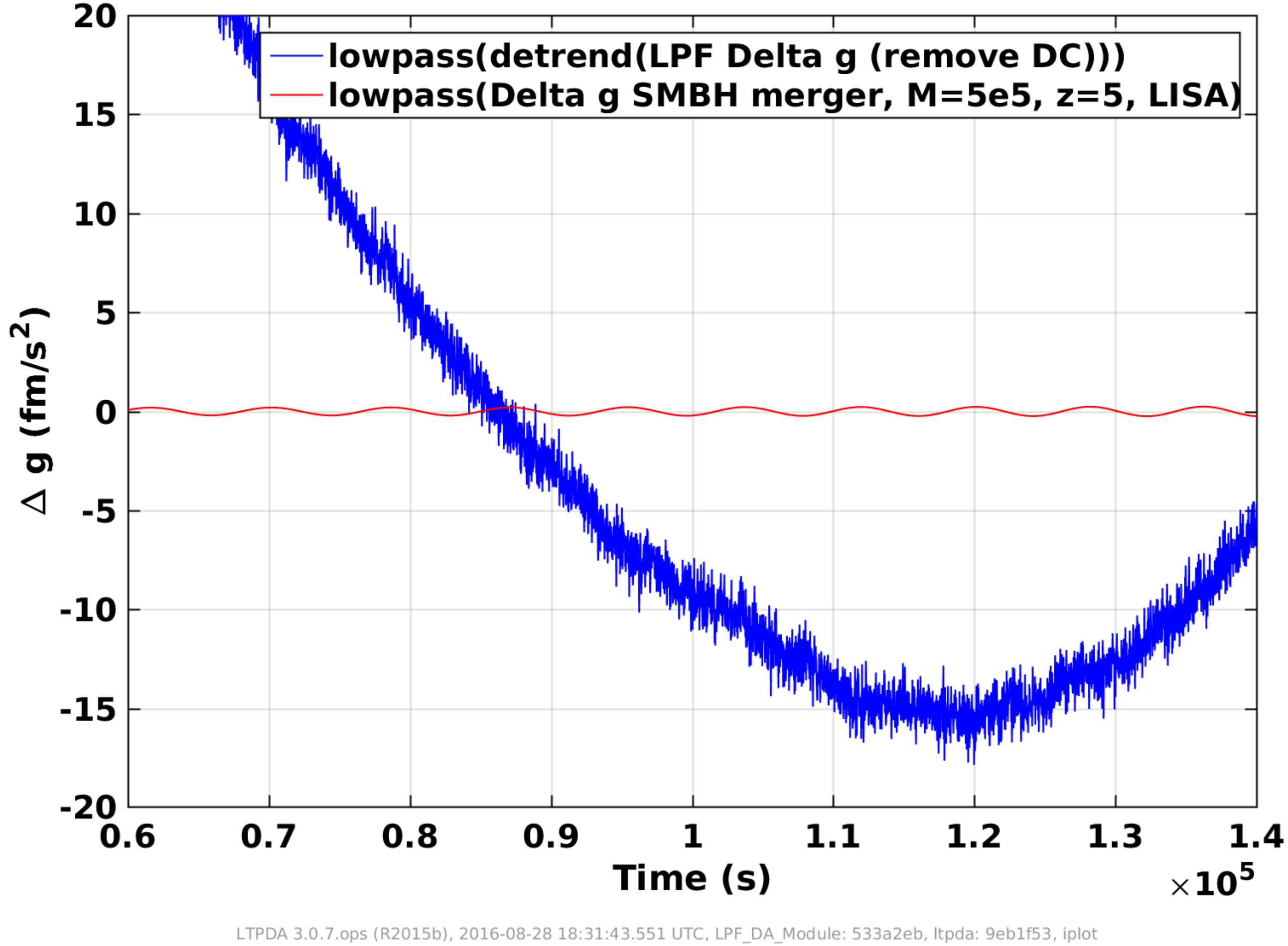

With LPF level of acceleration noise, can resolve every cycle «by eye» a week before merger

[Waveform thanks to Antoine Petiteau, APC]