LISA Pathfinder Free-Fall Mode

data analysis approaches for measuring sub-femto-g differential acceleration in presence of gaps in the data

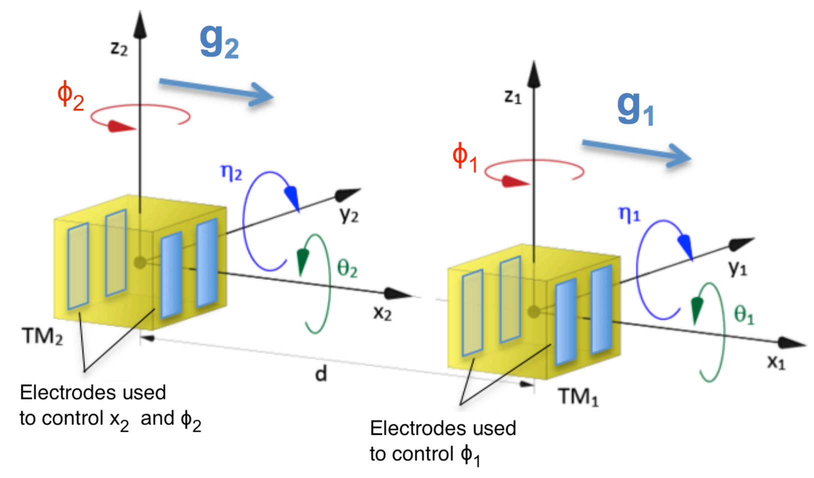
G. Russano, R. Giusteri, M. Hueller, S. Paczkowski, J.I. Thorpe, S. Vitale and W. J. Weber for LPF Collaboration

LISA Pathfinder: Free-fall Mode experiment

LPF as an accelerometer: measurement of small time-varying accelerations in the presence of a large DC (or very low frequency) acceleration

Compensating such DC/low frequency accelerations with applied forces can limit sensitivity

Compensate for the DC acceleration imbalance → Electrostatic actuation



LPF: 2 reference TM, 1 measurement axis

- → Spacecraft cannot follow both TM
- → Must force TM2 to follow TM1
- → Actuation noise on x axis not representative of LISA and scales with force level
- → Force level dictated by spacecraft self-gravity

Fluctuations from electrostatic force component $F \propto V_{ACT}^2$

Actuation force noise contribution if actuating with 1 electrode to compensate Delta g

$$S_{\Delta g_{ACT}}^{1/2} \approx 2\Delta g_{DC} S_{\delta V/V}^{1/2}$$

$$S_{\delta V/V}^{1/2} \approx 5\ ppm/\sqrt{Hz}$$

Considering both x / ϕ forces and torque and suspension authorities:

$$S_{\Delta g_{ACT}}^{1/2} \approx 2\Delta g_{EFF} S_{\delta V/V}^{1/2}$$

$$\Delta g_{EFF} \approx 50\ pm/s^2$$

Effective acceleration as a function of torque and forces and suspension authority

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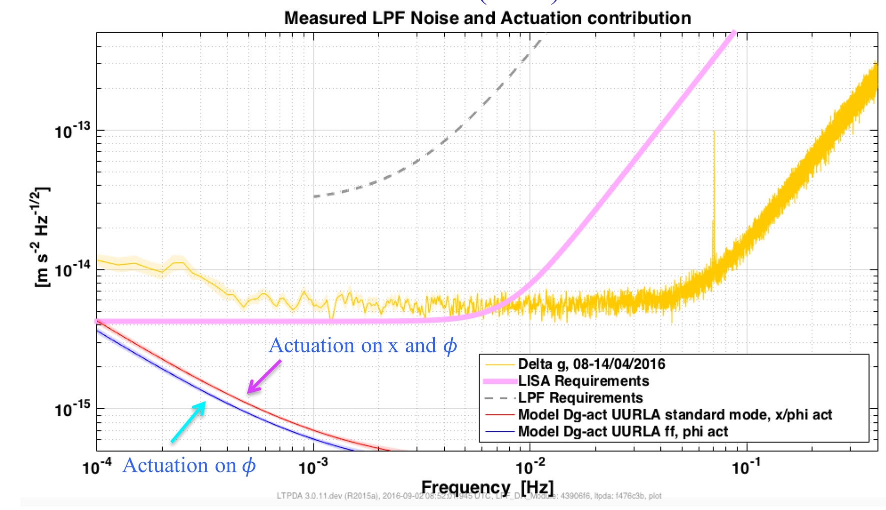


Measured differential acceleration noise (Apr 2016)

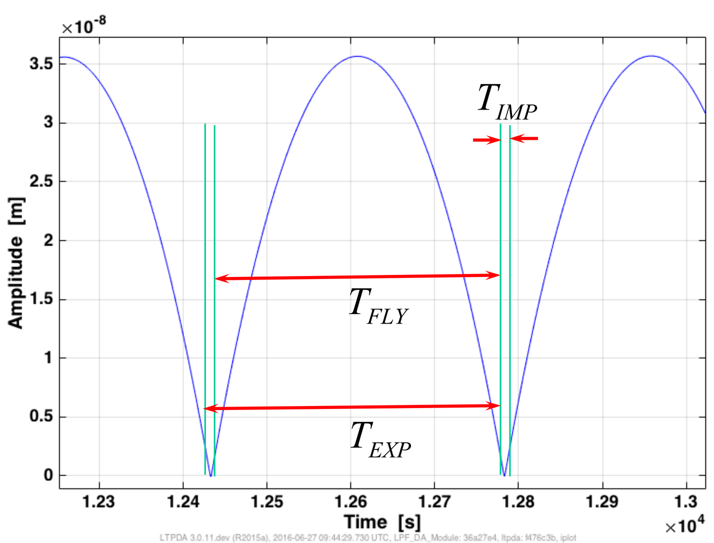
$$S_{\Delta g}^{1/2} = 5.2 \pm 0.1\ fm\ s^2/\sqrt{Hz}$$

@ 0.7 – 20 mHz

$$\Delta g_{DC} = -1.08\ pm/s^2$$

$\ll 600\ pm/s^2$ of requirements

Experimental Concept and Implementation



Cycle time: $T_{EXP} = 350.2\ s$

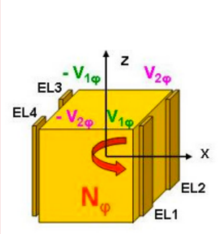
Impulse duration: $T_{IMP} = \chi\, T_{EXP} = 1\ s$

Flight time: $T_{FLY} = (1-\chi)\, T_{EXP} = 349.2\ s$

Duty cycle: $\chi = T_{IMP}/T_{EXP} = 0.0028$

- Compensate force – not continuously – but with series of impulses
- Throw out data during impulses
- Analyze data for the actuation-free «quasi-parabolic» flights between impulses
- Reduced actuation noise and completely independent Δg calibration

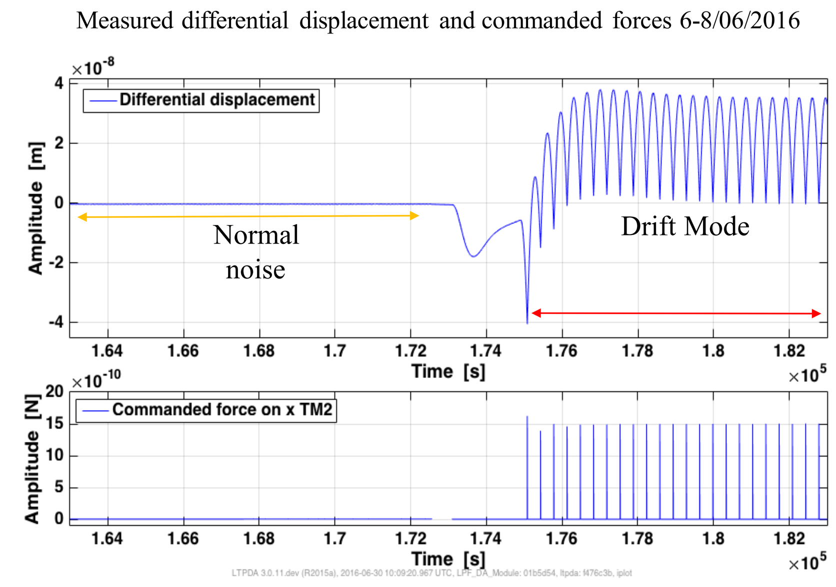
$$\Delta g(t) = \Delta\ddot{x}_{12} + \Delta\omega^2 (x_1 - x_{SC}) + \omega_{2p}^2 \Delta x_{12}$$

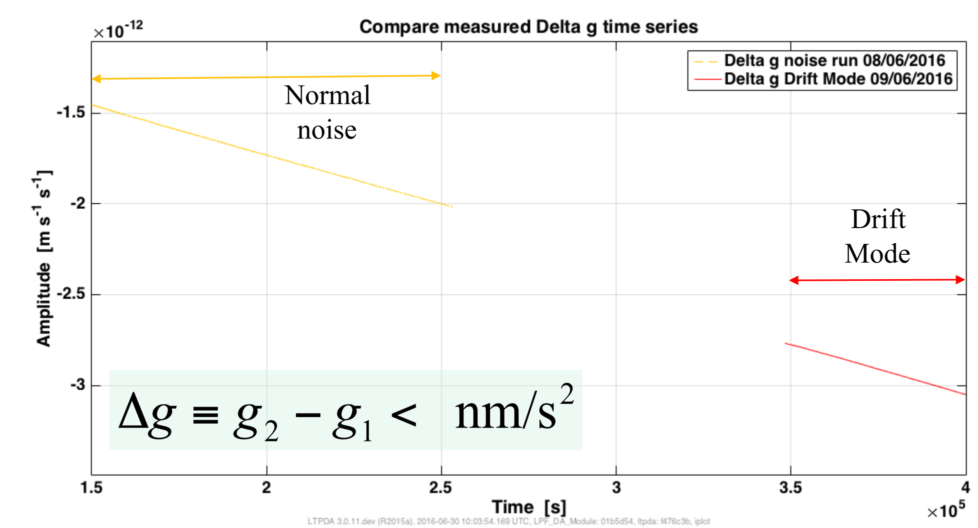


- **Authority** x electrodes: 11V High Res., 135V half time Wide Range
  - ➢ drift HR, kick WR
- Actuation authority WR: $F_{x_1}^{MAX} = 0, F_{x_2}^{MAX} \sim 1\ \mu N$
  - → $\sim 3\ \mu N$ with 0.3% of duty cycle

Applied differential actuation force to compensate self gravity difference → $f = m\Delta g_{DC} \approx 2\ nN$ with $|\Delta g_{DC}| \approx 3\ pm/s^2$

Measured differential displacement and commanded forces 6-8/06/2016





Measured time series (9-10/06/2016)

- 2 days of drift mode in two actuation configurations
- # flights 453
- Avg Drift len. = 349.2 s, Avg kick len. = 1s
- Avg Kick Amplitude = 1.94 nN
- Flights amplitude ~ 35 nm
- Sensitive only to the interferometer noise and not to the actuator calibration during free phases

Operational questions:

Can we recover true «actuation-free» acceleration noise at fm/s²/Hz$^{1/2}$ level:

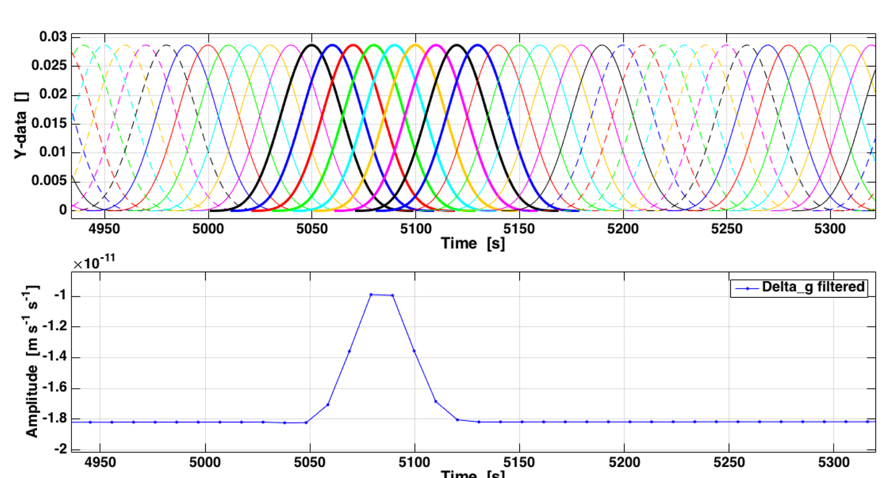
- ➢ with gaps in data?
- ➢ with much larger displacement dynamic range?

Data analysis techniques

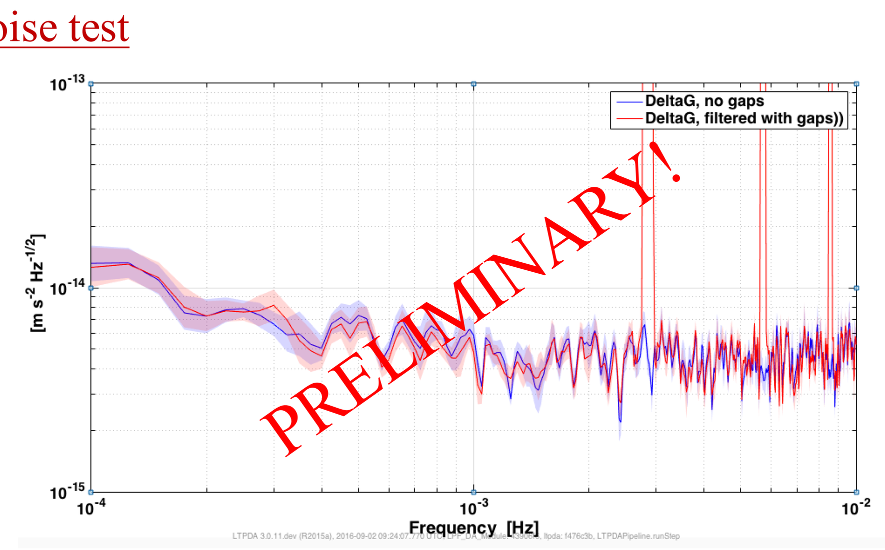
Blackmann-Harris technique

Approach description:

- Low pass filter with a Blackmann-Harris window normalized to give unit transfer function at f=0
- Data decimated of a factor 103 (sample time: 10.3 s), put to zero data in the gap
  - Total number of samples per flight: $n_{tot} = 34$
  - Number of samples in the gap: $n_{keep} = 9$
- Length of window: $T_{win} = T_{fly} - 2 \cdot margin - (n_{keep} - 1)T_{samp} \sim 98s$



Noise test

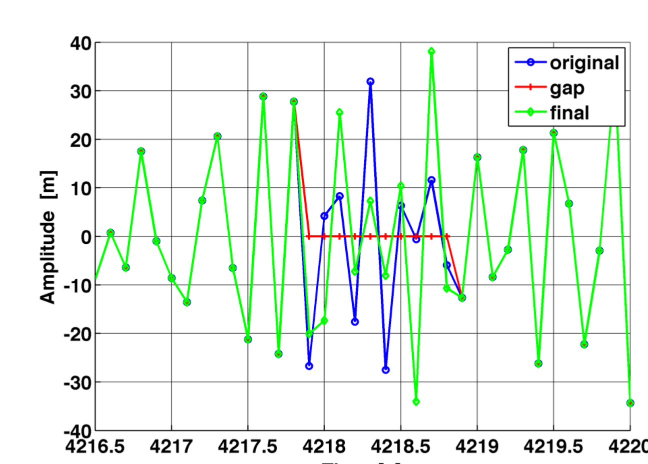


- Technique applied on a standard science noise run
- PSD corrected for gap ratio (n_{tot}/n_{keep}) and BH filter transfer function
  - Bias is model dependent
  - Still under consolidation

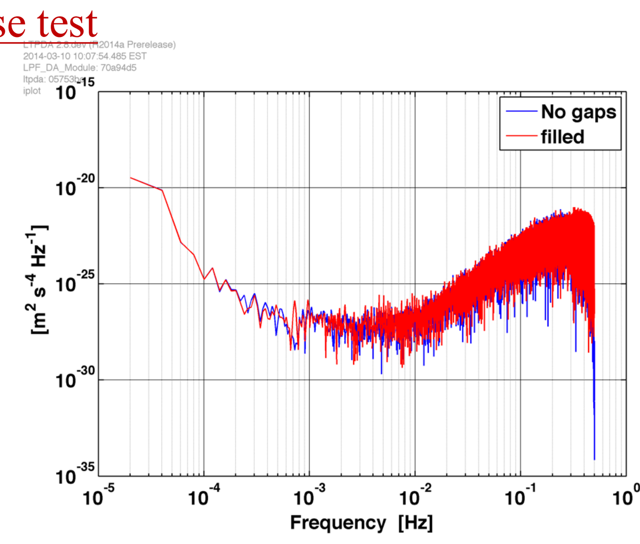
Constrained gaussian gap - patching

Approach description:

- Fill gaps with random data generated from an assumption of an underlying noise spectrum
- Algorithm
  - Create two-point function from model spectrum draw zero-mean random samples matching that distribution
  - Use data adjacent to gaps and two-point function to adjust mean of random samples
  - Update spectral model and iterate if necessary



Noise test



Bias of the technique

Comparison of best-fit parameters for spectral model

$$S_{mod}(f) = P_{-6} \cdot f^{-6} + P_{-2} \cdot f^{-2} + P_0 \cdot f^0 + P_4 \cdot f^{+4}$$

for original and CG patched spectral densities.

	original		CG patching		
	μ	σ	μ	σ	$\frac{\mu-\mu_{orig}}{\sqrt{\sigma^2+\sigma_{orig}^2}}$
$P_{-6} \times 10^{53}$	0.66	0.66	0.66	0.71	0.03
$P_{-2} \times 10^{35}$	1.14	0.18	1.08	0.20	-0.2
$P_0 \times 10^{29}$	2.25	0.16	2.31	0.19	0.3
$P_{+4} \times 10^{20}$	6.23	0.03	6.22	0.03	0.09

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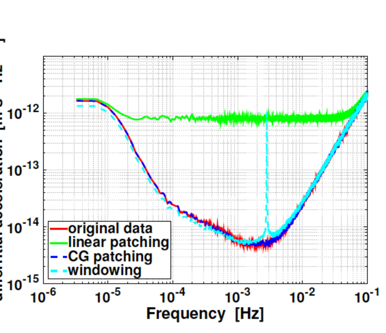


(a) Ensemble-averaged noise spectral densities

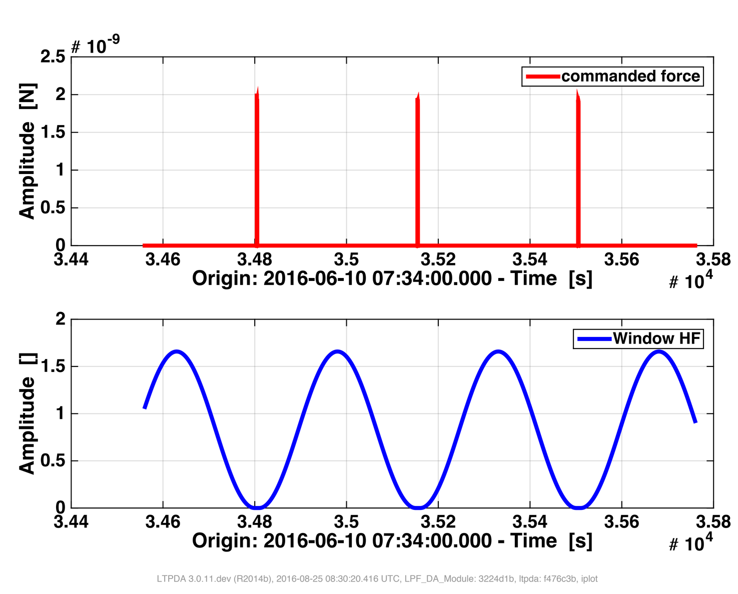
Windowing method

Approach description:

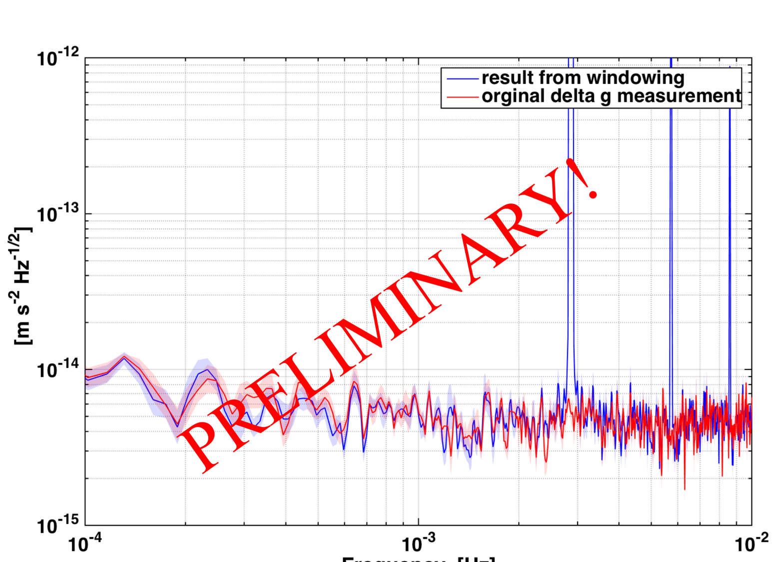
- do a simplex fit using an adapted logarithmic likelihood function on the non-windowed data and verify results with MCMC
- also fit DC acceleration to remove the effect of the window

$$\ddot{o}_{12} = -\omega_1 o_{12} + g_{12} + \dot{g}_0 t$$

- Build a customized window that smoothly goes to zero at each gap location(suppress gap transfer function)
  - ➢ note: window is normalised such that no spectral leakage from white noise occurs
- Apply normal PSD estimation techniques



Noise test



- Technique applied on a standard science noise run
- Bayesian model selection is pending
- Known bias in method of up to 20% (underestimate) at 0.1mHz

Comparisons and results

Calibration of the experiment:

- Low pass data with a Blackmann-Harris (~ 60 mHz)
- Fit to each flight

$$\ddot{o}_{12} = -\omega_{12} o_1 - \omega_1 o_{12} + g_{12} + \dot{g}_0 t$$

- Evaluate the Delta g to analyze with different techniques

Parameters from fitting the flight segments		
Parameter	**mean value**	**error**
Diff stiffness [s^-2]	-1.2707e-07	4.0704e-08
Stiffness 2 [s^-2]	-4.5856e-07	1.8691e-09
Diff DC Acc [m s^-2]	-3.0295e-12	8.9170e-15
Acceleration variation [m s^-2 D^-1]	-4.9304e-13	1.5688e-14

ω_2 prediction from electrostatic =[-4.308 ± 0.05] e-07 s-2