LISA Pathfinder: Achieving and measuring sub-femto-g free-fall for gravitational wave astrophysics

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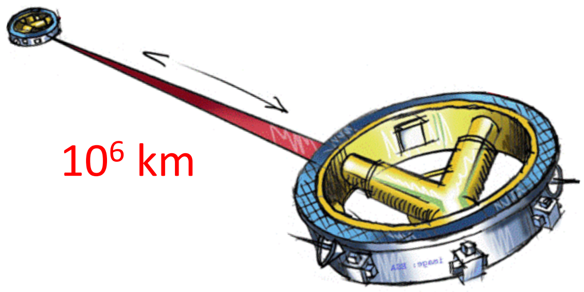
for the LISA Pathfinder team

LISA Symposium 10, U. Florida, May 2014

eLISA link as a differential accelerometer (2 TM in distant SC)

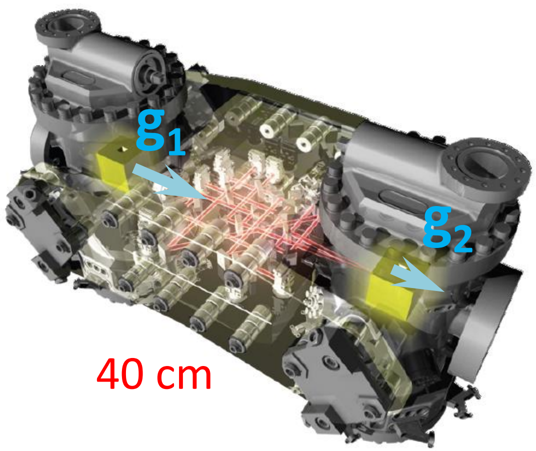


IFO doppler signal

Difference in stray force per unit mass

$$\frac{\dot{\nu}_r - \dot{\nu}_e}{\nu} = \frac{\left[\dot{h}(t) - \dot{h}(t - L/c)\right]}{2} + \frac{g_r(t) - g_e(t - L/c)}{c}$$

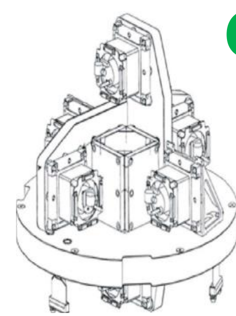
LPF as a differential accelerometer (2 TM in 1 SC)

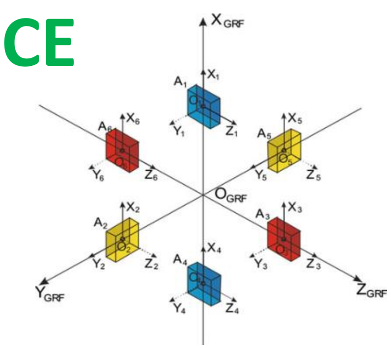


$$c\,\frac{\Delta \dot{\nu}}{\nu} = \frac{\lambda}{2\pi}\ddot{\phi} = \Delta g$$

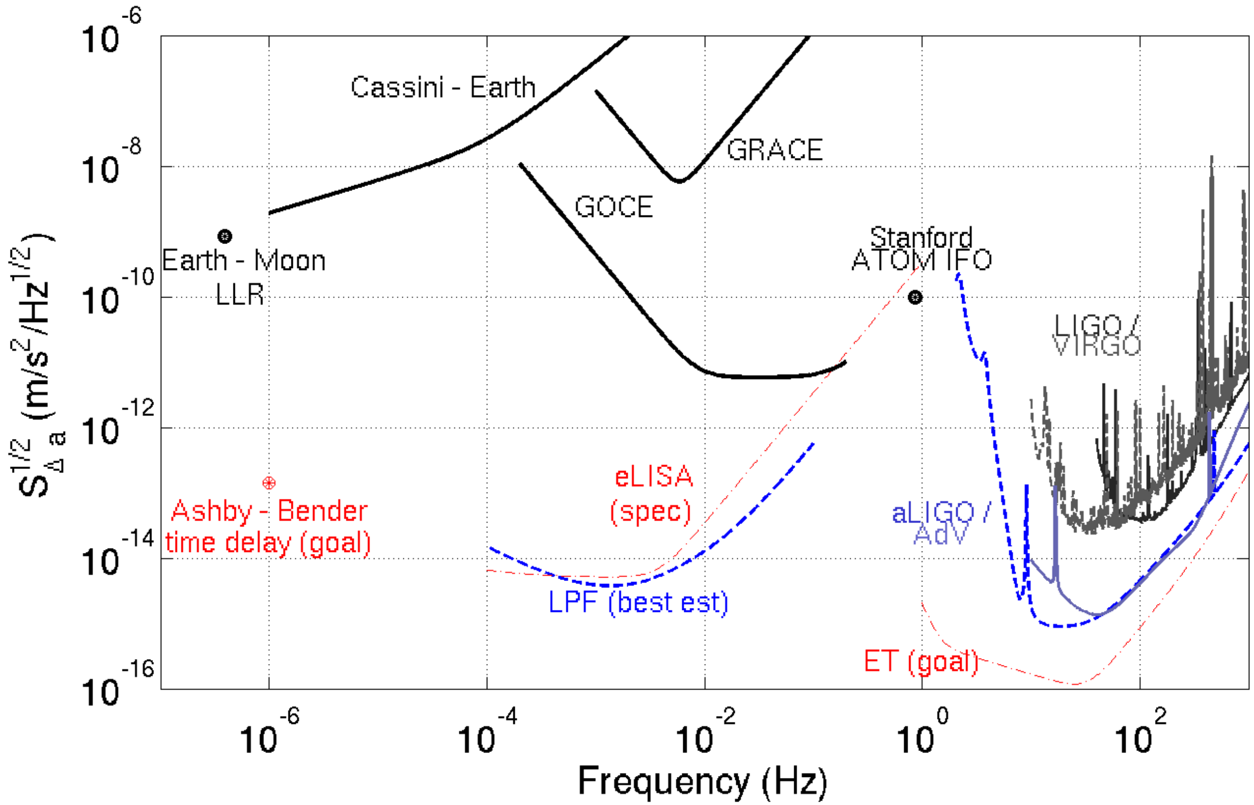
LPF similar to 1 axis of a geodesy gravity gradiometer

GOCE





Demonstrating eLISA differential accelerometer performance with LPF

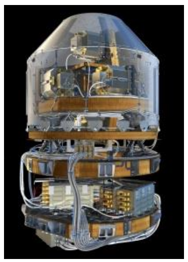


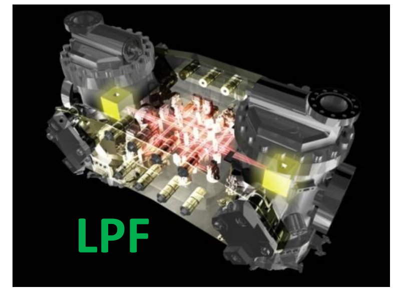
- Why LPF can improve upon GOCE performance by more than a factor 1000
  - design, analysis, experiment

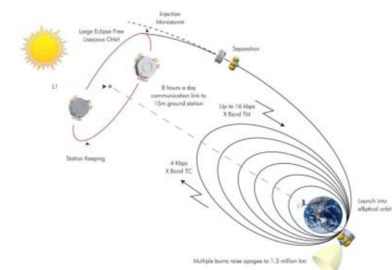
- How LPF will demonstrate this

From pico-g/Hz$^{1/2}$ to sub-femto-g/Hz$^{1/2}$: LPF design innovations

- 2 TM, 40-50 cm baseline gradiometer in a drag-free spacecraft
- pm/Hz$^{1/2}$ displacment sensitivity







Actuation force noise «accelerometer range»

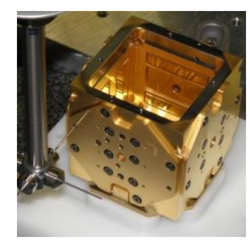
LEO
µm/s^2(Terrestrial)
residual atmosphere

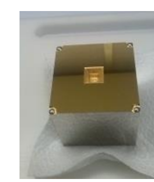
L1
nm/s^2 (spacecraft **g**) → **0 for eLISA !!**
deep space

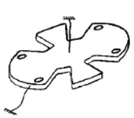
GRS surface force noise

300 gm TM
100 µm gaps
discharge wire

2 kg TM
3-4 mm gaps
no contacts



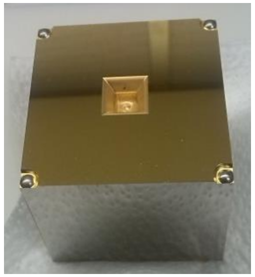




tough caging
UV discharge

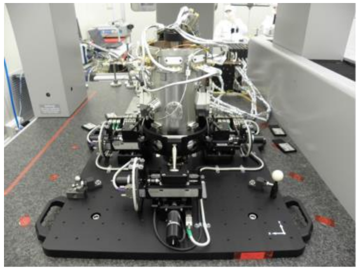
need IFO Talks H. Ward, D. Robertson

Gravitational reference sensor (GRS) subsystem



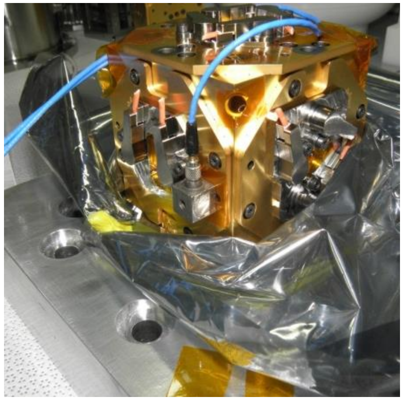
TM + surrounding electrostatic sensor / actuator
+ vacuum + UV discharge + caging

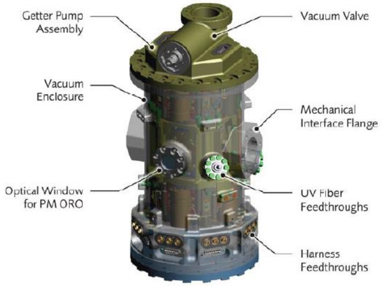
- nm/$Hz^{1/2}$ capacitive position sensing on all axes
    - < 10 pm/$Hz^{1/2}$ science signal is IFO
- nN actuation forces (μN non-science)
- define environment that allows fN/$Hz^{1/2}$ on TM



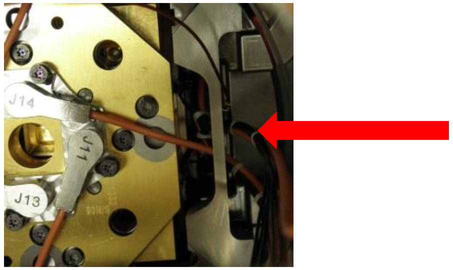
Designed to be full flight heritage for eLISA

OHB CGS





See talk Rita Dolesi



LISA Pathfinder as a differential accelerometer

Newton's Eqns:

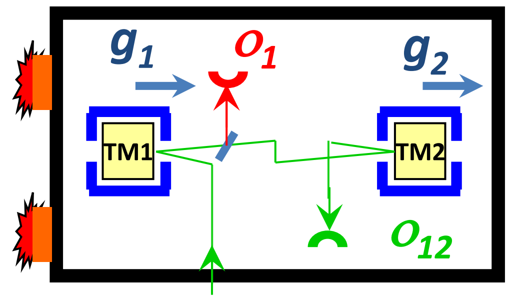
$$m\ddot{x}_1 = F_1 - m\omega_{1p}^2 (x_1 - x_{SC})$$

$$m\ddot{x}_2 = F_2 - m\omega_{2p}^2 (x_2 - x_{SC}) + F_{ES}$$

IFO Readouts :

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

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



Control

Drag-free: thrust SC to follow TM1 (null **o1**, 1 Hz BW)

Electrostatic suspension: force TM2 to follow TM1 (null **o12**, 1 mHz BW)

IFO Acceleration

$$\Delta g \equiv \frac{F_2}{m} - \frac{F_1}{m} = \ddot{o}_{12} - \frac{F_{ES}}{m} + \left(\omega_{2p}^2 - \omega_{1p}^2\right) o_1 + \omega_{2p}^2 o_{12}$$

$$+ \ddot{n}_{12} + \left(\omega_{2p}^2 - \omega_{1p}^2\right) n_1 + \omega_{2p}^2 n_{12}$$

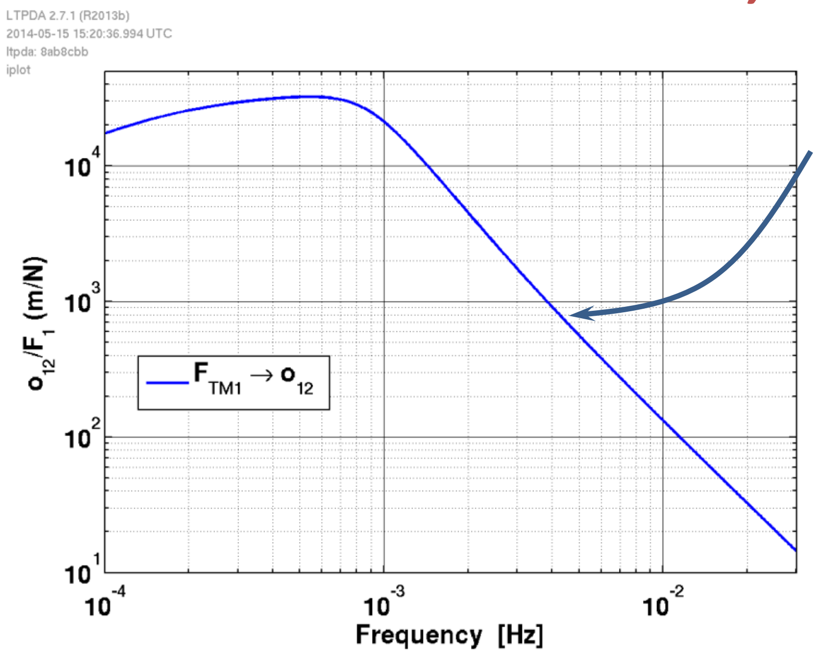
IFO Noise

Commanded control forces

Elastic coupling

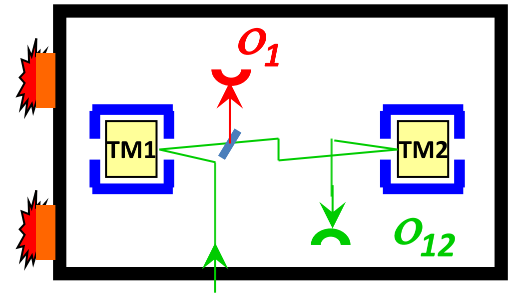
- Produce differential acceleration time series
- Spacecraft coupling term (stiffness) subtracted (also for LISA)

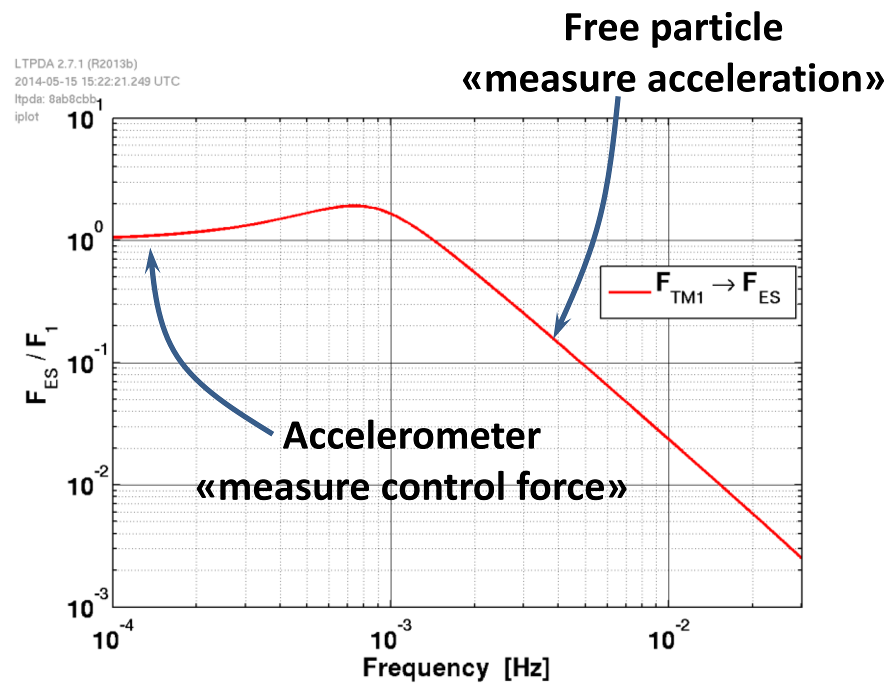
LISA Pathfinder control, displacement and acceleration



Free particle

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





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

«working in acceleration»

- use dynamic parameters but not transfer function
- remove long transients

Calibrating the LPF differential accelerometer

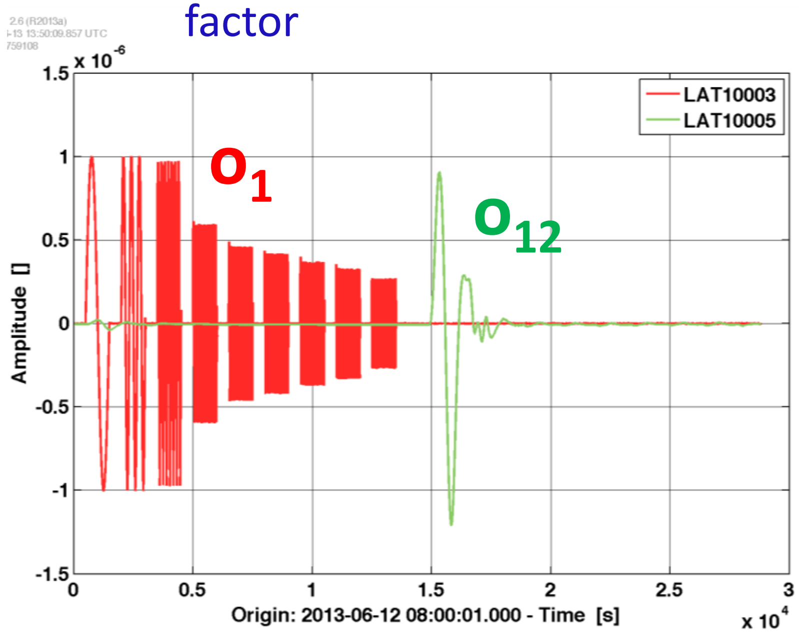
$$\Delta g = \ddot{o}_{12} - \frac{F_{ES}}{m} + \Delta\omega^2 o_1 + \omega^2_{2p} o_{12}$$

$$\ddot{o}_{12} = \alpha \frac{F_C}{m} - \Delta\omega^2 o_1 - \omega^2_{2p} o_{12} + \Delta g + \Delta g_{IFO}$$

Background force + IFO noise

Actuator calibration factor

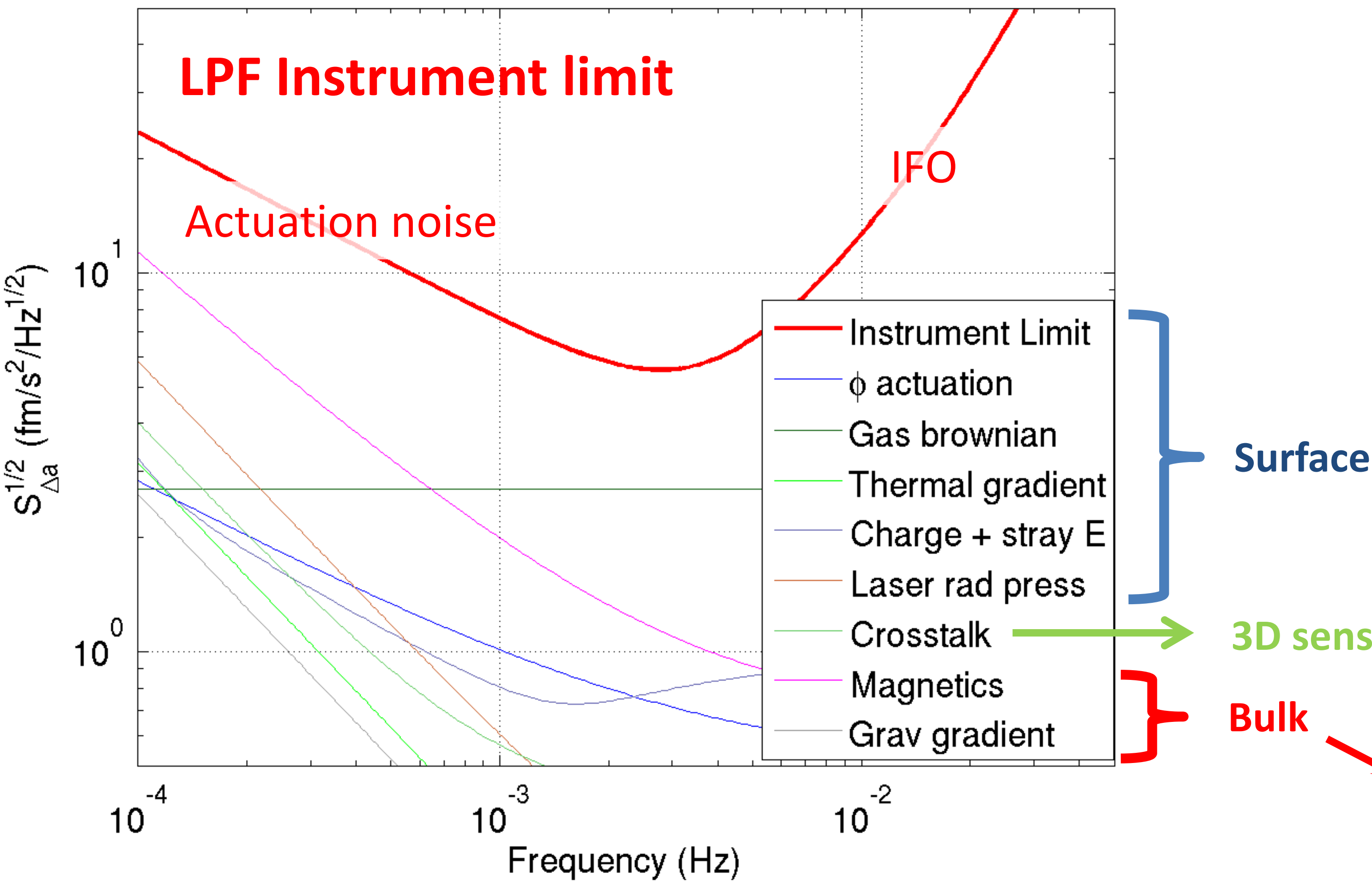
dynamical stiffness



- Modulate satellite drag-free and electrostatic setpoints
- Fit acceleration to commanded force (F_C), measured positions $\mathbf{o_{12}}$, $\mathbf{o_1}$ + other measured disturbances
- Background force (**Δg**) and IFO noise

See talks Martin Hewitson + Daniel Vetrugno

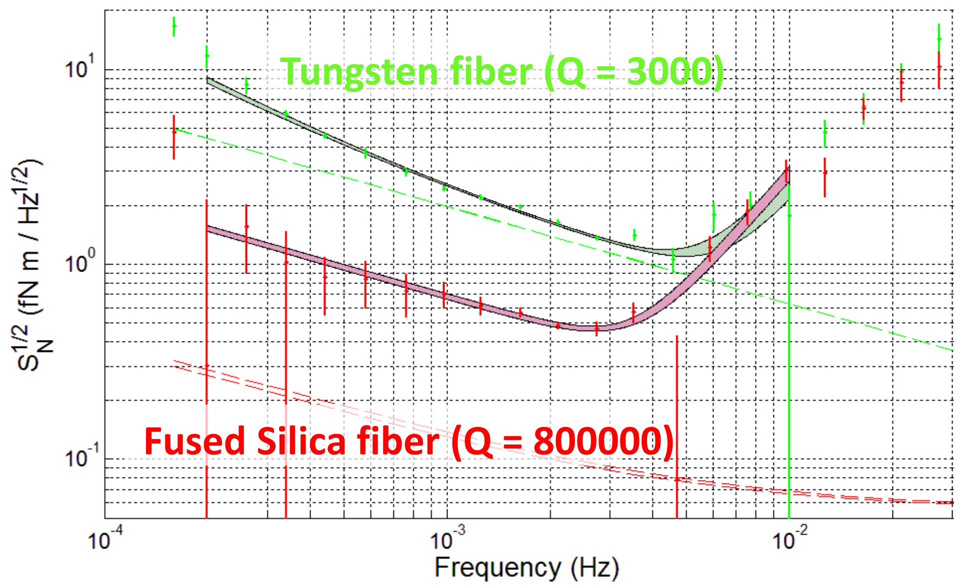
LPF performance and TM acceleration noise sources for eLISA



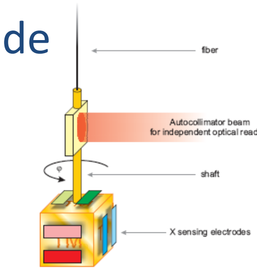
Torsion pendulum small force measurements (lightweight TM)

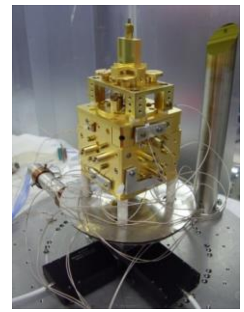
LISA Pathfinder flight test

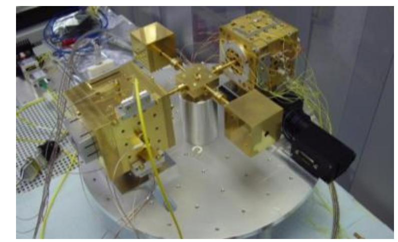
GRS surface force noise: overall upper limits with torsion pendulum



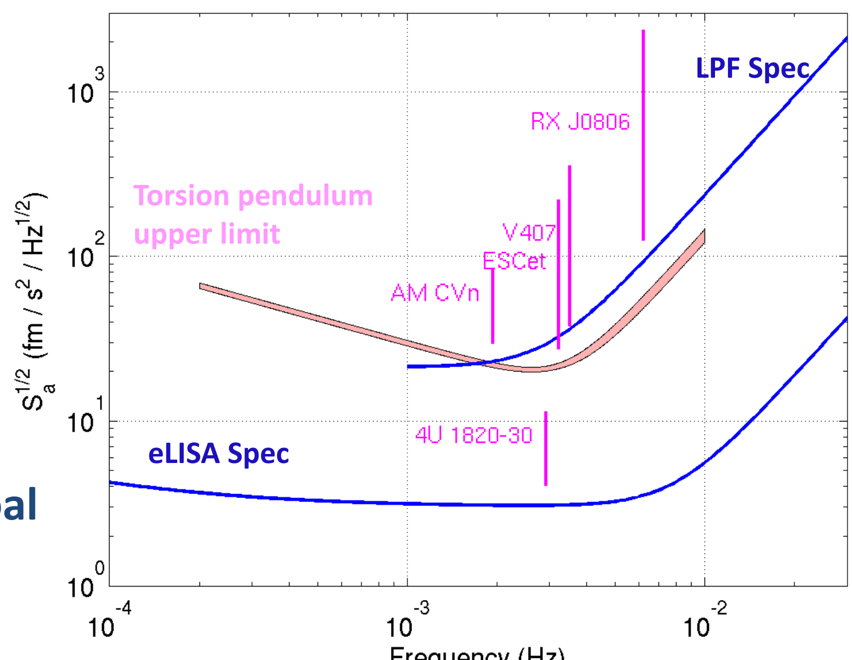
- LISA-like TM suspended inside prototype GRS with FEE



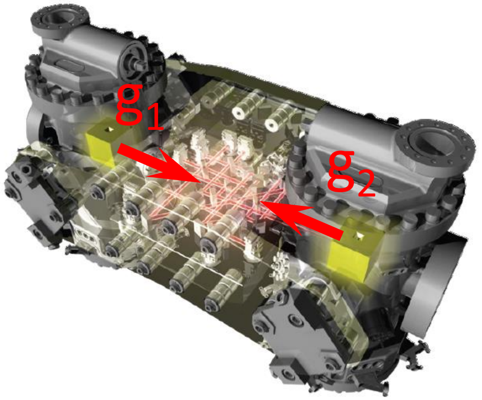




- Attribute **ALL** unexplained torque noise to interaction between GRS – TM
- Convert to equivalent acceleration
  → surface force noise upper limit
- **Within factor 2 of LPF spec at 1 mHz**
- **Many known forces measured to eLISA goal**



LPF instrument limit: noisy compensation of spacecraft self-gravity



«accelerometer dynamic range» problem

Noise in "DC" force applied to compensate local Δg

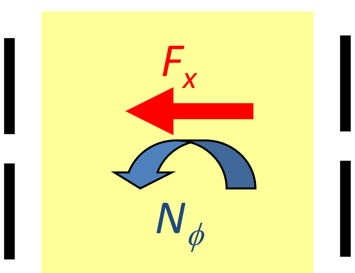
→ **Not present in eLISA!!**

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

Design specs

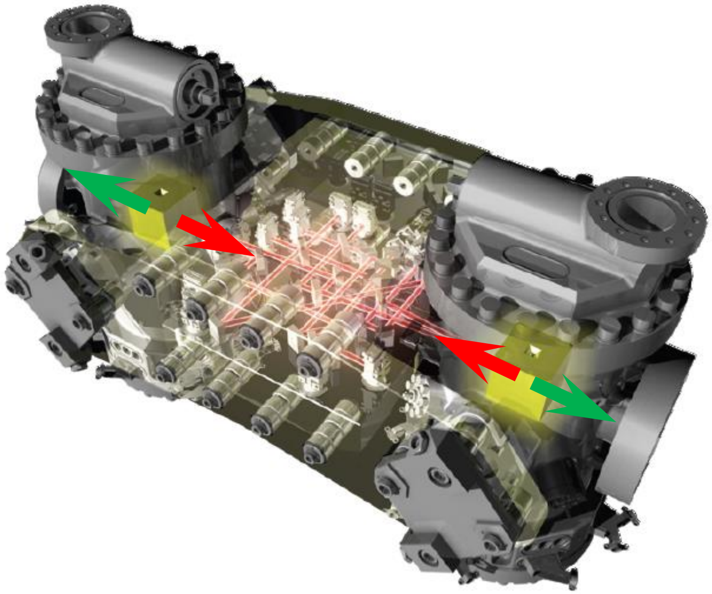
$\Delta g < 0.65 \text{ nm/s}^2$ → Current spacecraft mass balance **calculations** look better!

$S_{\delta V/V}^{1/2} < 2 \times 10^{-6} \text{/Hz}^{1/2}$ → Current measurements 2-3 worse



- **Expect < 8 fm/s²/Hz^1/2 at 1 mHz**
- full analysis complicated by uncorrelated voltage fluctuations, ϕ act

Gravitational balancing to $\Delta g < 1\ nm/s^2$



Opt bench + GRS	~ $-50\ nm/s^2$
(TM – TM)	~ $-2\ nm/s^2$
Spec	$0.65\ nm/s^2$
Model	~ $10\ nm/s^2$ level

compensate by GRS internal balancing masses (IBM) 1.8 kg W

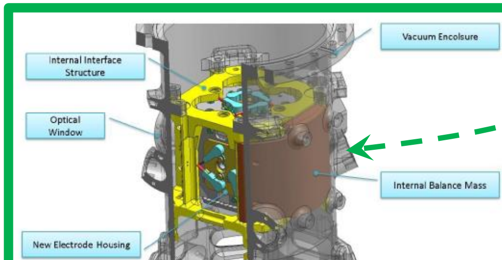
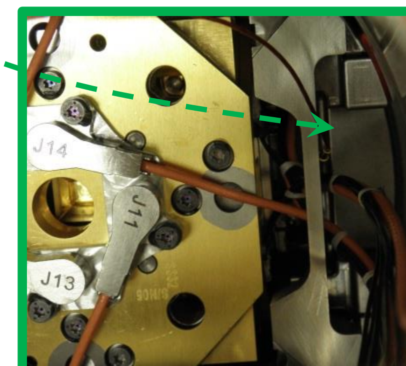
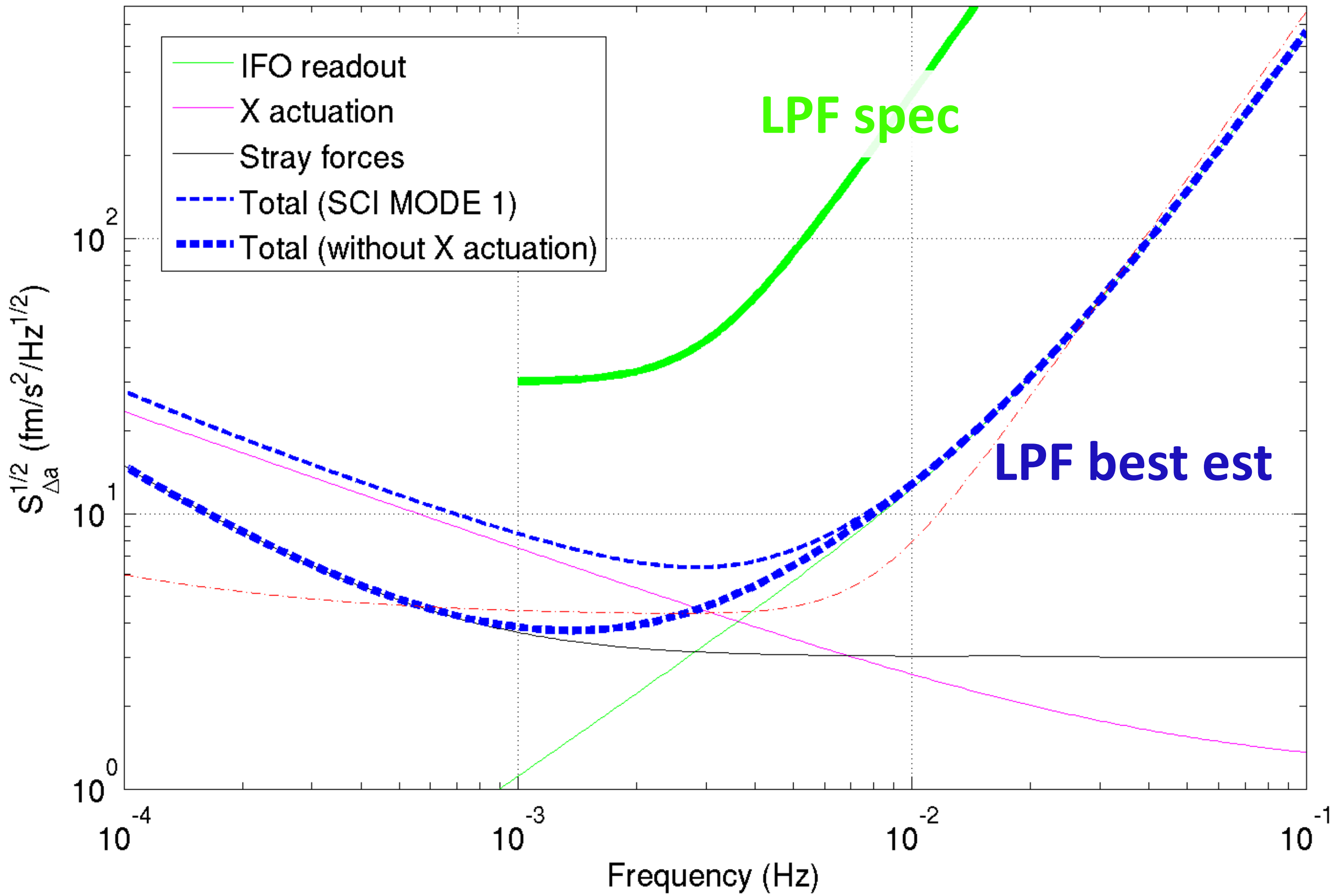


Figure 10.1- IBM inside the VE



- No full ground test:
  analysis ($1/r^2$) + mass + position measurements
- In flight: measure 3 trans + 6 rot gravitational balances
  + measure gravitational stiffnesses

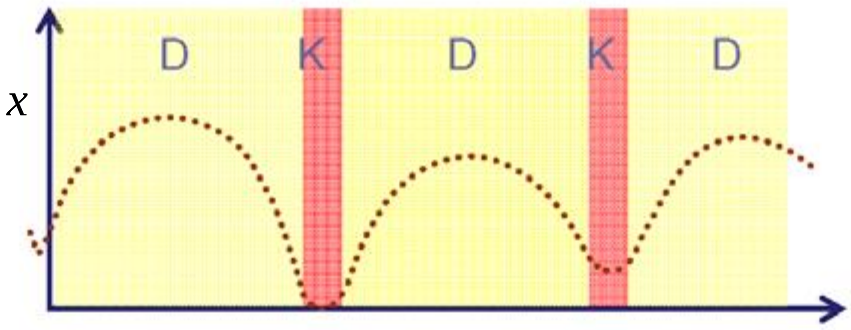
LISA Pathfinder performance: with and without x-actuation



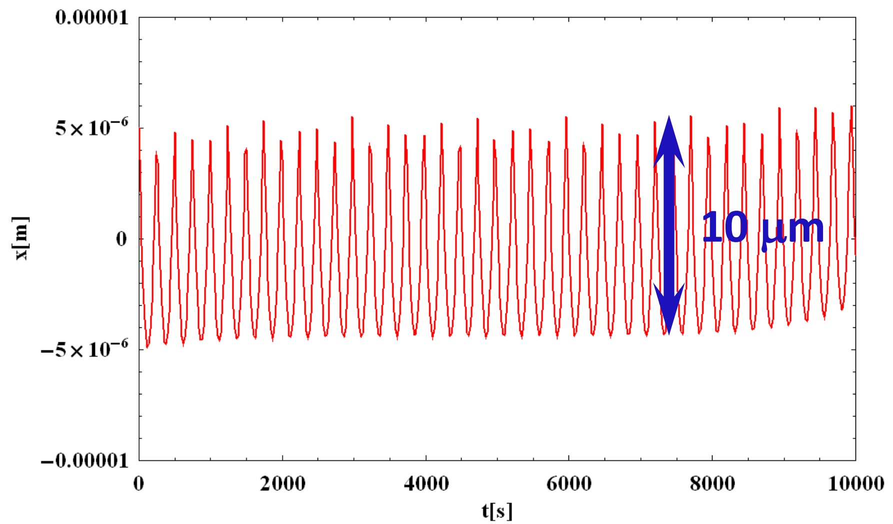
- Expect to beat LPF spec at all frequencies
- If gravitational balancing at spec level, likely limited by actuation that is not present in eLISA

LISA Pathfinder: avoiding actuation fluctuations with free-fall mode

compensate average DC force imbalance by applying a large impulse followed by free-fall (parabolic flight!)



Grynagier, *CQG* **26** (2009) 094007



- Example: Apply 100 x average needed force for 2.5 s, followed by 247.5 s free-fall

- **Analyze only free-fall data, avoid impulses**
  - window to avoid gaps (windowed PSD)
  - Iteratively extract noise to fill gaps (standard PSD)
  - Low pass / decimate / detrend, set gap data to 0 (standard PSD)

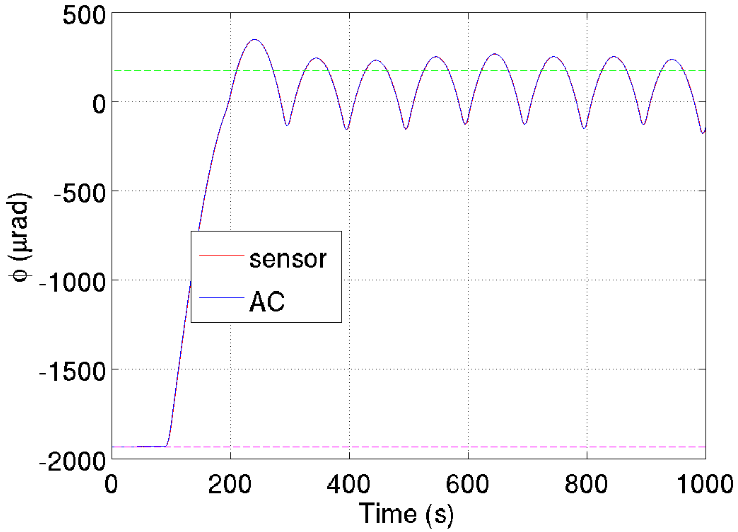
- **Can we recover intrinsic force noise at 10^{-3} -- 10^{-4} Hz in a series of 250 s experiments?**

Testing free-fall mode on the ground

- **Can we recover intrinsic force noise at 10^{-3} -- 10^{-4} Hz in a series of 250 s experiments?**
  - Data with gaps (spectral leakage)
  - Huge increase in dynamic range (displacement and velocity)
    - Sensing and dynamic non-linearities, timing
- **What are the conditions in which free-fall / impulse mode can be used?**
    - Force levels, displacement range, time of flight

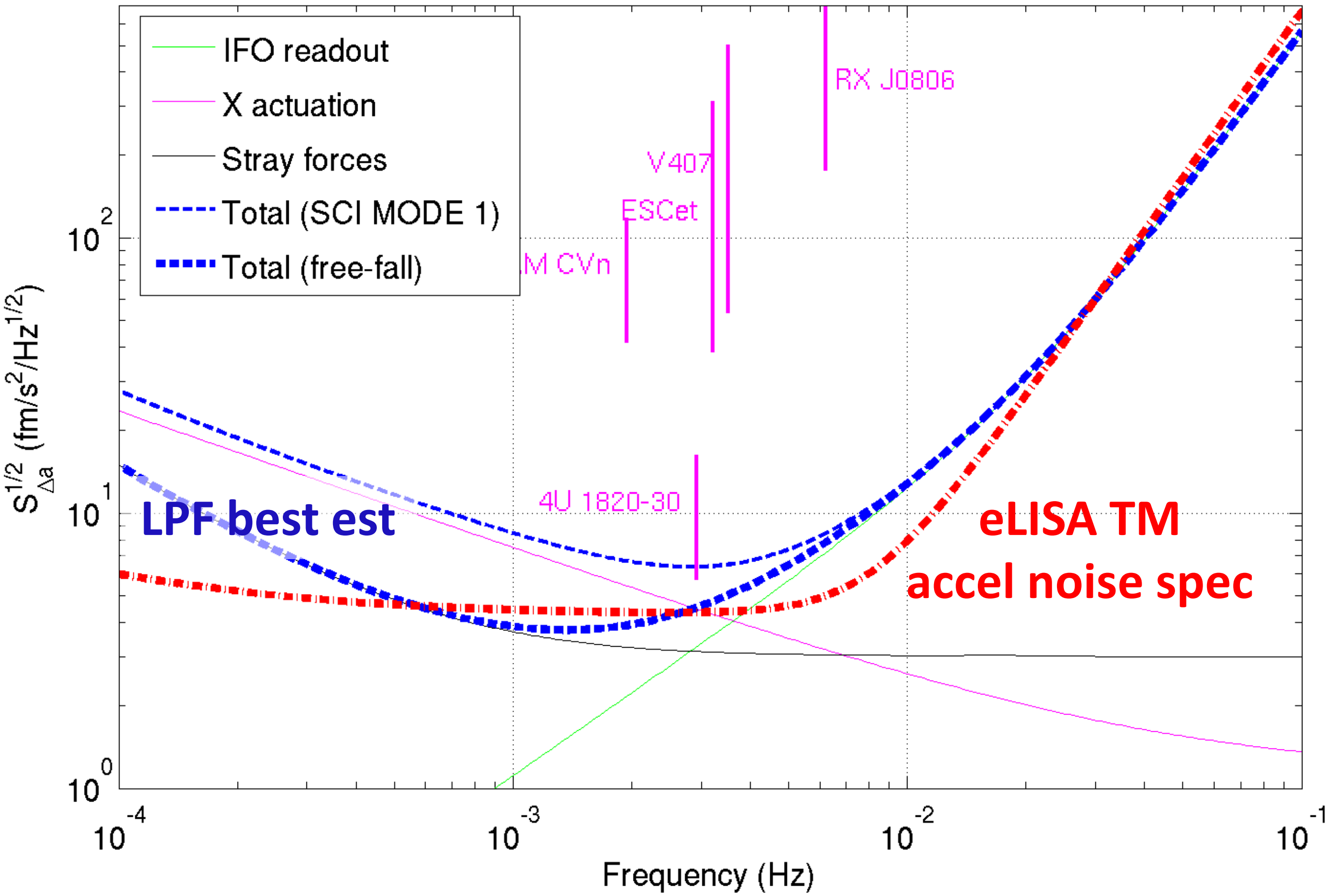
On-ground test:

- Rotated torsion pendulum forced to center
- Can choose levels of:
  - DC force (pendulum rotation)
  - Elastic coupling (applied voltages)
  - Flight and impulse times



Free-fall talks:
Ira Thorpe, **Giuliana Russano**, John Conklin

LISA Pathfinder performance prediction



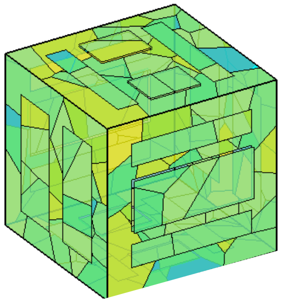
LISA Pathfinder should guarantee most of LISA science

(performance needed to observe calibration binaries with SNR=1 in 1 year)

LPF: a physical model of limits to measuring differential acceleration

In – orbit and on-ground

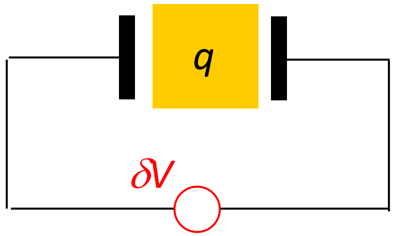
Example: electrostatics inside GRS



- stray electrostatic fields (patch effects)
- cosmic ray charging

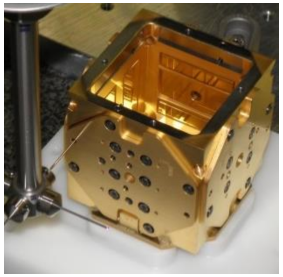
Largest interaction: TM charge + average residual E field

[*PRL* 108:181101 (2012)]



$$F_x = q\langle E_x\rangle = -q\Delta_x\left[\frac{1}{C_{TOT}}\left|\frac{\partial C_x}{\partial x}\right|\right] \propto \frac{1}{\text{gap}}$$

$$\Delta_x \equiv \frac{1}{\left|\frac{\partial C_x}{\partial x}\right|}\sum_{i(TM),\, j(S)} \frac{\partial C_{ij}}{\partial x}\left(\delta V_i - \delta V_j\right)$$



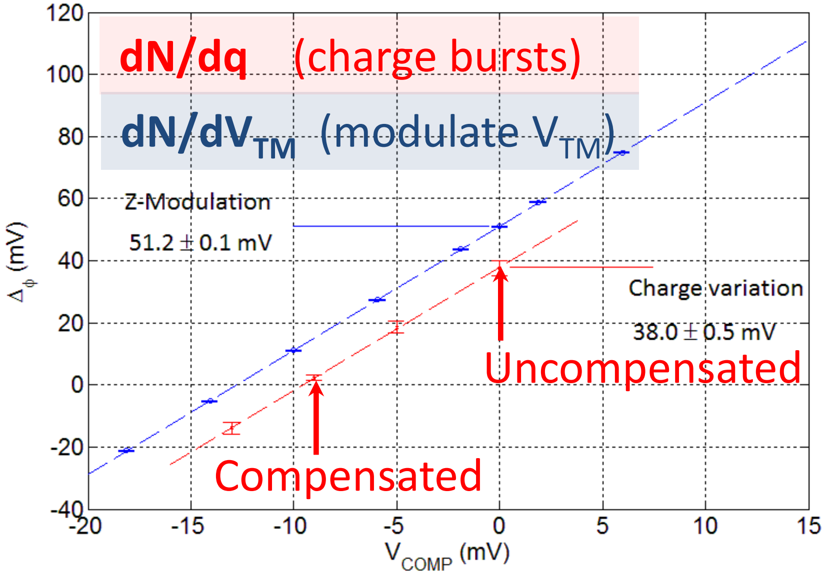
Δ_x : equiv. single electrode potential

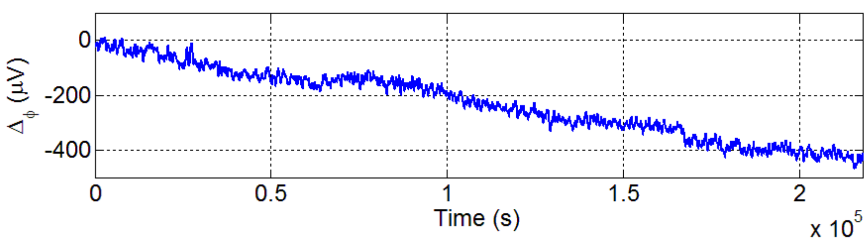
UV discharge of TM

Charge noise requires compensation of average stray field

Operation with non-zero q requires low fluctuations in stray field

Stray electrostatics (on ground):





Measure /compensate **dF/dq** (dN/dq)

- Measure / compensate 100 mV → < 1 mV
- Need to measure **dF/dq** by varying charge (not with modulated V_{TM})

Measure noise in **dF/dq** (dN/dq)

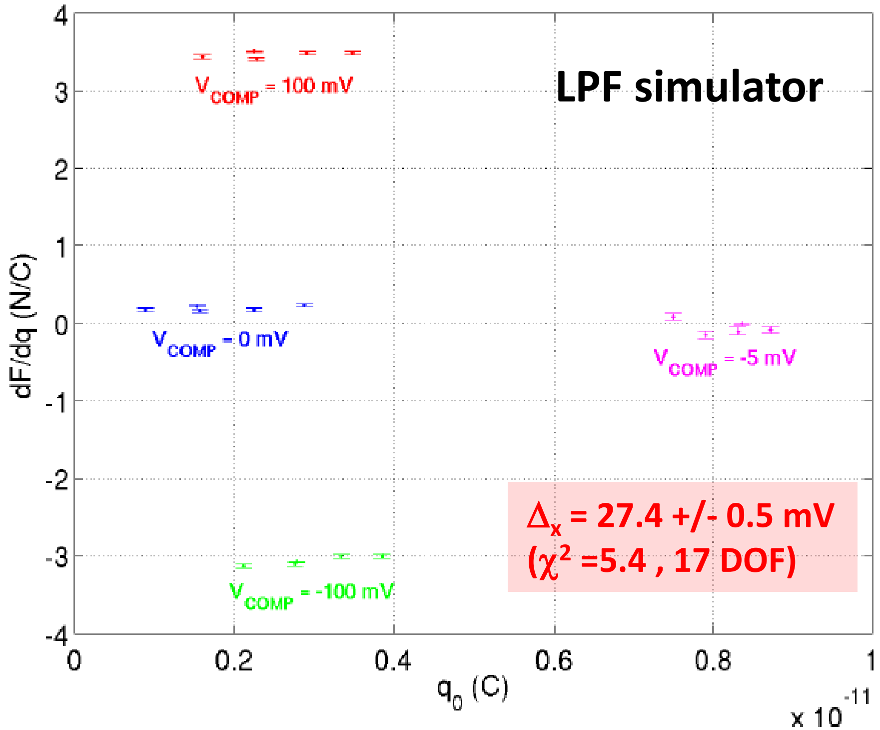
- Torque noise with charged TM

$$S_{\Delta_x}^{1/2} < 80\ \mu\text{V/Hz}^{1/2} \text{ at } 1 \text{ mHz}$$

- Single electrode (500 mm^2) < 12 $\mu V/Hz^{1/2}$
- **OK for eLISA (marginally)**

Tests of UV discharge, charge measurement

Stray electrostatics (In-flight):



See talk Valerio Ferroni

Measure compensate **dF/dq** with UV TM charge bursts and modulated voltages

- Performance and debugging
- Several times and for two TM

Measure long-term TM charge fluctuations

- How well / how often do we need to balance field?
- Confirm charging models, low freq noise
- Correlation with radiation monitor

Full UV discharge testing

- Fast discharge and continuous

If necessary ...

- force noise with charged TM
- effect of single (bad) electrode

Measurement science investigations with LPF

- Measure spacecraft **g** (3 translations and 6 rotations)
- Force noise from actuation (free-fall mode)

- Measure temperature fluctuations down to 10^{-4} Hz – and below – and $dF/d\Delta T$

Talk Ferran Gibert

- Measure magnetic environment and forces from applied B fields

Talk Miquel Nofrarias

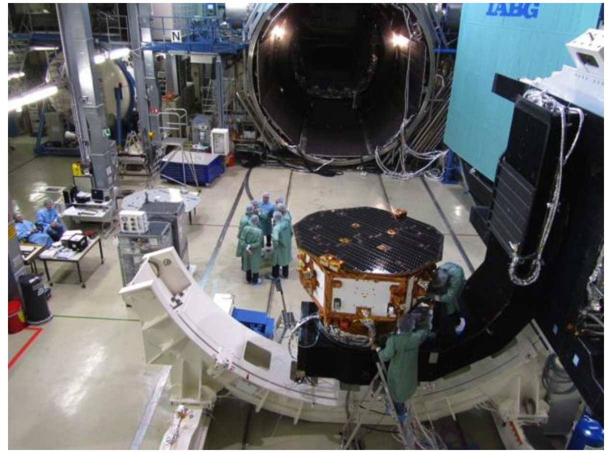
- Measurement and compensation of average stray E field (nulling dF/dq)
- Measure low frequency charge fluctuations with long term charge test

Talk Valerio Ferroni

- Stiffness / SC coupling / crosstalk measurements

Talk Daniel Vetrugno

Create physical model for limits to achieving perfect free-fall



Thank you!

and thanks to the LPF team

... see you in summer 2015!