Measuring and mitigating electrostatic forces aboard Lisa Pathfinder

V. Ferroni

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Outline

- LISA Pathfinder mission
- The inertial sensor
- Electrostatic disturbances
- Mitigation
- The DC bias experiment
- Simulation

LISA PATHFINDER

LPF

It is the challenge to prove that a space gravitational waves observatory is feasible

The mission will be put in L1 of Sun Earth system for baseline 6 months of experiments

Each experiment will aim to test specifically a physical disturbance or a system characteristic and our current understanding

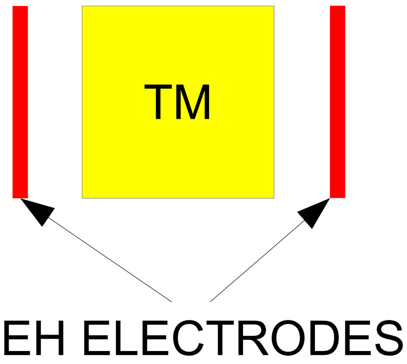
The primary goal of the LPF test is to verify that a test-mass can be put in pure gravitational free-fall within a few tens of femto-Newtons noise in the bandwidth from 1 to 30 mHz

LPF OPERATIONS ARE THE MISSION ITSELF

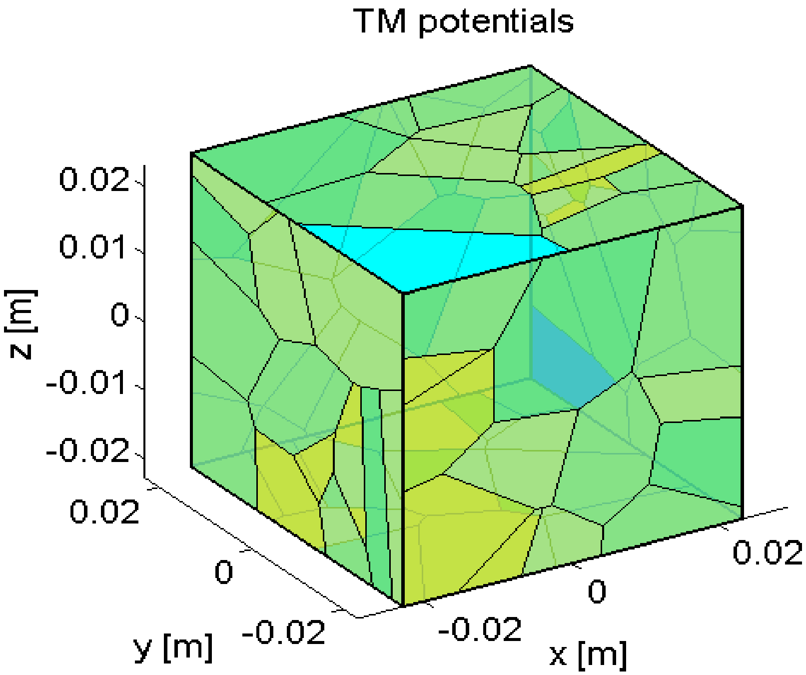
The Inertial Sensor

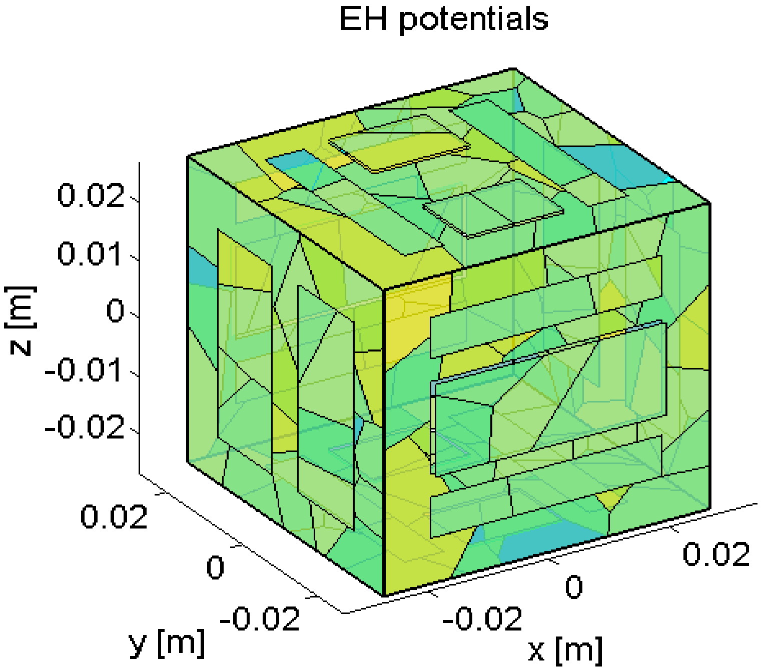
Electrostatic model

- **Test Mass free floating**
- **18 electrodes for sensing and control**
- **Millimetric gaps**



- **Gold coated surfaces**
- **Conductors cannot be taken as equipotentials**
- **Patch potentials add to the conductor background**





Electrostatic Force

$$F_x = \frac{1}{2} \sum_{\alpha,\beta<\alpha} \frac{\partial C_{\alpha,\beta}}{\partial x} \left(V_\alpha - V_\beta\right)^2$$

α , β are the TM and EH equipotential domains

Net force results basically proportional to:

- TM to EH squared background potential difference
- TM squared charge
- TM to EH squared patch potentials difference
- TM charge to EH patch potentials difference

Electrostatic disturbance vehicles

TM charge, patch potentials, electronics (FEE)

Charge to Patch Potentials Coupling

$$F_x = \frac{q}{C_{TOT}} \sum_{i(TM),j(S)} \frac{\partial C_{ij}}{\partial x}\left(\delta V_i - \delta V_j\right)$$

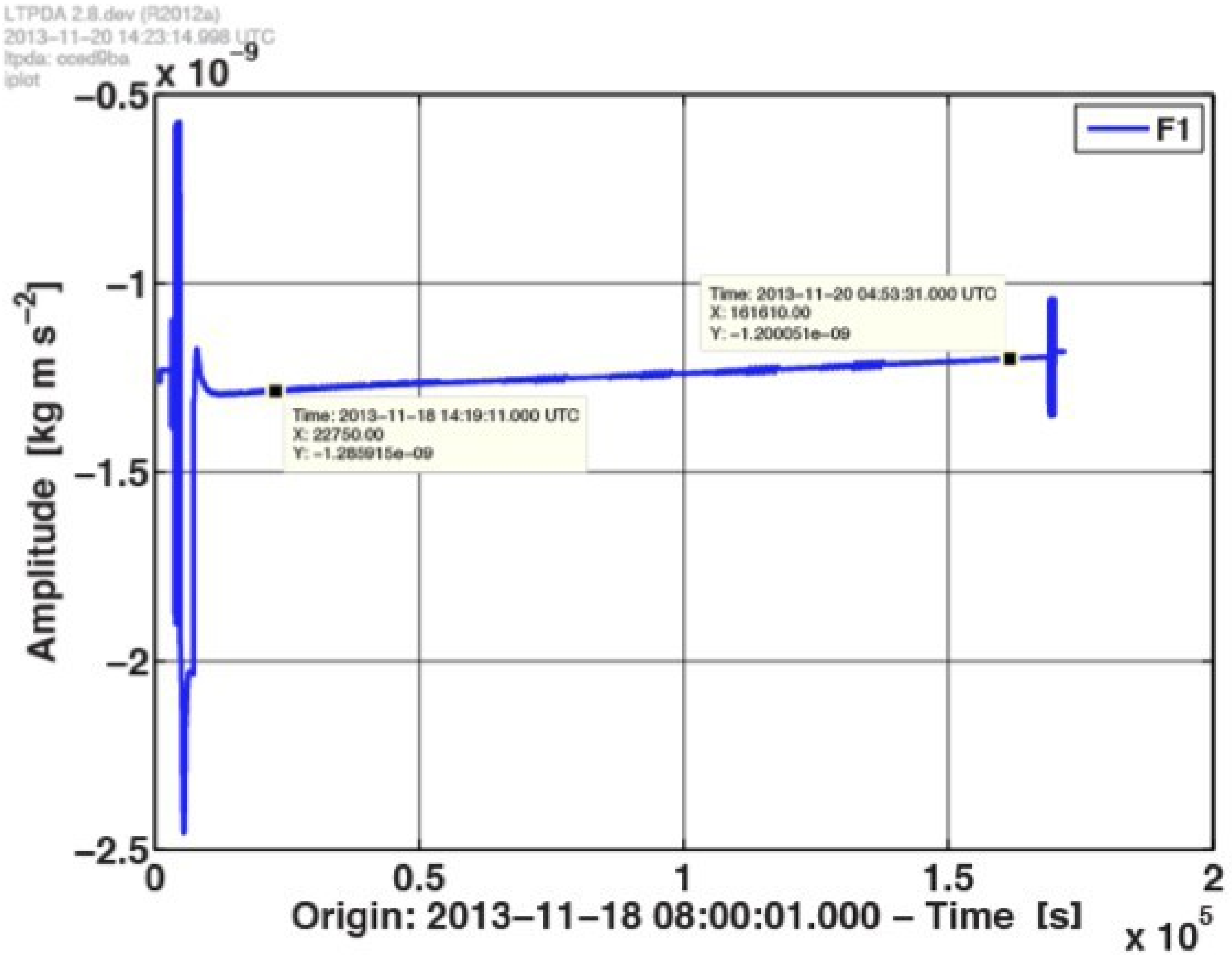
$$\equiv \frac{q}{C_{TOT}} \left|\frac{\partial C_x}{\partial x}\right| \Delta_x$$

$\boldsymbol{\Delta}_{\mathbf{x}}$: DC Bias

the effective potential difference due to patch potentials
(or FEE bias)

Example

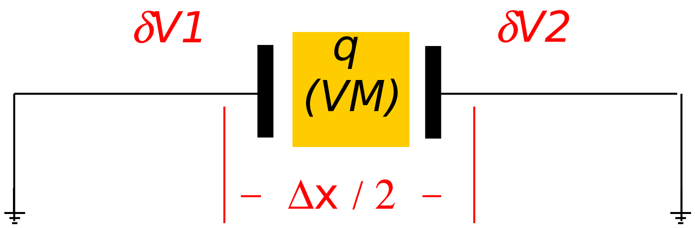
$Q(t) \longrightarrow F(t)$



Noise

$$F_x = \frac{q}{C_{TOT}} \sum_{i(TM),j(S)} \frac{\partial C_{ij}}{\partial x}\left(\delta V_i - \delta V_j\right)$$

$$\equiv \frac{q}{C_{TOT}} \left|\frac{\partial C_x}{\partial x}\right| \Delta_x$$



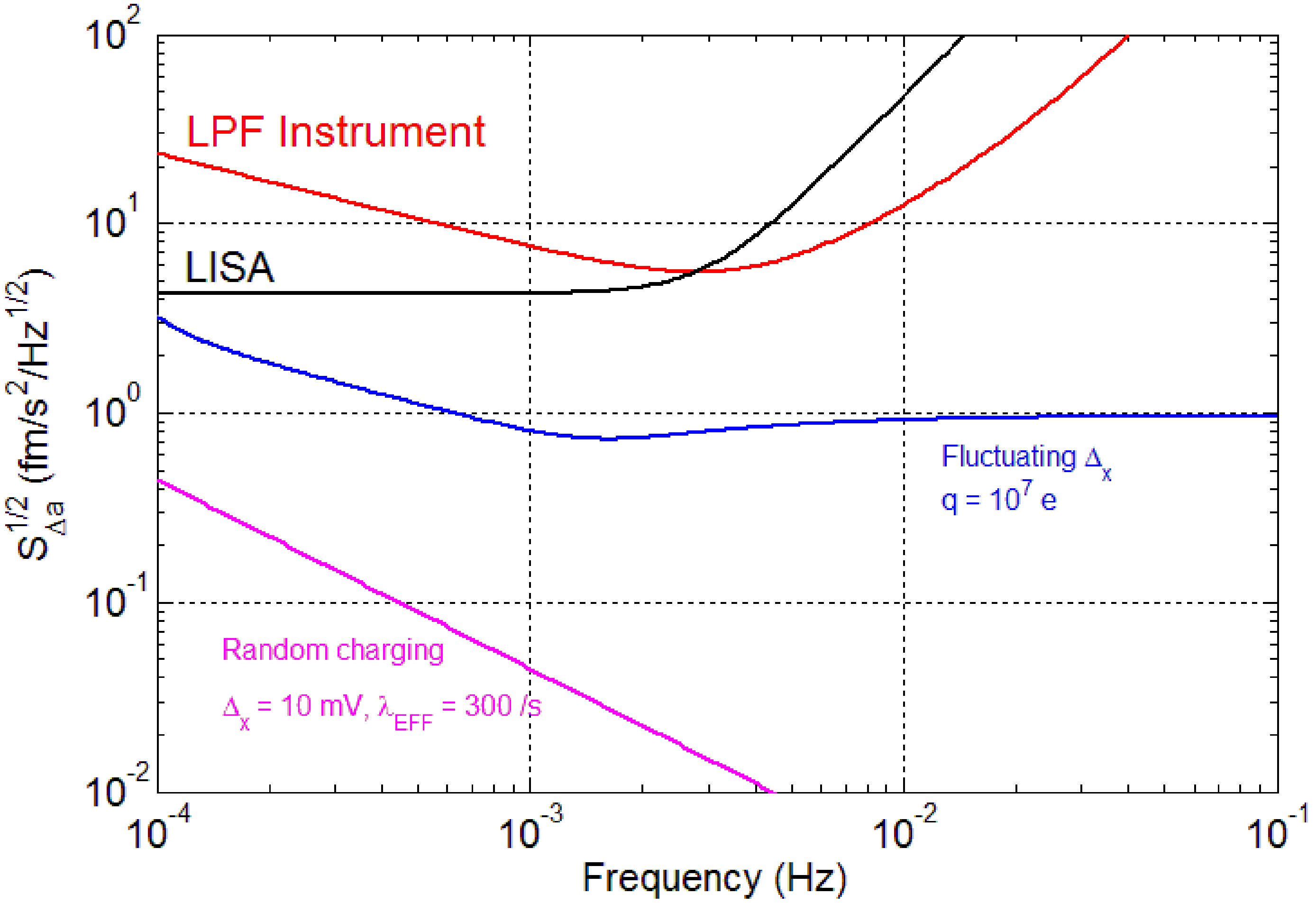
TM charge ***Q***
Patch potentials ***δV***

$$\left\{\begin{aligned}
S_F^{1/2} &= \frac{\sqrt{2e^2\lambda_{EFF}}}{\omega C_T}\left|\frac{\partial C}{\partial x}\right|\Delta_x \\
&\approx 7\ \mathrm{fN/Hz}^{1/2} \times \left(\frac{\Delta_x}{100\ \mathrm{mV}}\right) \times \left(\frac{\lambda_{EFF}}{300\ /\mathrm{s}}\right)^{1/2} \times \left(\frac{f}{0.1\ \mathrm{mHz}}\right)^{-1} \\
S_F^{1/2} &= \frac{\langle q \rangle}{C_T}\left|\frac{\partial C}{\partial x}\right| S_{\Delta_x}^{1/2} \\
&\approx 1.6\ \mathrm{fN/Hz}^{1/2} \times \left(\frac{\langle q \rangle}{10^7\ e}\right) \times \left(\frac{S_{\Delta_x}^{1/2}}{100\ \mu\mathrm{V/Hz}^{1/2}}\right)
\end{aligned}\right.$$

Random charge shot noise mixing with DC bias (Δ_x)

Noisy average “DC” bias ($S\Delta_x$) mixing with mean charge

Noise Chart



[*PRL* **108**,
181101 (2012)]

Noise proportional to 1/gap

Mitigation

MECHANISMS

UV lamps illuminating electrodes or TM

- Neutralize TM charge
- Periodic or continuous activity
- Lead by CMS
- Charge measurement

DC compensation: we need to measure Δ_x

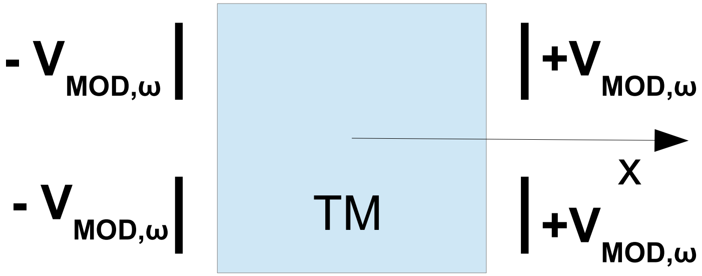
- The DC Bias Experiment

Charge Management

Basic mechanism of the CMS

$$F_x = -4\frac{q}{C_{TOT}}\left|\frac{\partial C_x}{\partial x}\right| V_{MOD}\sin\left(2\pi f_{MOD}t\right)$$

Sinusoidal varying potential



- Charge by demodulating and scaling
- Charge rate by using previous measurement
- UV lamp illumination
- DC voltage applied to help the process

PROCESS LAST AN HOUR OR SO

Long term charge measurement

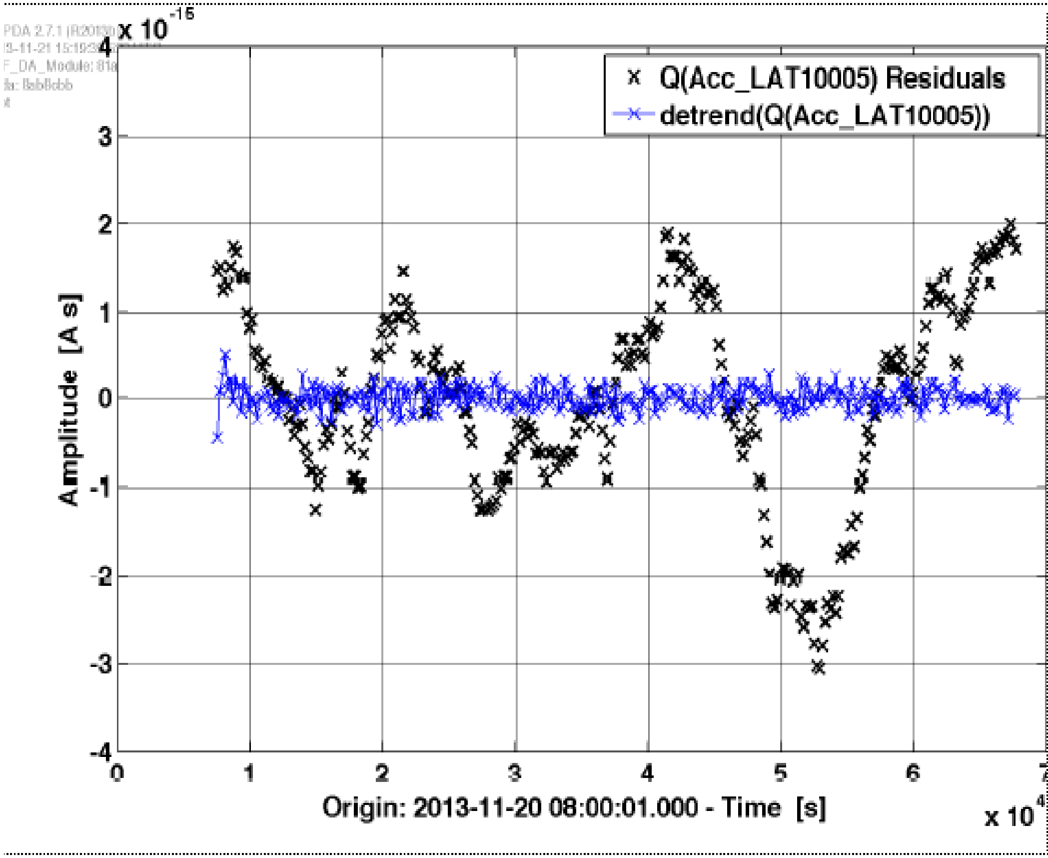
IT TAKES ALMOST A DAY

- Extract TM charge and TM charge rate
- Highlight drift term due to uncompensated DC bias
- Estimate the random charging

→ Noise projection from charge to acceleration

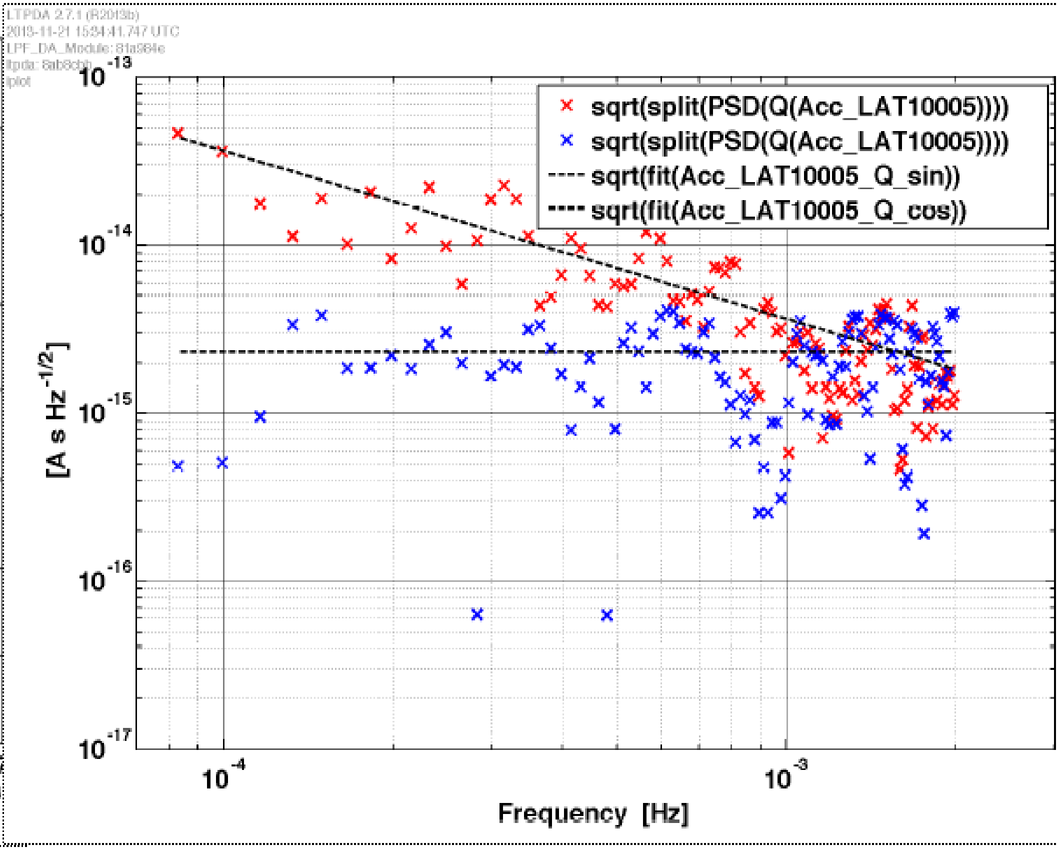
Example

Random charging



Charge residuals time series

Data range ~ 4 [fC]



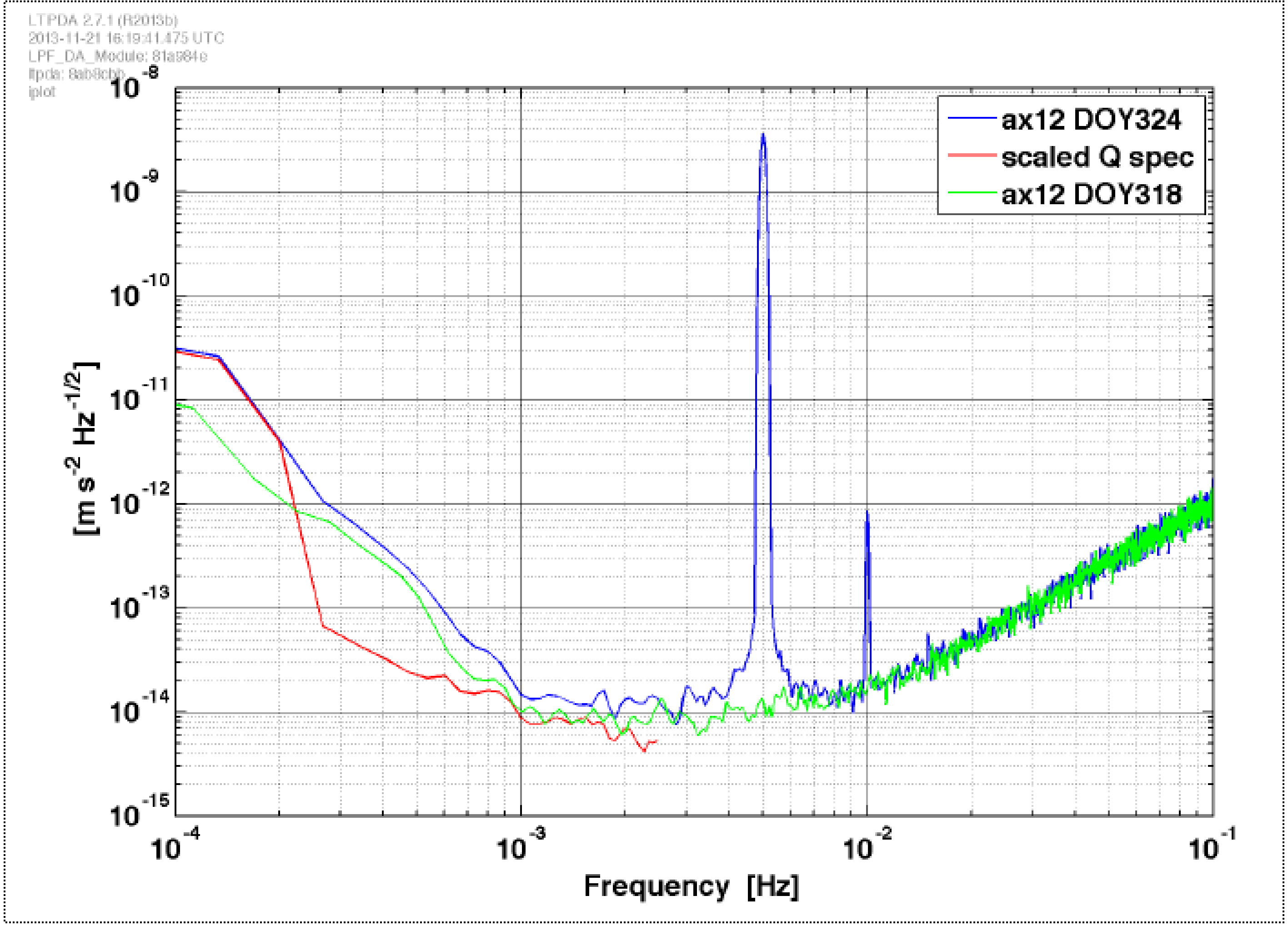
Charge residuals spectrum

$S^{1/2}(q) \sim 2$ [fC/Hz$^{1/2}$]

EXAMPLE

Projected charge noise
Noise run
Long charge measurement

$$S_F^{1/2} = \frac{S_q^{1/2}}{C_{TOT}} \left| \frac{\partial C_x}{\partial x} \right| \Delta_x$$

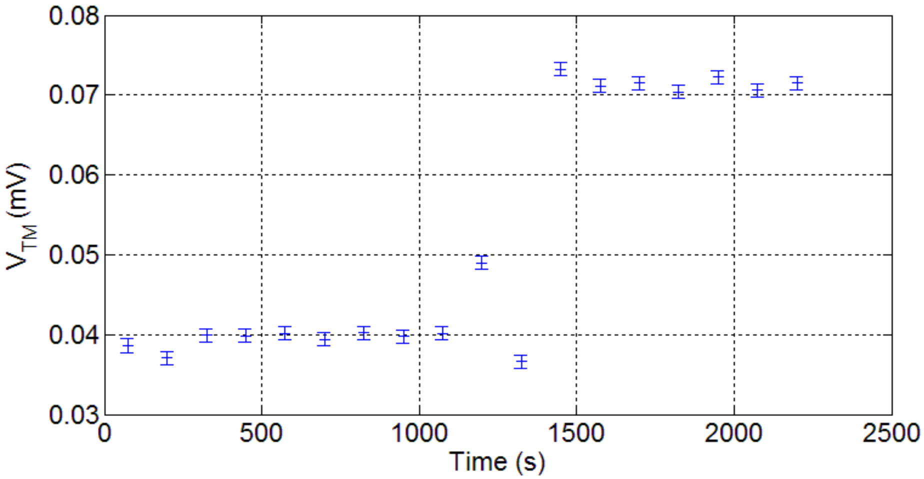


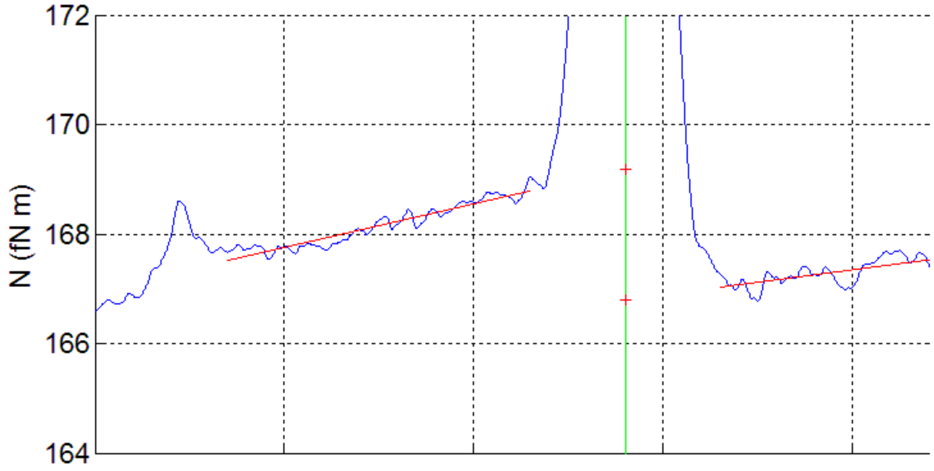
DC Bias Experiment: The LAB Experience

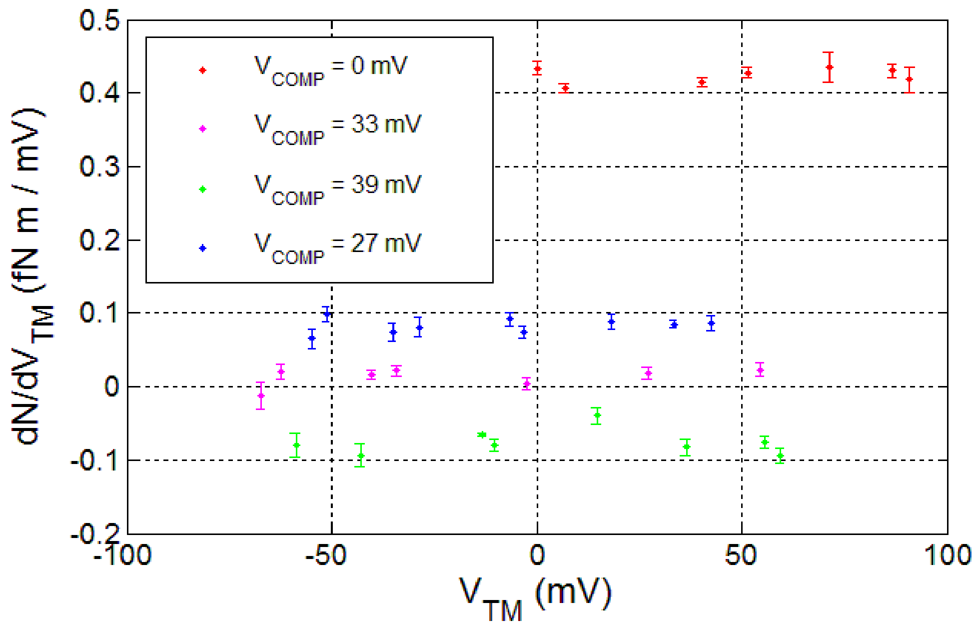
Ideal measurement of Δ_x : vary Q and measure dF/dQ

- We need to change the TM charge
- Measure ΔF and ΔQ
- Extrapolate compensation voltages

In LAB we measure torque! **N** instead of **F.** Δ_ϕ instead of Δ_x







Roughly -2 fN m for 30 mV TM potential change (5 million charges) and Δ_ϕ ~ +20 mV

DC Bias Experiment: The LAB Experience

Compensation voltage pattern

$-V_{comp}$ $+V_{comp}$

TM x

$-V_{comp}$ $+V_{comp}$

Force to charge gradient as a function of $\mathbf{V}_{\mathbf{comp}}$

$$\frac{\partial F_x}{\partial q} = -\frac{1}{C_{TOT}}\frac{\partial C_x}{\partial x}(\Delta_x + 4V_{COMP})$$

The right compensation is that that nulls the force gradient

On Board

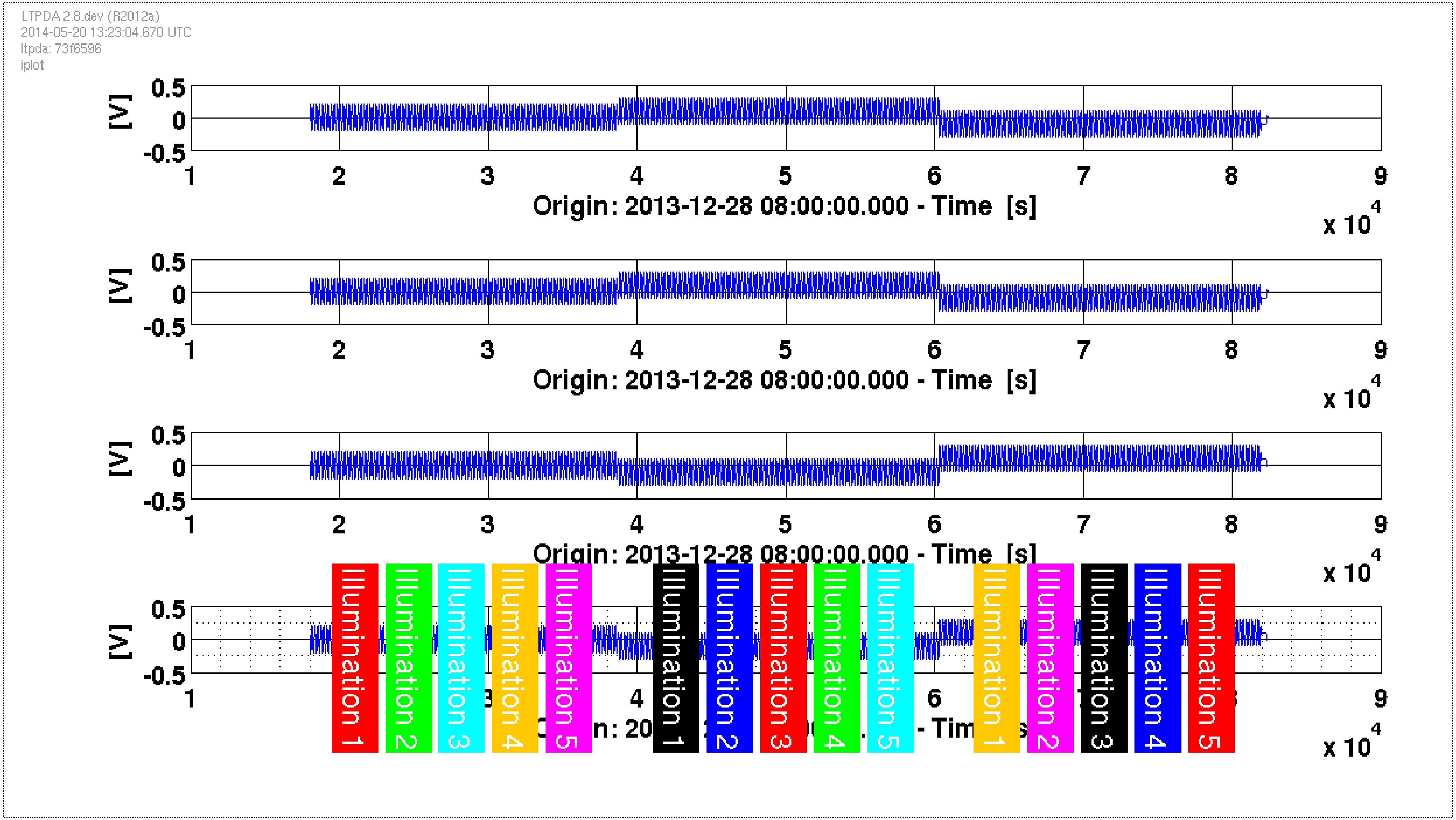
The DC Bias experiment is scheduled in the LPF operations

THE EXPERIMENT

- We use the UV lamp to produce charge step on the TM
- We add a charge measurement signal
- We use three (or more) sets of DC bias voltages
- We extrapolate the one that compensates for Δ_x

DC Bias Experiment

The commands

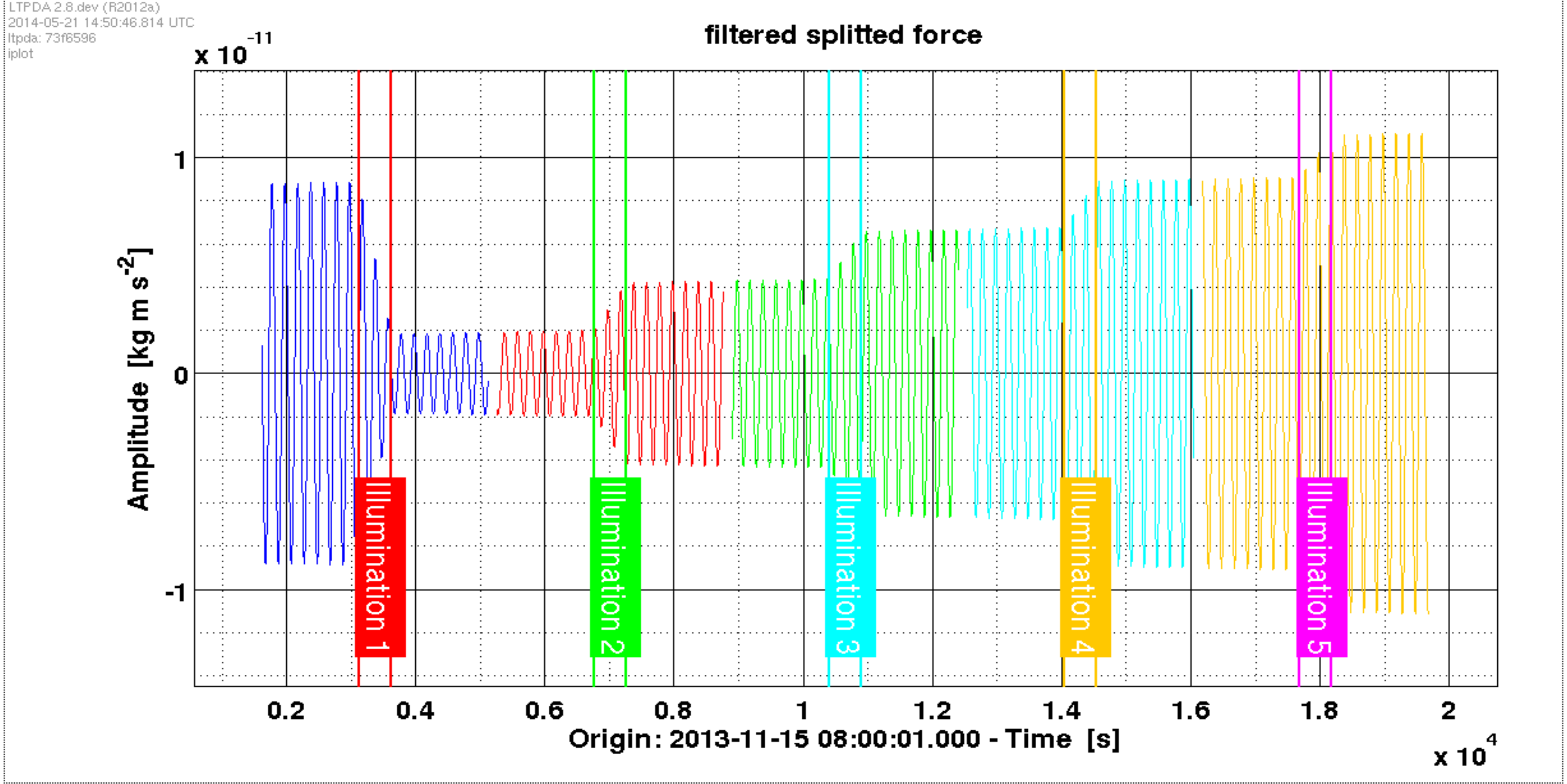


Data Analysis Technique

Extract force from IFO measurements

Mild whitening mainly to remove low frequency drift

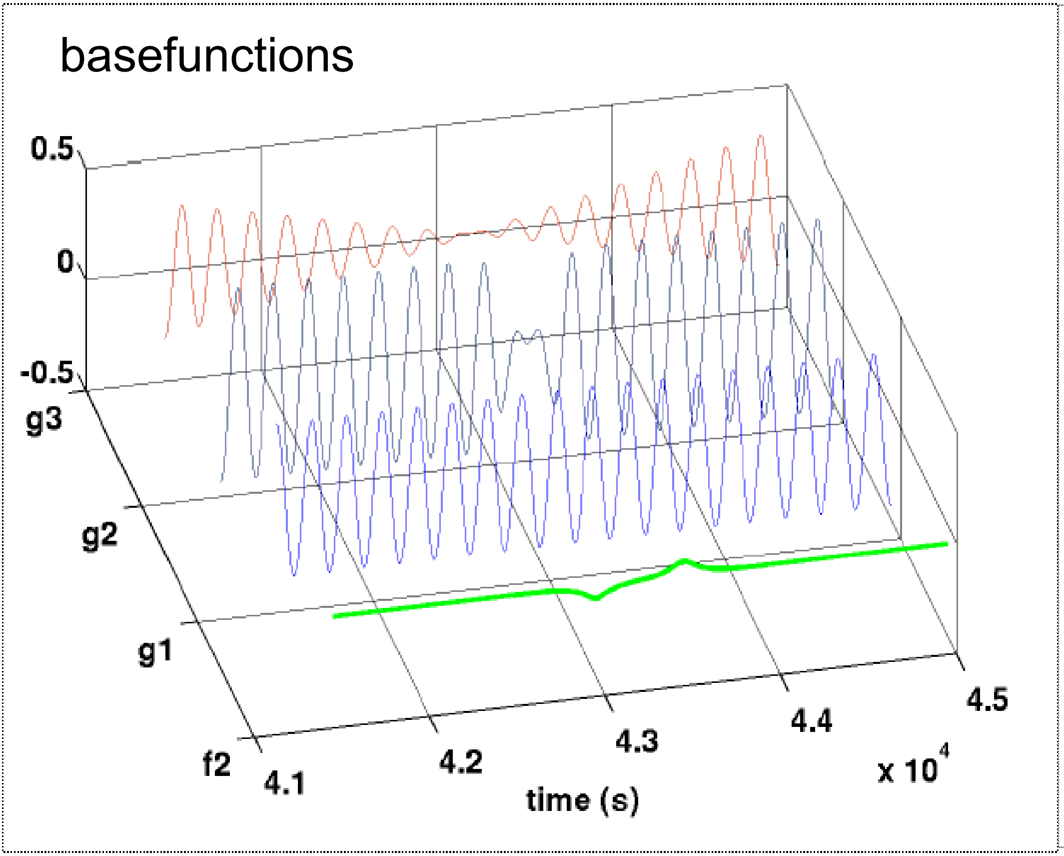
$$F_x = -\frac{q}{C_{TOT}}\left|\frac{\partial C_x}{\partial x}\right|\left[4V_{MOD,\omega} + (\Delta_x + 4V_{COMP})\right] + \frac{q^2}{C_{TOT}^2}\frac{\partial^2 C_{TOT}}{\partial x^2}(x - x_0) + \ldots$$

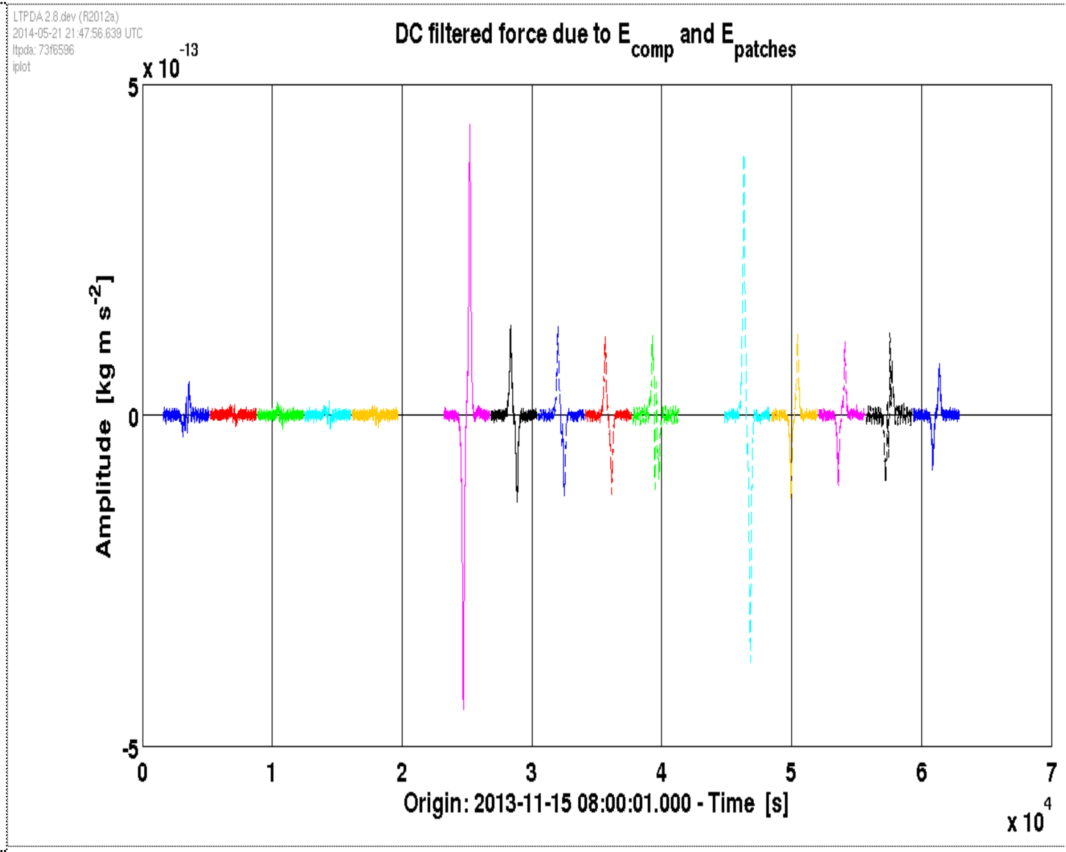


Data Analysis Technique

Fit in time, per UV step, to extract the charge and the charge rate

Subtract the force signal due to charge measurement





Force steps due to charge to patch potential coupling

Data Analysis Technique

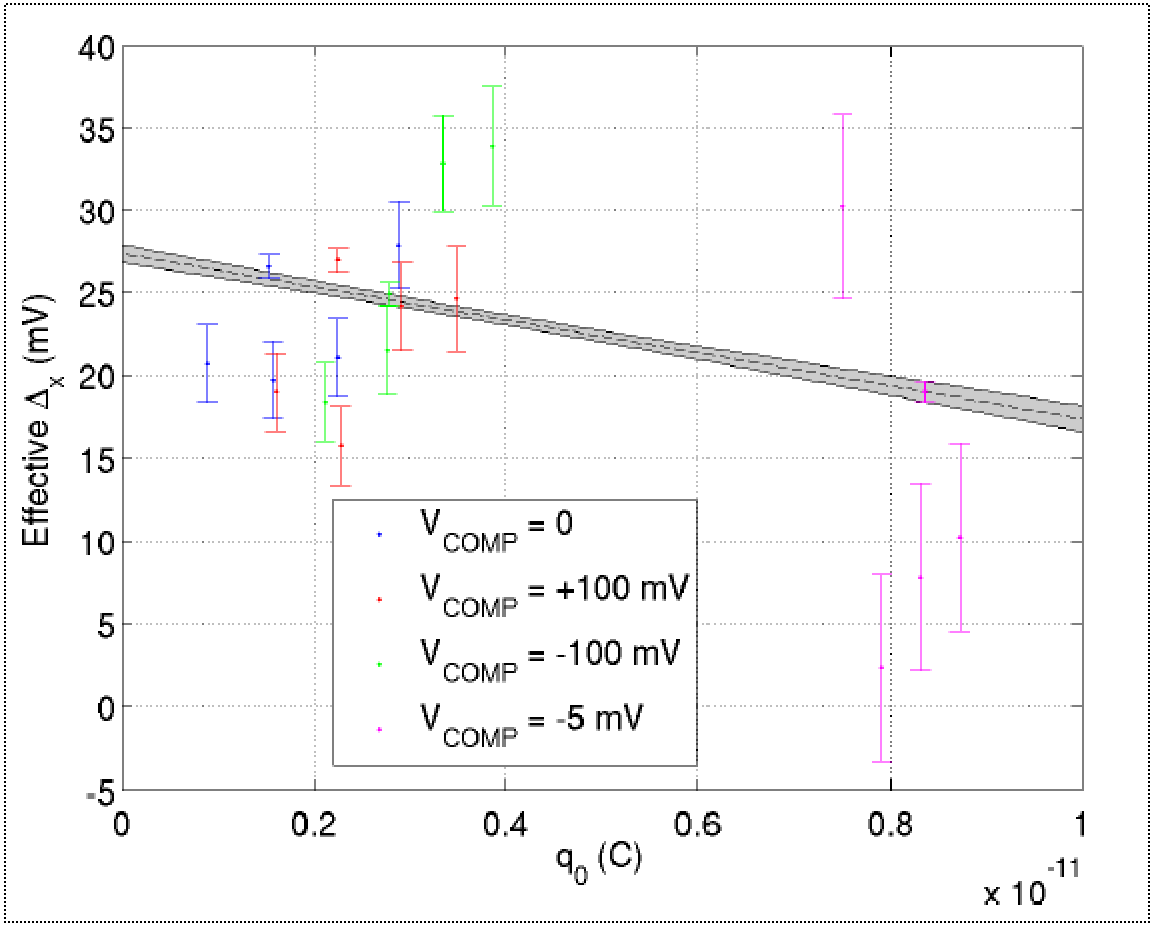
Fit: residual force versus charge, per UV step, to calculate the force to charge gradient (the dF/dQ!)

Fit all the dF/dQ data points versus the charge and different sets of V_{comp} to get Δ_x

A priory estimate of dF/dQ running step 1 on noise run data

$$\delta\left(\frac{\partial F_x}{\partial q}\right) = \sqrt{\left(\frac{\delta\left(\Delta F\right)}{\Delta q}\right)^2 + \left(\frac{\Delta F}{\Delta q}\right)^2 \left(\frac{\delta\left(\Delta q\right)}{\Delta q}\right)^2}$$

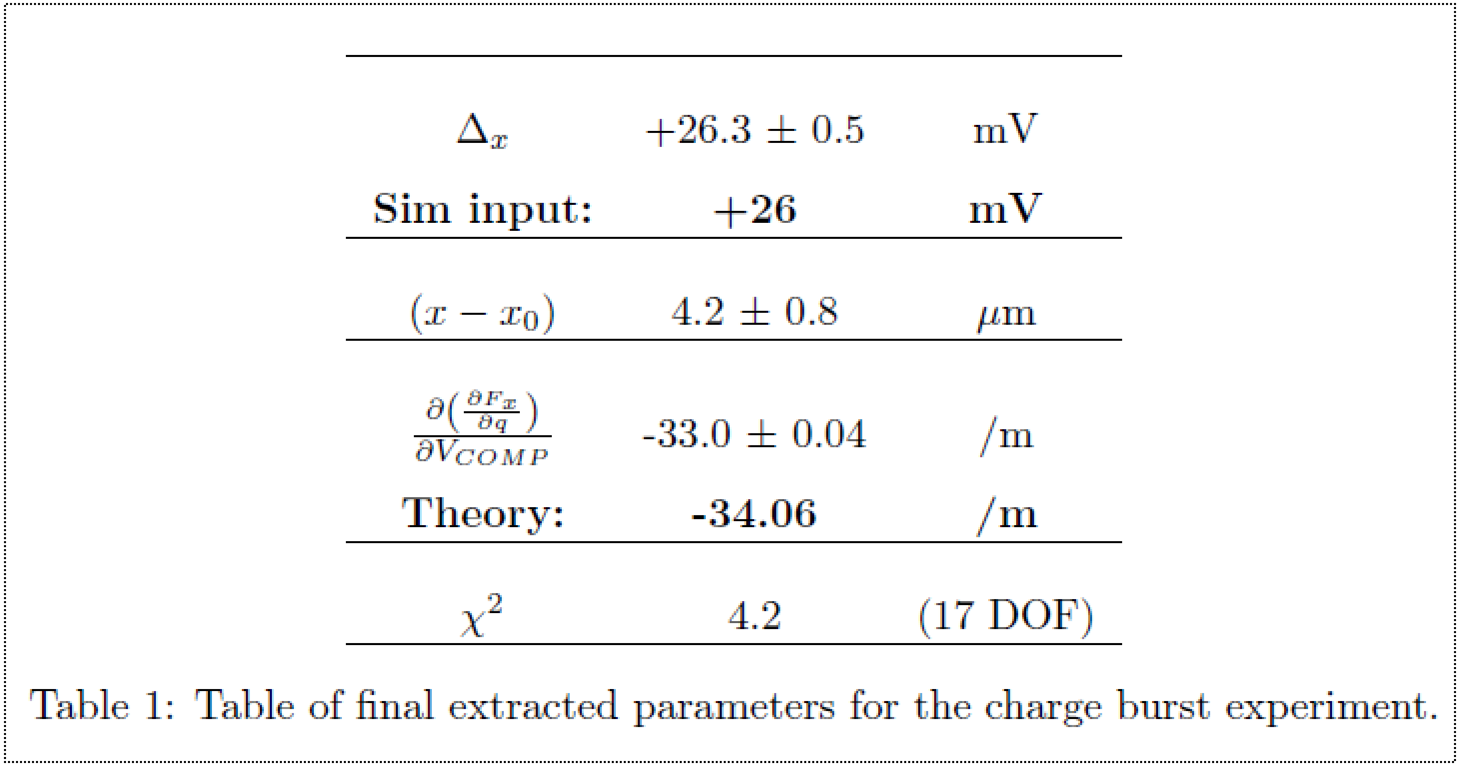
Ideal would be being at q~0. Different sets of dF/dq data for different charging status of the TM have a beneficial leverage effect.



Simulation Results

- 20 UV steps of charge
- 4 sets of compensation voltages
- Charge range from 1 to 9 [pC]

OSE simulator data



Δ_x	$+26.3 \pm 0.5$	mV
Sim input:	$+26$	mV
$(x - x_0)$	4.2 ± 0.8	μm
$\frac{\partial(\frac{\partial F_x}{\partial q})}{\partial V_{COMP}}$	-33.0 ± 0.04	/m
Theory:	-34.06	/m
χ^2	4.2	(17 DOF)

Table 1: Table of final extracted parameters for the charge burst experiment.

SOLID TECHNIQUE. RESULTS REMAIN CONSISTENT WITH MANY RUNS OF SIM DATA

Conclusions

- Patch effects are expected to be at the **fN/Hz$^{1/2}$**
- Patch effects could be an issue for eLISA, not for LPF
- Mitigation techniques are available, tested on the ground and with SIM data
- LPF is the bench test