Geodesic reference performance limits for space gravitational wave missions

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for the LISA Pathfinder Project

Gravitational Wave Advanced Detector Workshop

Isola d'Elba, 24 May 2013

GW detection as “differential accelerometry” measurement

- Tidal accelerations between 2 or more geodesic reference test masses
- Need reference masses in free-fall(*) and measurement of their separation

$$\Delta a_h \approx \omega^2 L h$$

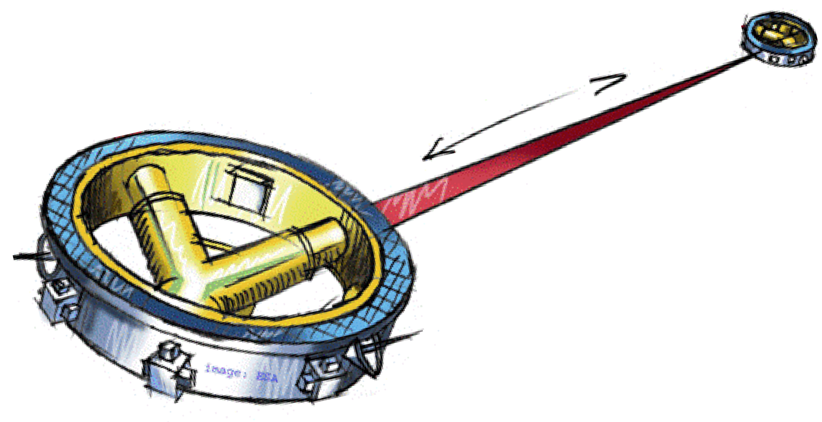
Effective “GW acceleration”

$$\Delta a_{measure} \approx \omega^2 x_n$$

distance measurement noise

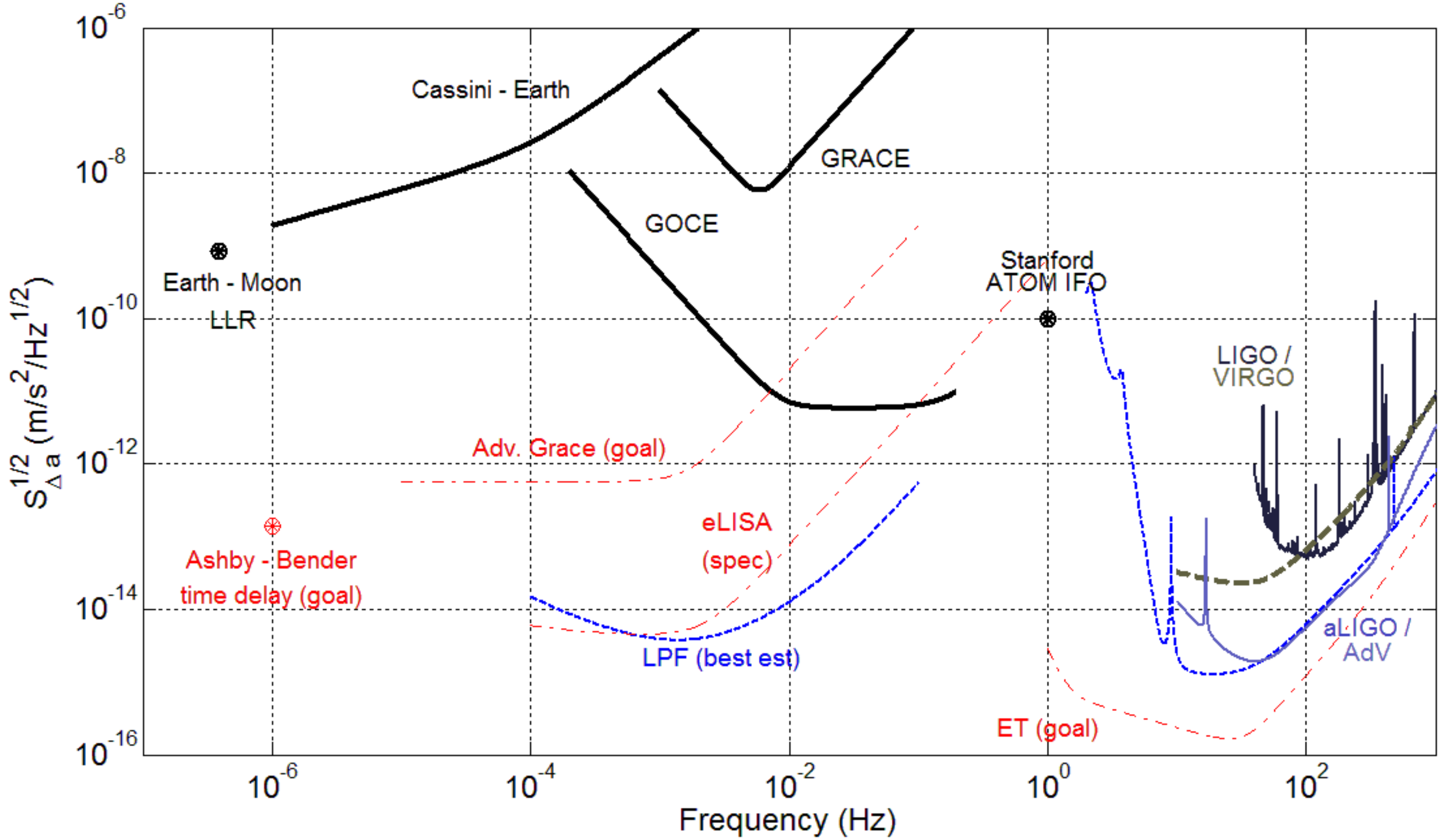
$$\Delta a_{force} \approx \frac{\Delta f}{m}$$

Stray force noise (imperfect geodesic motion)



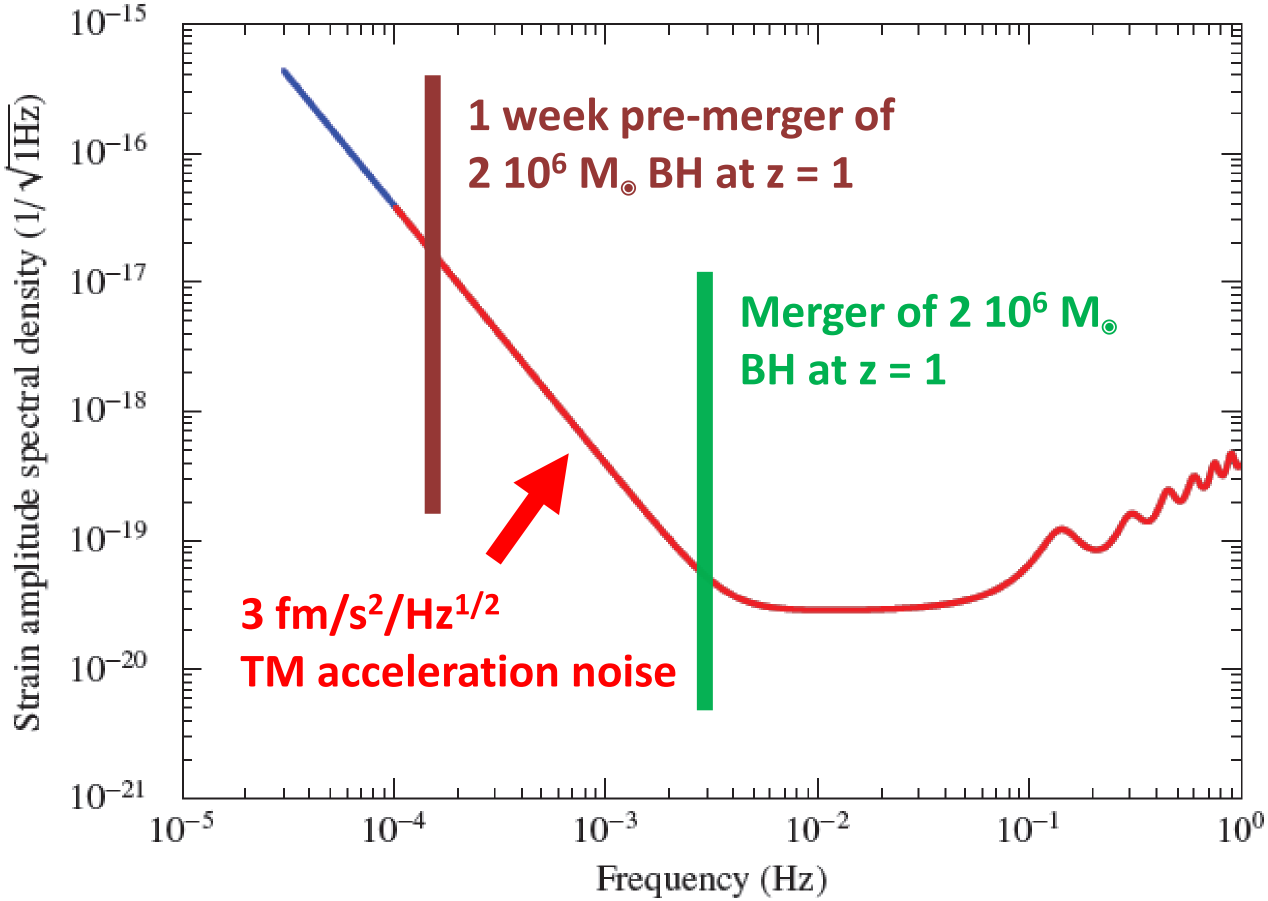
(*) Force free except for known, calibrated control / suspension forces

Differential acceleration measurement in experimental gravitation



- space GW observation: requirements and design
- What we know: main limits, tests on ground and space (LISA Pathfinder)
- Extensions of eLISA /LPF GRS heritage to future missions

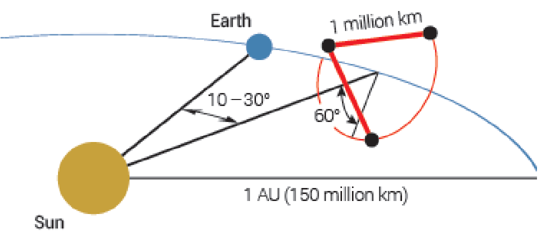
eLISA Strain Noise and Massive Black Hole Science



- Acceleration noise dominates GW sensitivity below 5 mHz
- Low frequency performance critical to massive black hole science

eLISA Measurement Concept

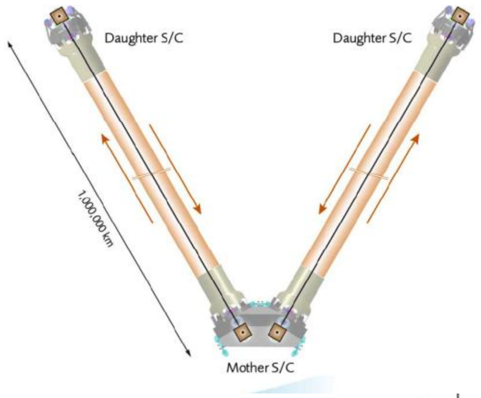
[ESA L2 mission candidate: http://support.elisascience.org/]



- synthesized 1 million km Michelson with free-falling TM
- interferometer TM – TM measurement in 3 parts:

  TM-SC → SC-SC → SC-TM

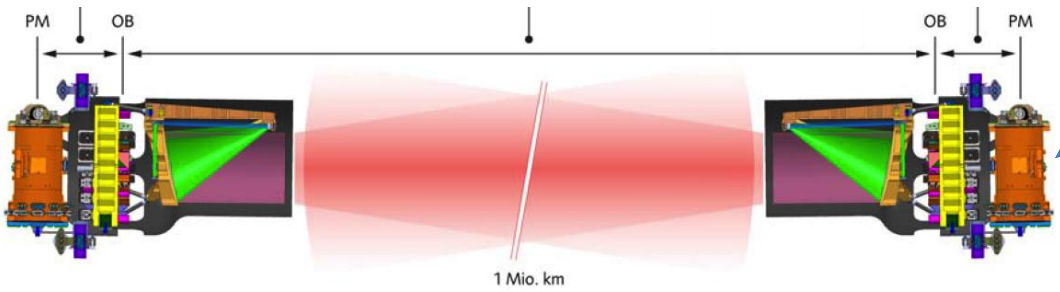
  → **12 pm/Hz$^{1/2}$**



- Drag-free TM → SC follows TM along sensitive axes

  → **3 fm/s^2/Hz$^{1/2}$**

- nm/Hz$^{1/2}$ spacecraft control
- nN force control on non-IFO axes



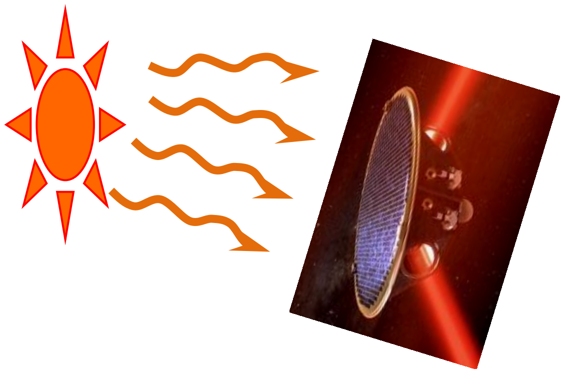
Test mass Inside GRS

W. J. Weber
GWADW, May 2013

The road to eLISA GRS design (what we can't do)

Spacecraft as a geodesic reference (Cassini, Pioneer)

Solar radiation pressure



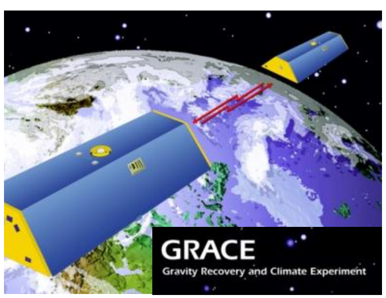
On a 5 m^2 / 300 kg spacecraft

DC acceleration **100 nm/s^2**

Fluctuations **10^{-10} $m/s^2/Hz^{1/2}$**

Locating spacecraft CM also difficult

A reference TM accelerometer to correct satellite motion

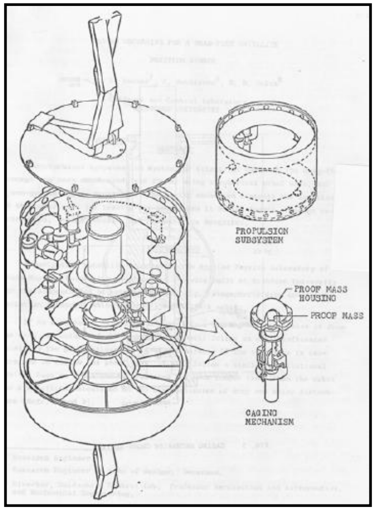


- Microwave ranging between satellites
- Accelerometers corrects for non-inertial spacecraft motion
- **Accelerometer TM "forced" to follow spacecraft**

→ can't apply 100 nm/s^2 with < $fm/s^2/Hz^{1/2}$ noise

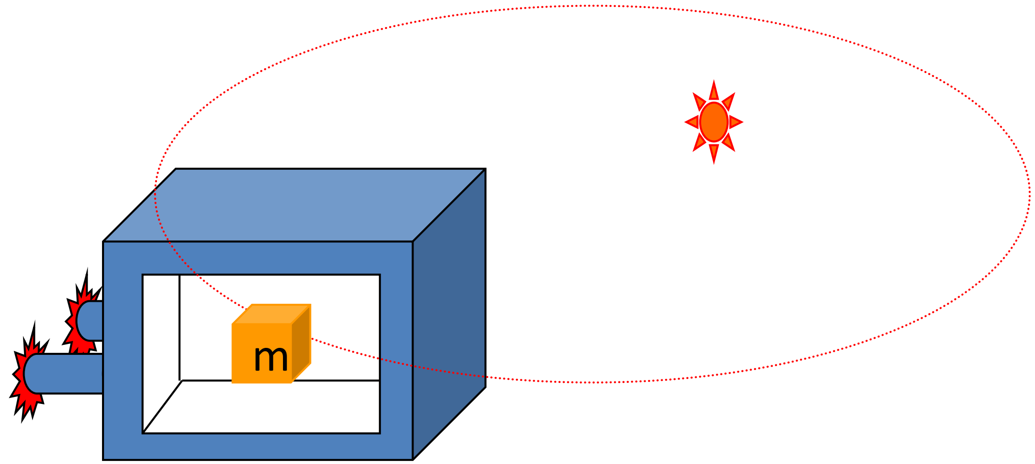
→ Requires "drag-free" spacecraft shielding a free-falling reference TM

Drag-free control for precision geodesic reference TM



TRIAD, 1972
[from *CQG* **28,** 094015 (2011)]

- Triad, GPB
- Control satellite to follow a free-falling reference TM
  - → Microthrusters with control gain ω_{DF}^2
- No forces on TM, at least on measurement axis



$$a_{res} = g + \omega_p^2 \left(x_n + \frac{F_{SC}}{M\omega_{DF}^2} \right)$$

SC jitter Δx

Free-fall of TM limited by:

g – acceleration from noisy stray forces

$\boldsymbol{\omega_p^2 * \Delta x}$ – elastic coupling * SC jitter

For LISA: need free-falling TM (not satellite)

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LISA Pathfinder esa

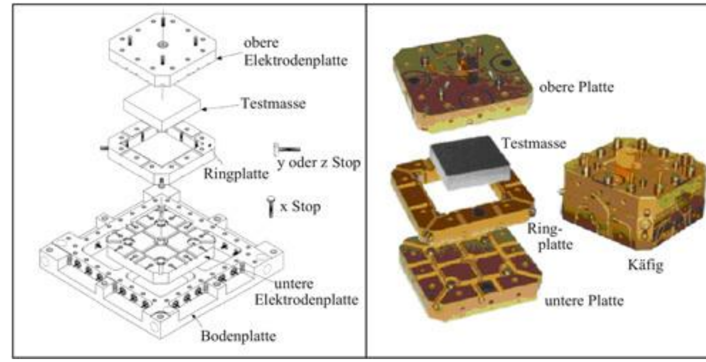
UNIVERSITÀ DEGLI STUDI DI TRENTO

INFN Istituto Nazionale di Fisica Nucleare

Existing space electrostatic accelerometers

TM – electrode gaps of order 100 microns

GPB (30 μm), GRACE/GOCE/μ–Scope (200-300 μm)



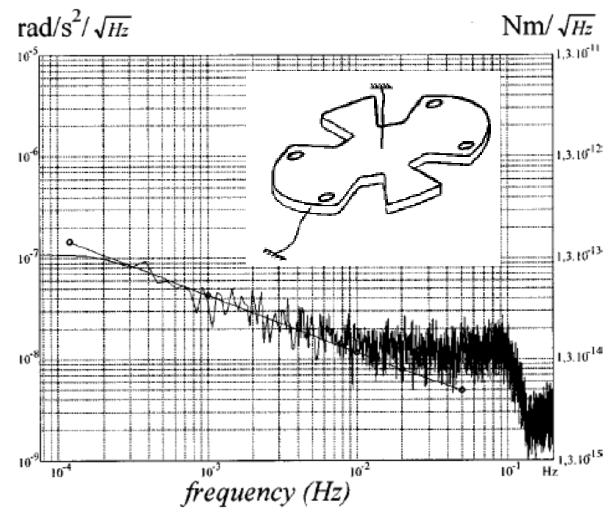
With 300 μm gaps

- Electrostatic: 10 μV/Hz$^{1/2}$, 10 mV → 10 fN/Hz$^{1/2}$
- Brownian gas noise, 10^{-8} mB → 30 fN/Hz$^{1/2}$

Thin TM discharge wire

GRACE/GOCE/μ–Scope

7 μm Au wire → thermal noise pN/Hz$^{1/2}$ at 1 mHz

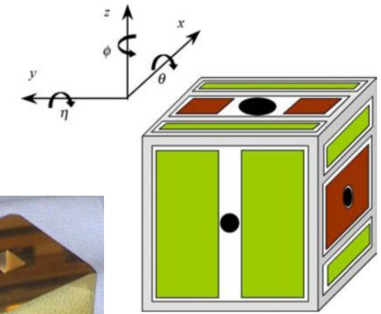


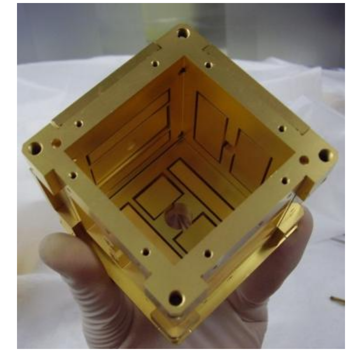
Willemenot and Touboul
Rev Sci Inst **71**, 302 (2000)

→ Need big gaps, no strings attached!

eLISA / LISA Pathfinder gravitational reference sensor (GRS)

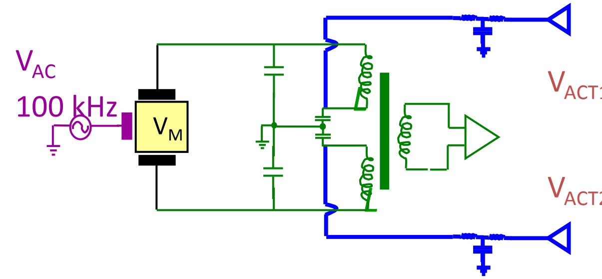
- **Defines TM environment**
- **nm/Hz$^{1/2}$ measurement on all axes**
  - **10 pm/Hz$^{1/2}$ interferometer used on *x* axis**
- **nN actuation forces (μN non-science)**

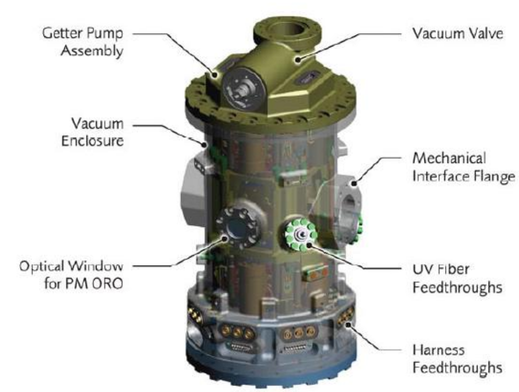




GRS design for LISA PF / LISA

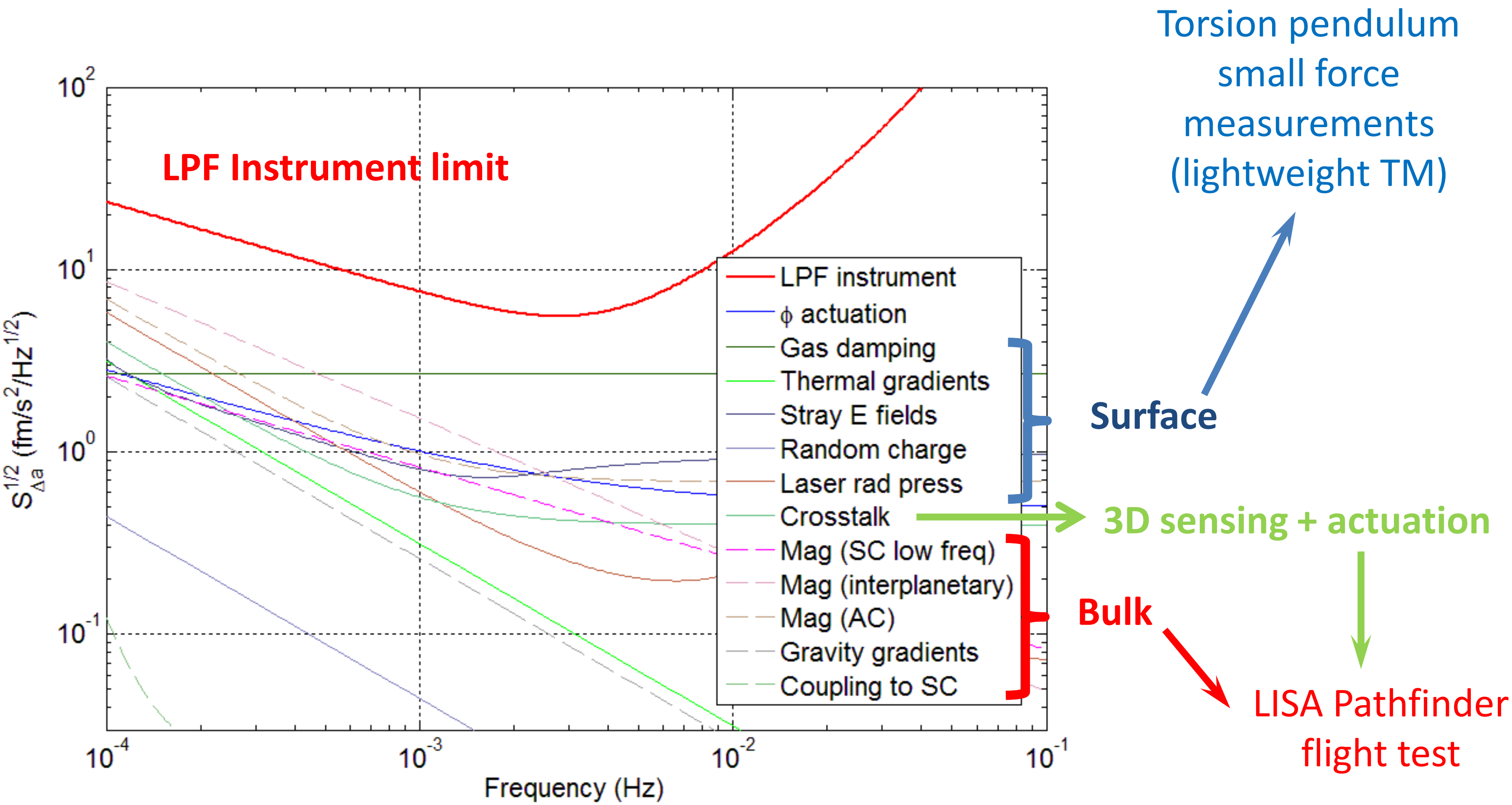
- 46 mm cubic Au / Pt test mass (2 kg)
- 6 DOF capacitive "gap" sensor w/ AC readout
- Audio freq electrostatic force actuation → avoid DC voltages
- Large gaps (3 – 4 mm) → limit electrostatic disturbances
- High thermal conductivity metal / sapphire → limit thermal gradients
- High vacuum (p = 2 μPa) → limit Brownian, radiometric effects
- UV photoelectric discharge
- Caging mechanism for launch lock





Sources of acceleration noise

- **What do we know about about stray forces and what will we learn with LPF?**
- **What should we be able to "guarantee" for eLISA and beyond?**



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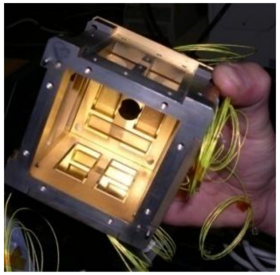
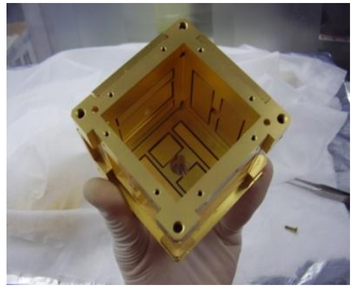
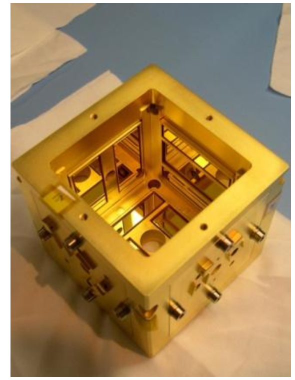
Torsion pendulum measurement of surface forces: free-fall inside LISA / LPF GRS prototypes



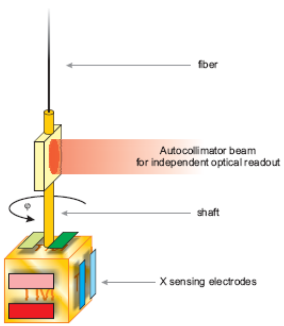
Mo / Shapal EM
(4 mm gaps,
LPF geometry)



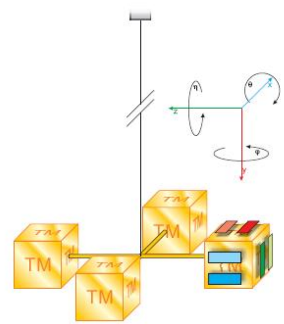
Mo / Sapphire LPF EM



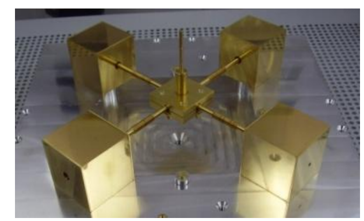
LPF FM-replica +
ELM electronics



1-mass torsion
pendulum
(torques)



4TM pendulum
(force sensitivity)

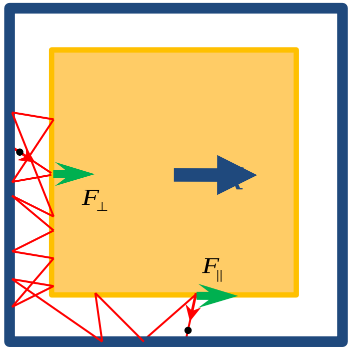


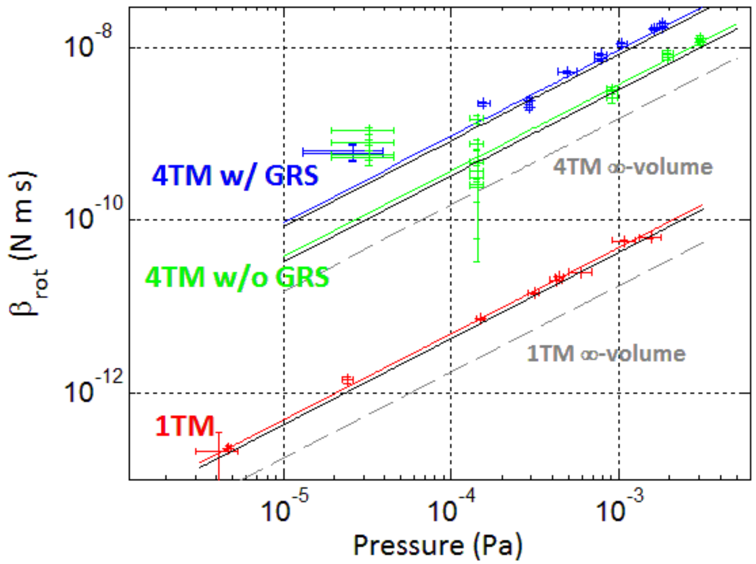
Lightweight TM → test surface forces
Trento, UW, Firenze / Roma / Napoli, Florida
Bulk forces (grav + mag) tested separately with LPF

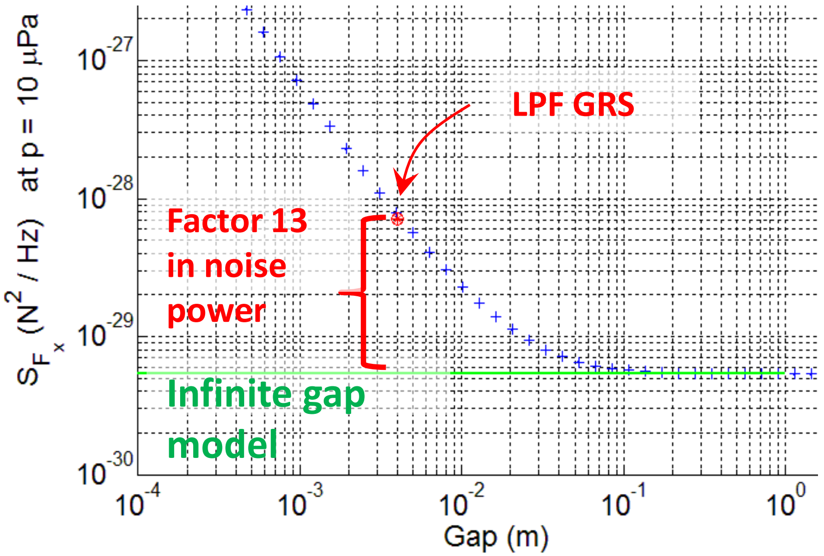
Noise source: Residual gas impacts

Excess damping + Brownian noise in constrained volume

PRL, **103** 140601 (2009) , *Phys Lett A,* **374** 3365 (2010)







Single TM gas damping noise

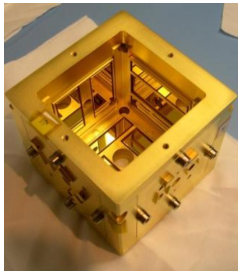
$$S_a^{1/2} \approx 1.8\,\text{fm/s}^2/\text{Hz}^{1/2} \times \left(\frac{p}{2\,\mu\text{Pa}}\right)^{1/2} \left(\frac{m_0}{30}\right)^{1/4}$$

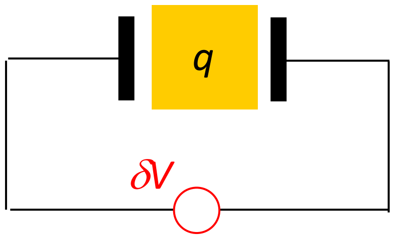
- well modeled and measured
- OK for LISA with 2 μPa
- vent to space → should do much better!

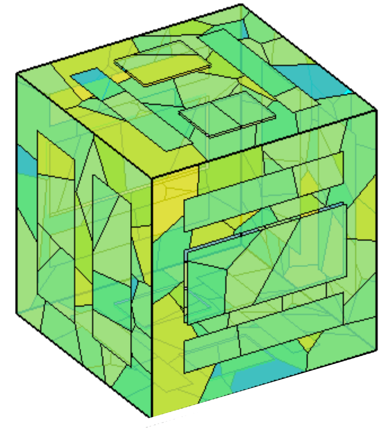
Noise source: stray electrostatics inside GRS

- Conducting Au-coated shield not truly equipotential (patch effects)
- TM charged randomly by cosmic rays (*1/f* or worse!)

[Requires periodic or continuous discharge (UV)]







Largest interaction: TM charge + average residual E field

PRL **108**:181101 (2012)

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

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

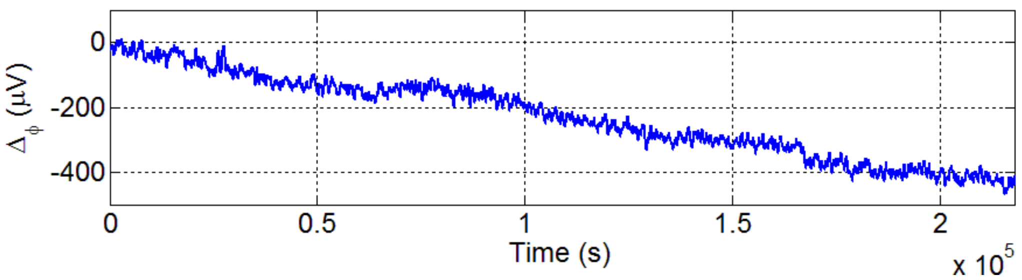
Δ_x : equiv. single electrode potential

- Measure and compensate average DC field

from $\Delta \approx 100$ mV intrinsic to better $\Delta < 1$ mV
lots of experience in lab, will test on LPF

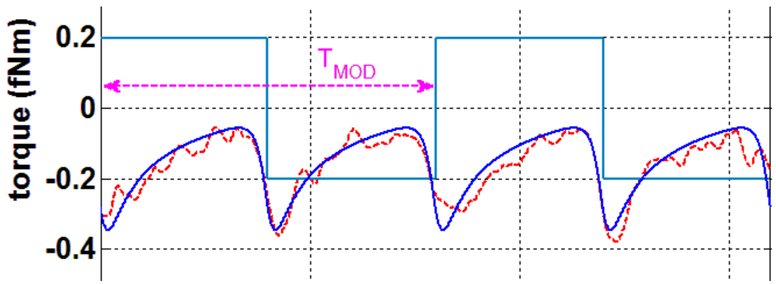
- Need stray potential fluctuations < 20-50 μV/Hz$^{1/2}$

Lab measurement of stray surface potential fluctuations



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

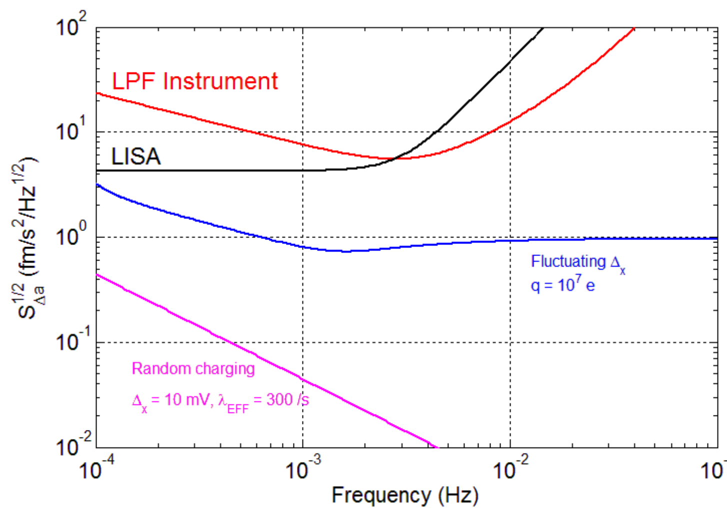
- Single electrode (500 mm^2) average surface potential noise < 12 μV/$Hz^{1/2}$



Electrostatic dissipation (thermal noise):

- "Vacuum gap" capacitor: detect $\delta = 3\ 10^{-7}$
- Thermal contribution ≈ 1 μV/$Hz^{1/2}$

- Upper limits already acceptable for eLISA
- Marginal at 0.1 mHz
- Improving lab measurement



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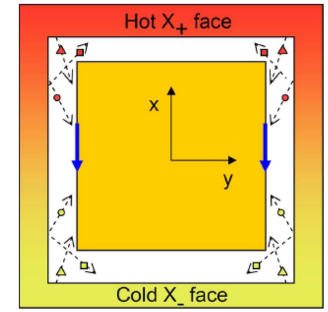
GWADW, May 2013

Noise source: Thermal gradient-induced forces

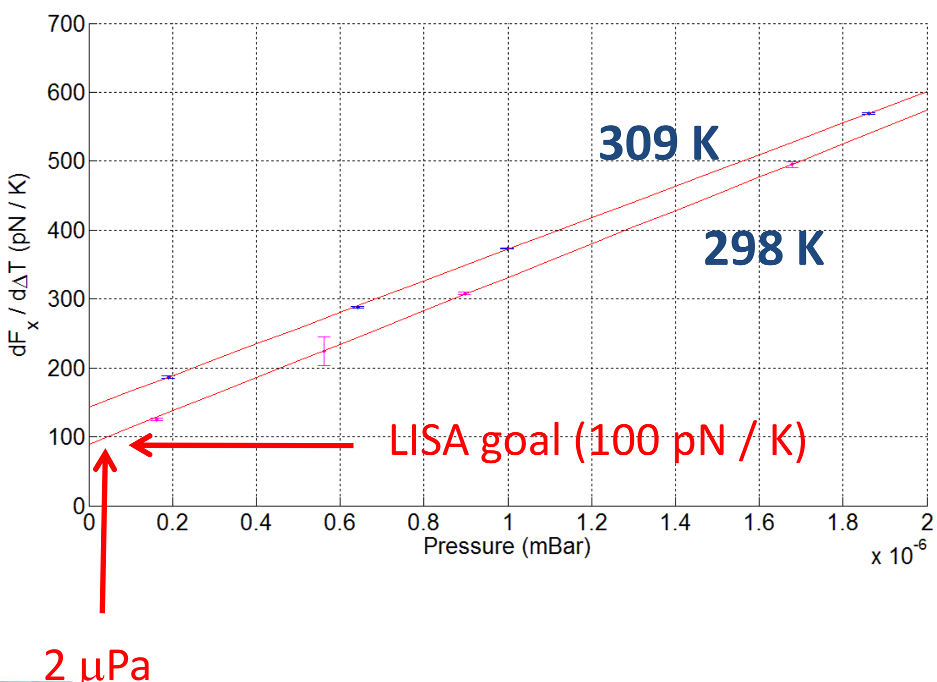
[*PRD,* **76** 102003 (2007); *CQG*, **26** 094012 (2009)]



→ Noise budget: **$dF/d\Delta T$ ~ 100 pN / K**
$S_{\Delta T}^{1/2}$ < 10 μK / $Hz^{1/2}$

→ Radiometric and radiation pressure effects well modeled

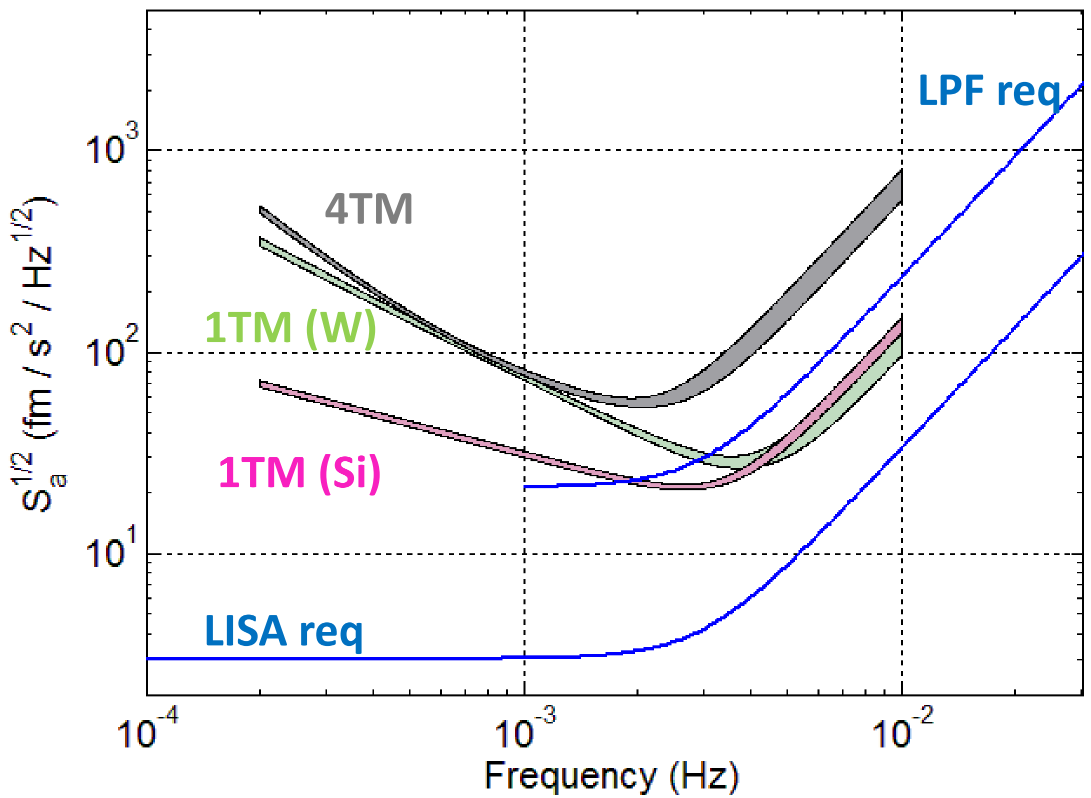
→ Asymmetric outgassing requires measurement (applied ΔT)

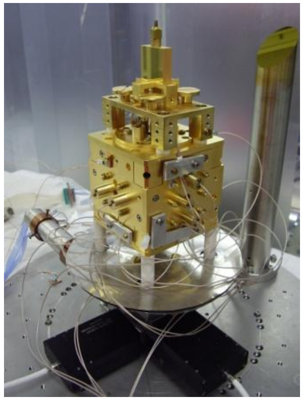


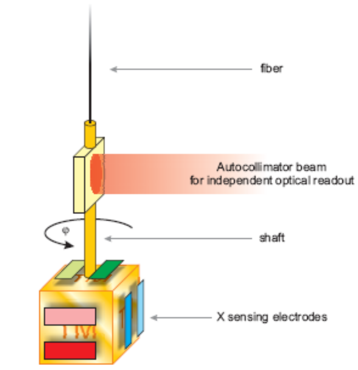
Force measurement with EM GRS

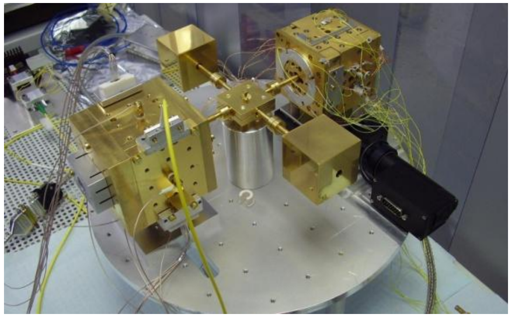
- Verify radiometric model (10%)
- Outgassing observed (pre-bake)
  →*p* = 0 data increase faster than radiation pressure T^3
- **OK for LPF and LISA**

Torsion pendulum upper limits on GRS force noise: conversion from torque → force → acceleration



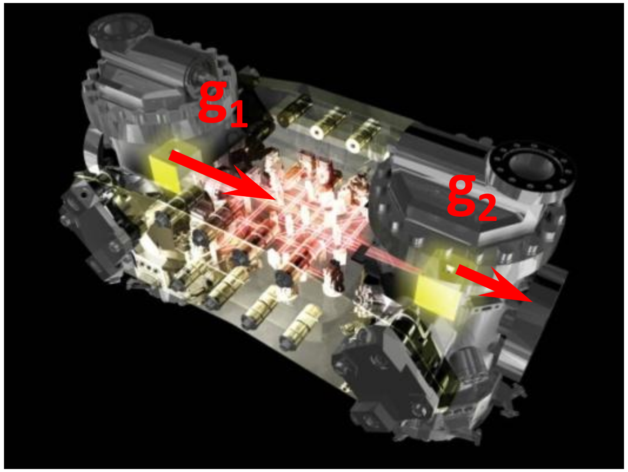




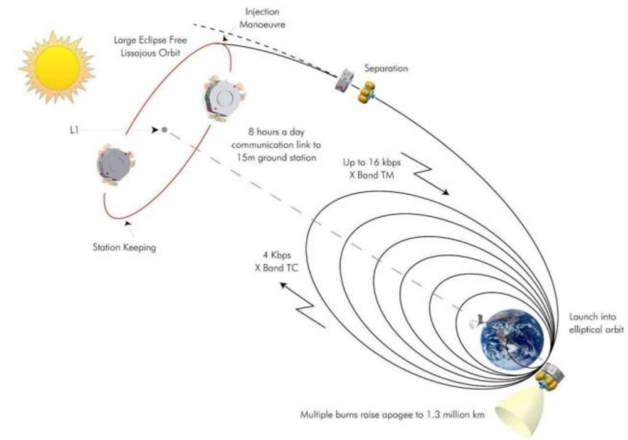


- rule out large class of TM surface disturbances at level of 30 fm/s^2/Hz$^{1/2}$ at 1 mHz
  - within factor 1.5 of LPF goal
  - **bulk forces → LISA Pathfinder**

LISA Pathfinder: Einstein’s Geodesic Explorer (2015)

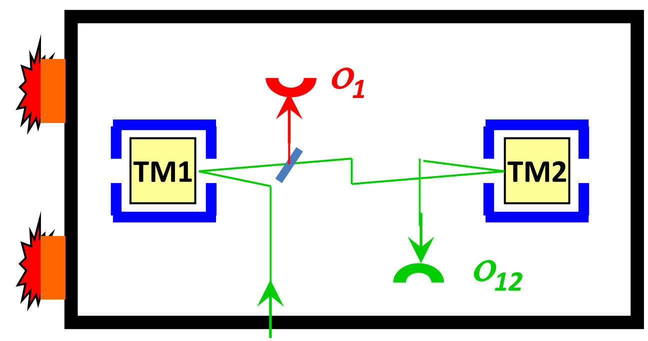


At L1 Lagrange point



Compress single eLISA arm to 40 cm inside 1 spacecraft

Measure differential TM acceleration



Test of eLISA GRS and local IFO measurement

→ flight heritage for eLISA

→ commissioning for eLISA in-flight operations:

drag-free, TM uncaging and discharge, calibrations and tuning

→ physical model of disturbances for free-falling reference TM

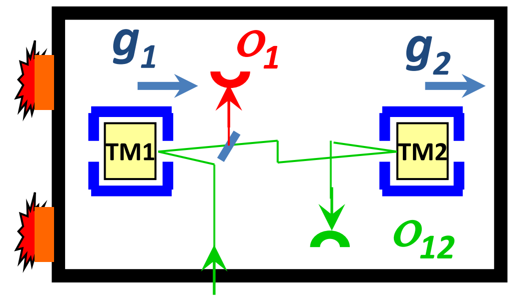
LISA Pathfinder as differential accelerometer (time domain)

Newton's Eqns:

$$m\ddot{x}_1 = mg_1 - m\omega_{1p}^2 (x_1 - x_{SC})$$
$$m\ddot{x}_2 = mg_2 - m\omega_{2p}^2 (x_2 - x_{SC}) + F_{ES}$$

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

IFO Noise

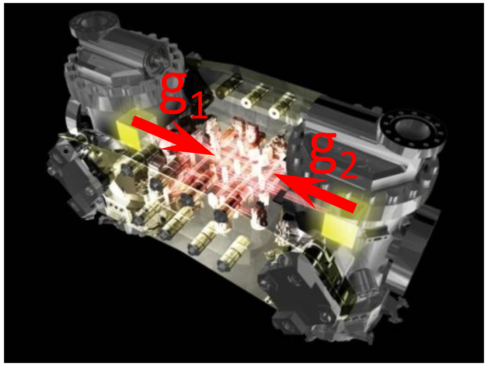
$$g_2 - g_1 = \ddot{o}_{12} - F_{ES} + (\omega_{2p}^2 - \omega_{1p}^2) o_1 + \omega_{2p}^2 o_{12} \quad + \ddot{n}_{12} + (\omega_{2p}^2 - \omega_{1p}^2) n_1 + \omega_{2p}^2 n_{12}$$

Commanded control forces

Elastic coupling

- Produce differential acceleration time series $g_2 - g_1$
- Spacecraft coupling term (stiffness) subtracted (also for LISA)
- Need to measure dynamic parameters: stiffness, actuator calibration, crosstalk

LPF instrument limit: noisy compensation of DC gravity imbalance



Noise in "DC" force applied to compensate difference in local **g**

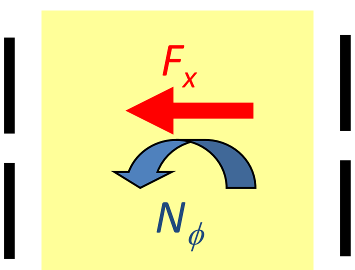
→ **Not present in eLISA!!**

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

Design specs

$\Delta g < 1.3\ \mathrm{nm/s^2}$ → Current **calculations** look better!

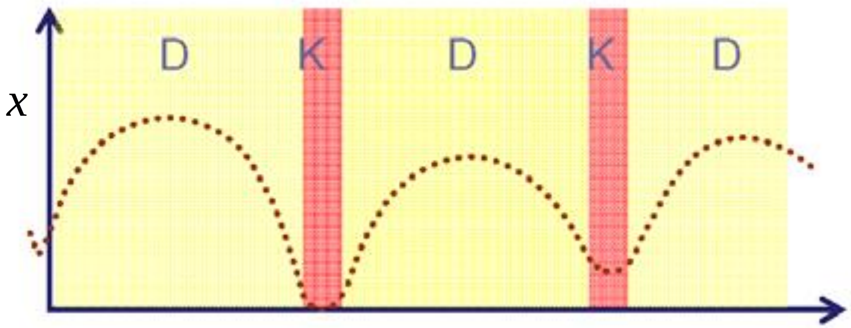
$S_{\delta V/V}^{1/2} < 2 \times 10^{-6}\ /\mathrm{Hz}^{1/2}$ → Current measurements 2-3 worse



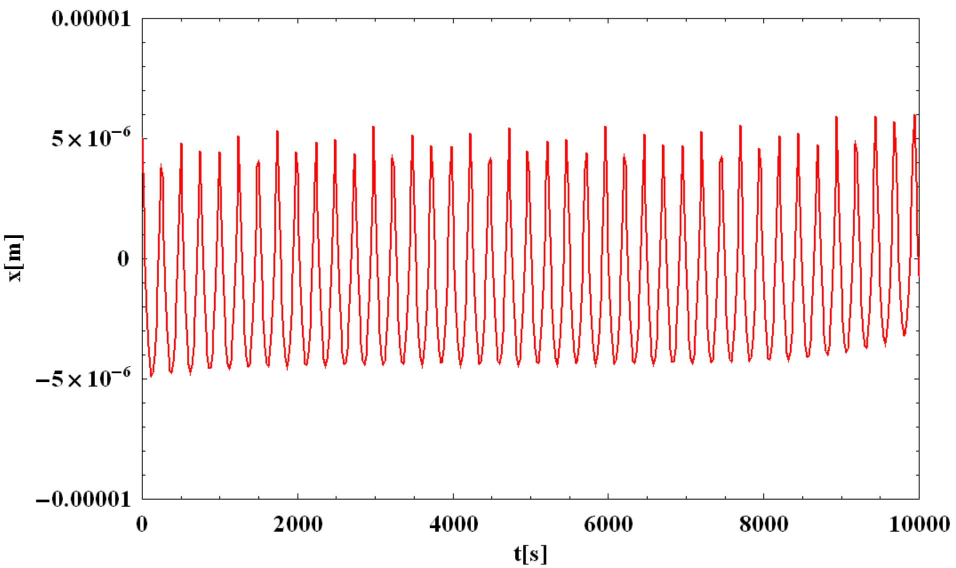
- **Expect < 8 fm/s²/Hz¹ᐟ² at 1 mHz**
- full analysis complicated by uncorrelated voltage fluctuations, ϕ act

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!)

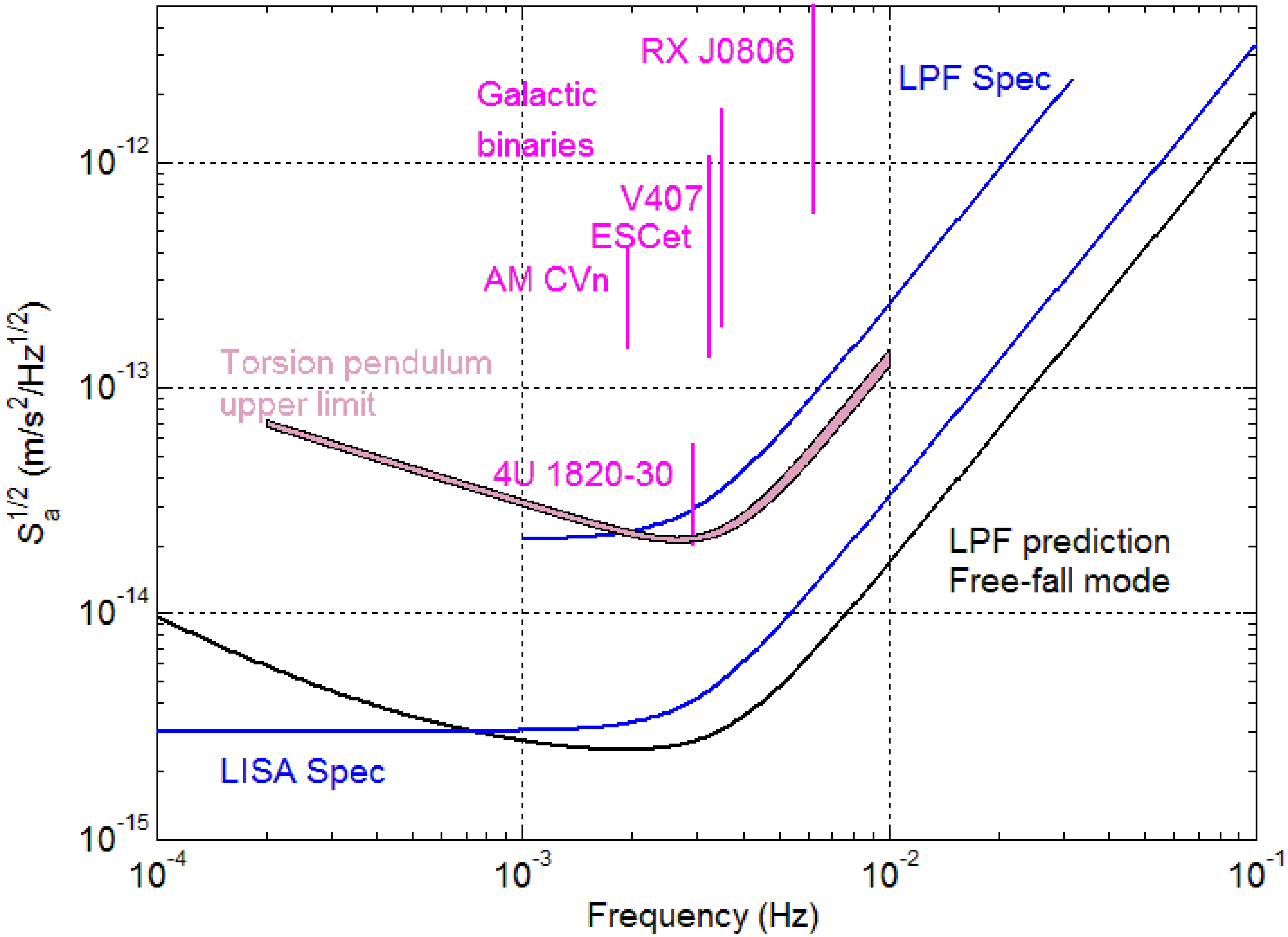


Grynagier, *CQG* **26** (2009) 094007



- Example: Apply 250 x average needed force for 1s, followed by 249 s free-fall
- Keep displacement to 10 micron range
- Throw out data during impulses to measure acceleration noise ***without applied actuation forces***, even to lower frequencies (careful analysis)

LISA Pathfinder performance prediction in free-fall mode



LISA Pathfinder should guarantee most of LISA science

W. J. Weber
GWADW, May 2013

LISA Pathfinder · esa · UNIVERSITÀ DEGLI STUDI DI TRENTO · INFN

LPF also measures

- Measure spacecraft **g** (3 translations and 6 rotations)

Test gravitational balance to better than 10-10 m/s^2

- Force noise from actuation
- Measure temperature fluctuations down to 10^{-4} Hz – and below – and $dF/d\Delta T$
- Measure magnetic environment and forces from applied B
- Measurement and compensation of average stray E field (nulling dF/dq)
- Measure low frequency charge fluctuations with long term charge test
- Stiffness / SC coupling / crosstalk measurements

Create physical model for limits to achieving perfect free-fall

What will LPF teach about eLISA performance at $10^{-6} - 10^{-5}$ Hz?

- eLISA spec for $f > 10^{-4}$ Hz → testing too costly at lower frequencies

- Massive black hole merger ($10^7 - 10^8$ M_{SUN}) science rich at 10^{-5} Hz
- Future GR tests, time-delay need drag-free at 10^{-6} Hz

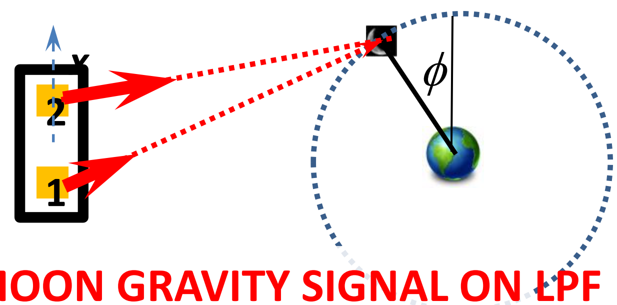
LPF

- 1-2 acceleration noise measurements cover 10^{-5} Hz (free-fall mode)
- Dedicated long term measurements of charge (+ T, B-field)

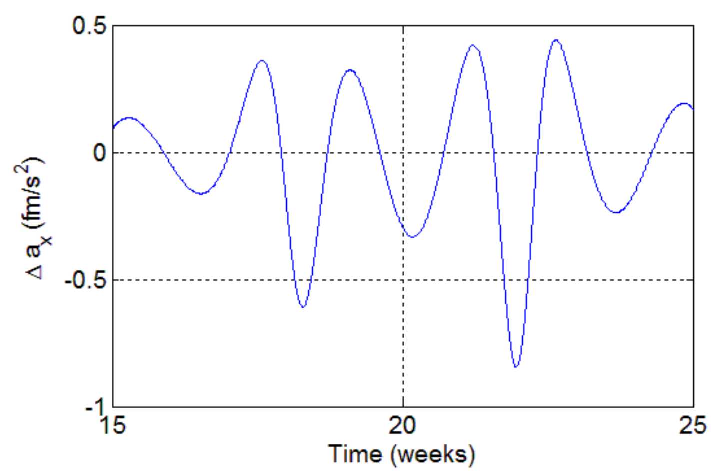
- μHz – Moon test → extract gravity signal from earth-moon system (2/month)
  →requires 8-10 x 1 day acceleration measurements over 1 month

  → SNR = 1 requires 0.5 $pm/s^2/Hz^{1/2}$ → same as time delay requirement!

LPF at L1



EARTH – MOON GRAVITY SIGNAL ON LPF



Improve eLISA GRS by factor 10 – 0.3 fm/s^2/Hz$^{1/2}$ at 0.1 mHz?

Starting with same GRS dimensions as eLISA GRS, need:

- $p < 2\ 10^{-8}$ Pa (near 10^{-10} mB) **[probably ok … lower outgassing, better bakeout]**

- Stray potentials < 0.5 mV, fluctuations $< 5\ \mu V/Hz^{1/2}$ on each electrode
  [DC correction ok … adjust DC correction 1/week]
  [fluctuations … improve factor 2 electronics, factor 10 stray fields limit]

- Thermal fluctuations $\Delta T < 2\ \mu K/Hz^{1/2}$ **[maybe OK … test on LPF]**

- Satellite coupling measure to 200 pm/Hz$^{1/2}$ with 1 μN/m **[probably OK, test with LPF]**

- Actuation + crosstalk 2 ppm/Hz$^{1/2}$ stability + gravity < 0.5 nm/s^2 trans / 200 prad/s^2 rot
  [measure g on LPF, test FEE on ground]
  [could cure with impulsed actuation, small electrode change]

- Spacecraft gravity fluctuations $< 10^{-16}$ m/s^2/Hz$^{1/2}$
  [probably analysis only … won't test at this level on LPF]

- **no show stoppers, but not trivial**
- **Testing a challenge (especially for gravitational fluctuations)**
- **Surface problems cured with larger mass, larger gaps**

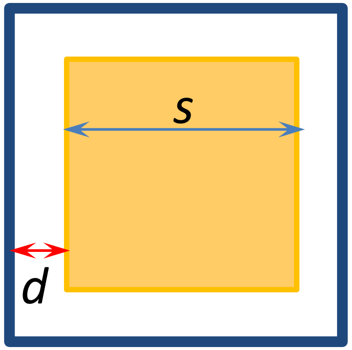
“Just make the mass bigger and the gaps larger”

- Yes, for many surface disturbances

electrostatic forces ~$1/d$, ~ $1/d^2$, or $1/d^3$

Brownian noise from gas ~ $1/d$ for $d << s$

Area $A \sim s^2$ mass $M \sim s^3$



- Somewhat for magnetics (for very close sources of field gradient)

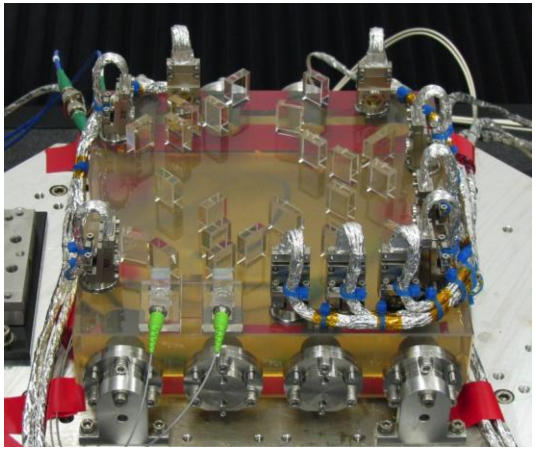
- No for gravity (except for closest sources)
- No for actuation noise, most crosstalk

- Larger gaps + larger TM: bigger, heavier, harder to actuate, harder to cage **$$$$**

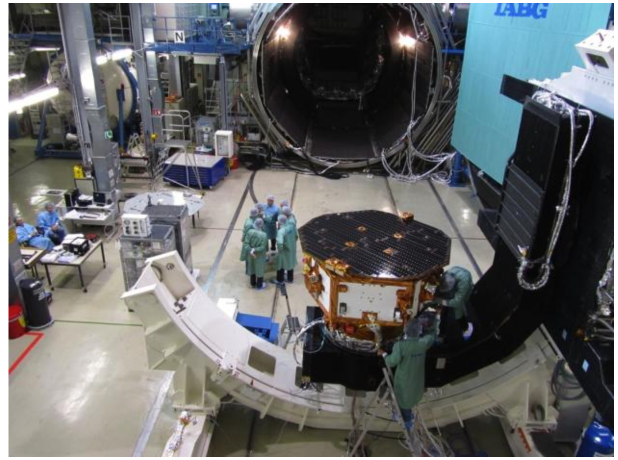
Example: gas damping for DECIGO **($4\ 10^{-19}$ m/s²/Hz$^{1/2}$ at 0.1 Hz)**
100 kg TM, assume ***d ~ s*** (no proximity effects)

$$S_a^{1/2} \propto p^{1/2} \frac{A^{1/2}}{M} \propto \frac{p^{1/2}}{\rho^{1/3} M^{2/3}}$$

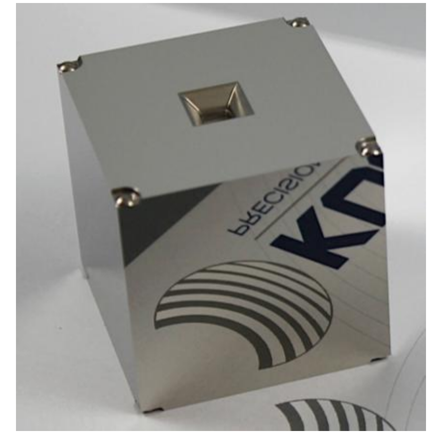
→ **need p < 10^{-9} Pa**



Optical bench



Spacecraft + optical bench tests



Uncoated TM

LPF Launch: July 2015

https://www.elisascience.org/articles/lisa-pathfinder/lpf-mission

STOC Simulations

VEGA (2 launches!)

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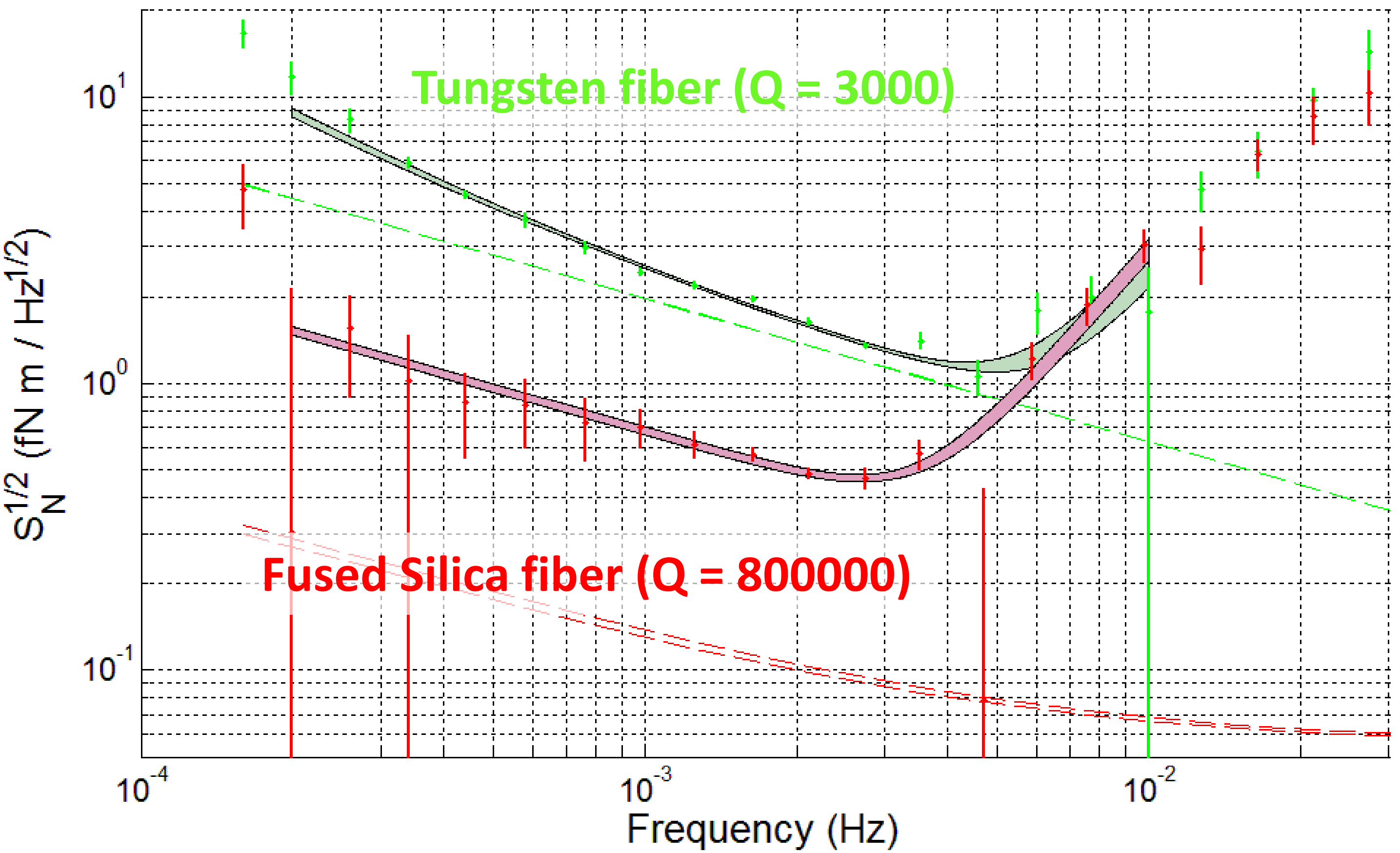
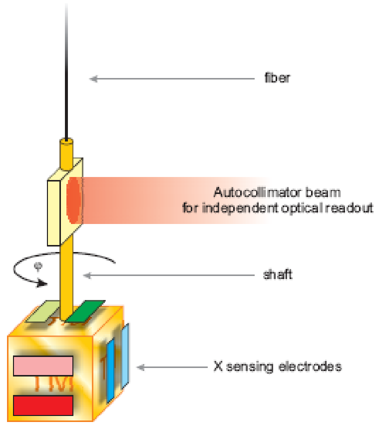
Extra stuff

Overall upper limits on GRS surface force noise:

Torsion pendulum noise floor with prototype LPF sensor + electronics





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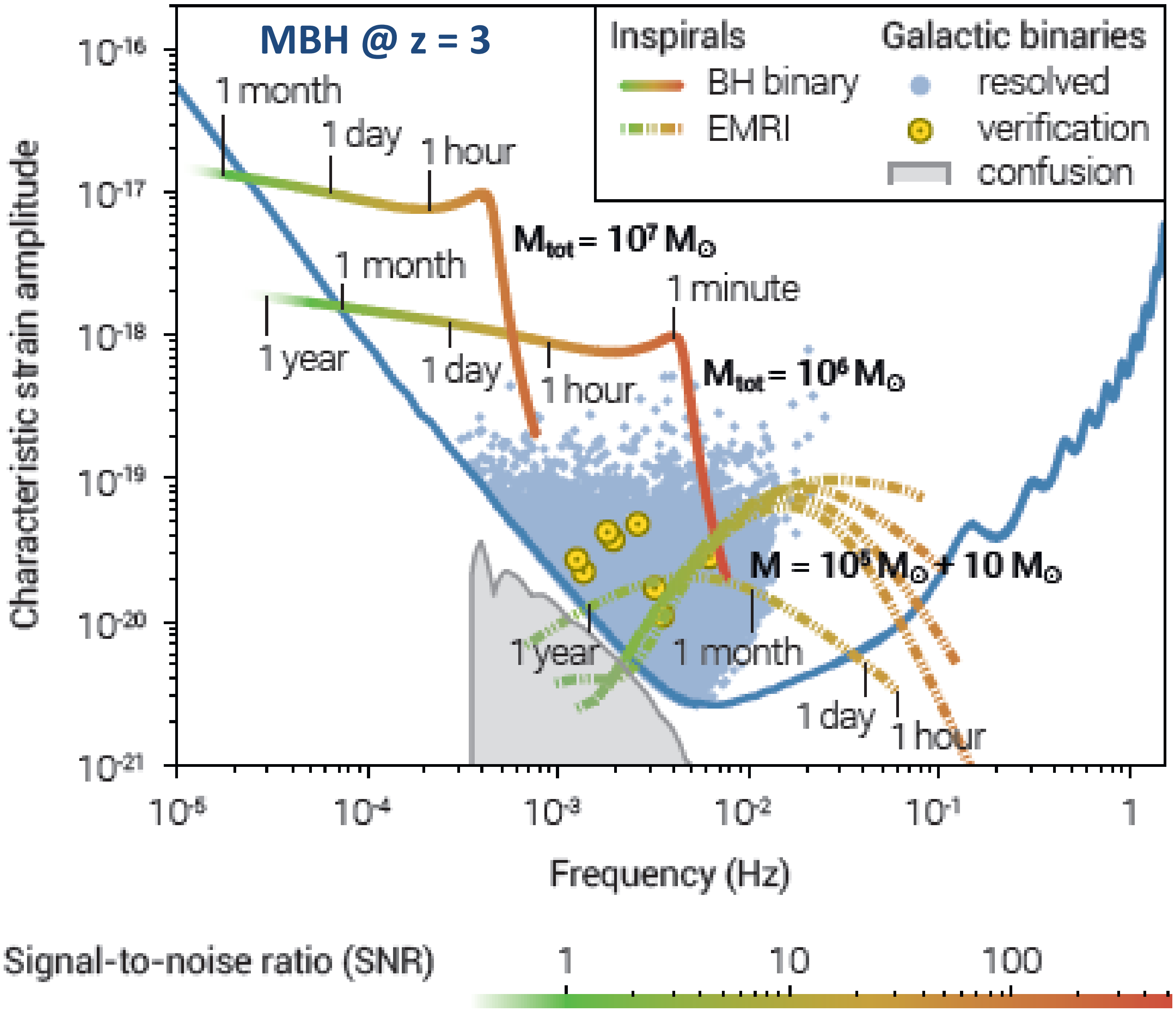

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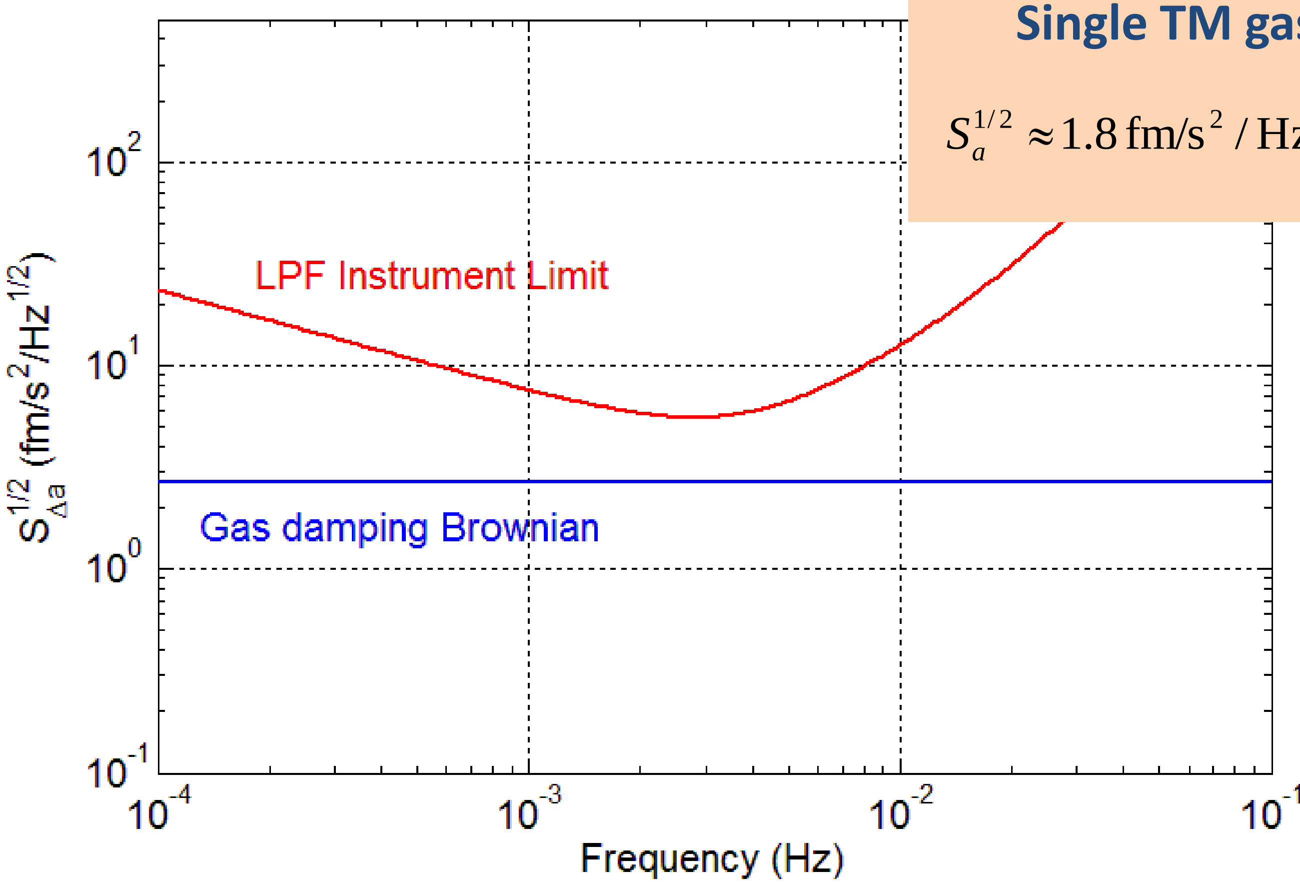
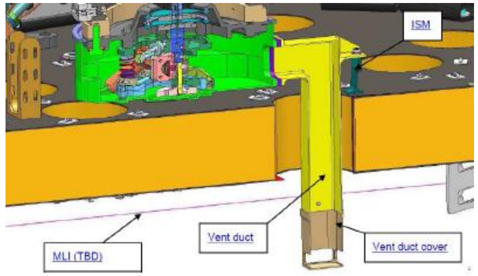
Noise source: Brownian noise from residual gas

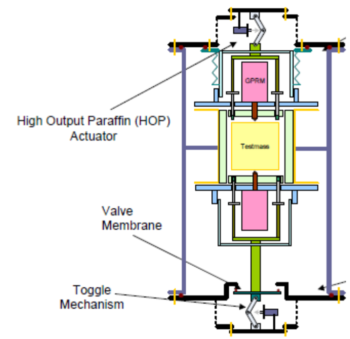


Single TM gas damping noise

$$S_a^{1/2} \approx 1.8\,\mathrm{fm/s^2/Hz^{1/2}} \times \left(\frac{p}{2\,\mu\mathrm{Pa}}\right)^{1/2} \left(\frac{m_0}{30}\right)^{1/4}$$



vent GRS to space



- 2 μPa: conservative upper limit based on measured gas loads
- worst case: can identify excess with radiometric effect

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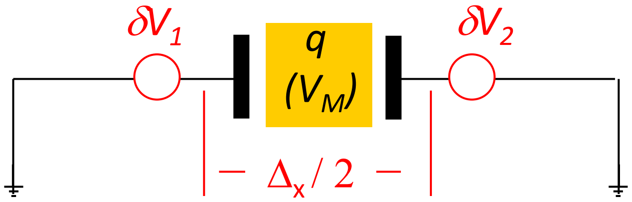
Electrostatic interaction between TM charge and average electrostatic field

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

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



TM charge ***Q***
Stray potentials ***δV***

$$S_F^{1/2} = \frac{\sqrt{2e^2 \lambda_{EFF}}}{\omega C_T} \left|\frac{\partial C}{\partial x}\right| \Delta_x$$

$$\approx 7\ \mathrm{fN/Hz}^{1/2} \times \left(\frac{\Delta_x}{100\ \mathrm{mV}}\right) \times \left(\frac{\lambda_{EFF}}{300\ /\mathrm{s}}\right)^{1/2} \times \left(\frac{f}{0.1\,\mathrm{mHz}}\right)$$

Random charge shot noise mixing with DC bias (Δ_x)

- need to measure average stray field compensation Δ_x to <1 mV

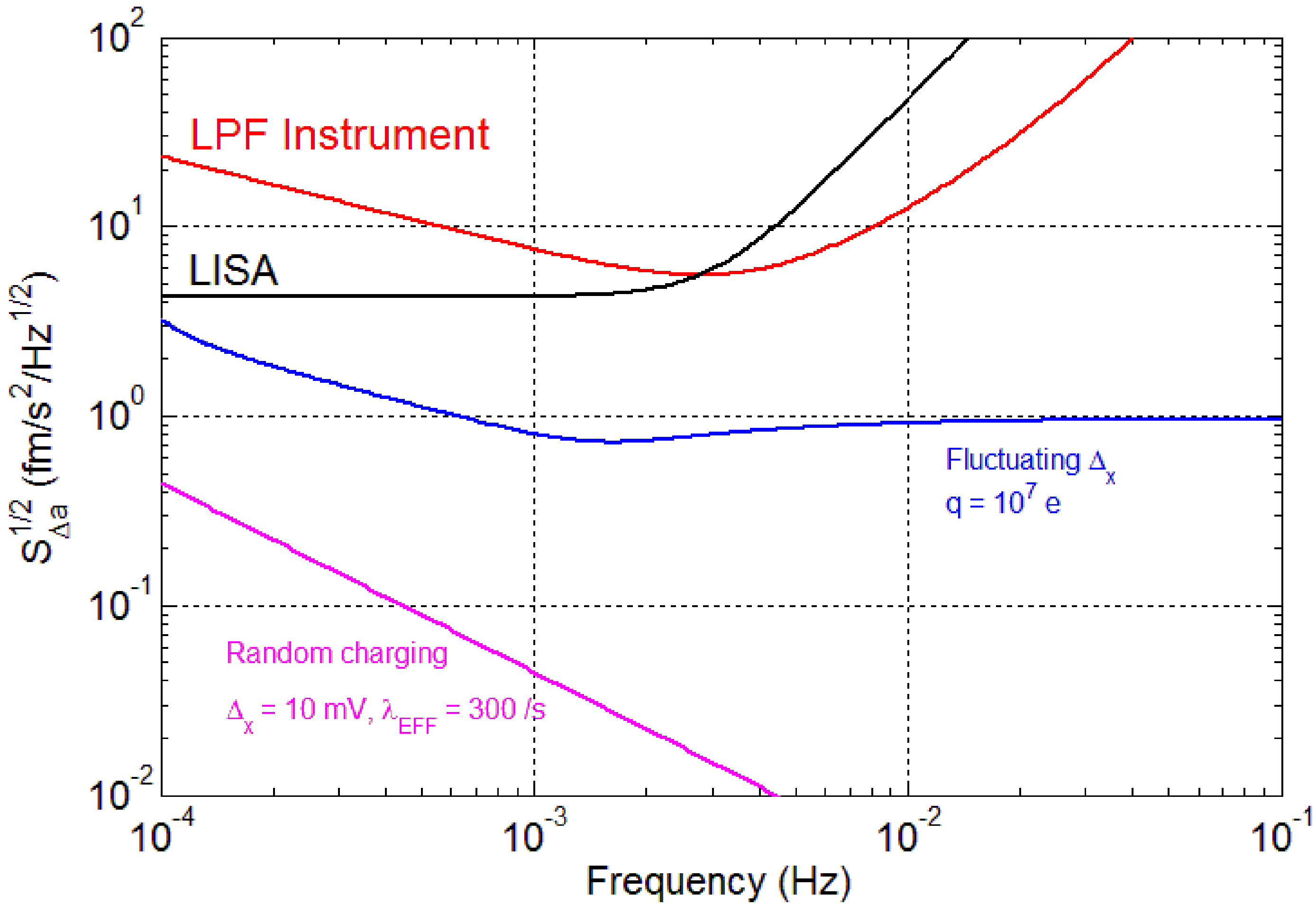
$$S_F^{1/2} = \frac{\langle q \rangle}{C_T} \left|\frac{\partial C}{\partial x}\right| S_{\Delta_x}^{1/2}$$

$$\approx 1.6\ \mathrm{fN/Hz}^{1/2} \times \left(\frac{\langle q \rangle}{10^7\ e}\right) \times \left(\frac{S_{\Delta_x}^{1/2}}{100\ \mu\mathrm{V/Hz}^{1/2}}\right)$$

Noisy average "DC" bias ($S_{\Delta x}$) mixing with mean charge

- non-stationary as charge drifts (2 10^6 -- 10^7 charge in one day)

Interaction between TM charge and stray electrostatic field



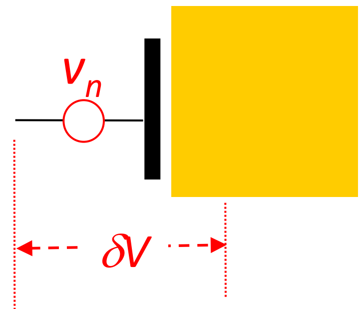
[*PRL* **108**, 181101 (2012)]

NB noise source proportional to **(1/gap)**

→ even cm size gaps will still require measurement + compensation!

Force noise from electrostatic dissipation

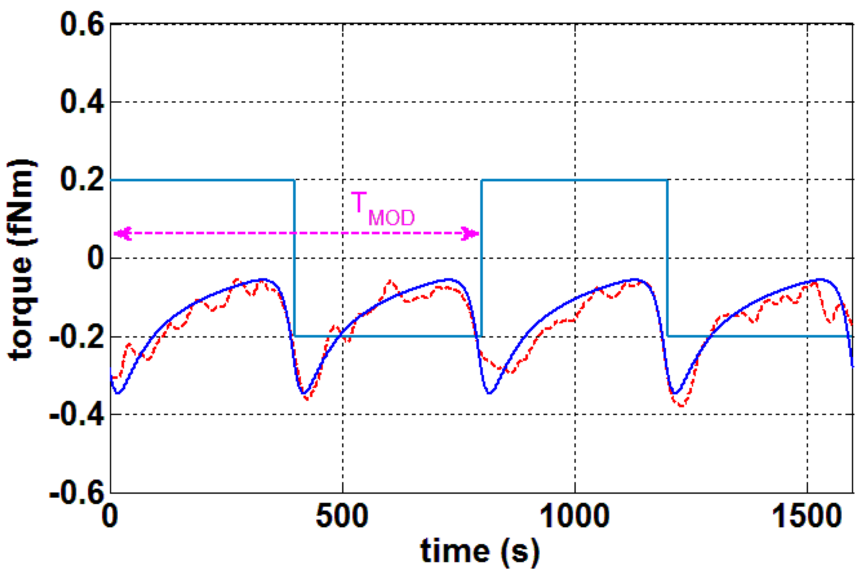
Thermodynamic voltage noise from surface dissipation mix with DC δV to give force noise

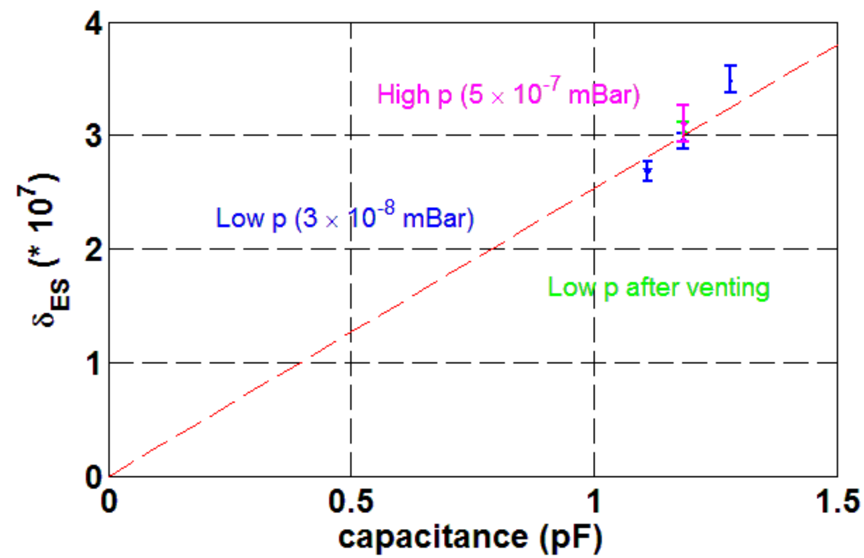


$$v_{\rm n} = \sqrt{4k_B T \frac{\delta}{\omega C}}$$

$$F = -\frac{C}{d}\delta V \; v_{\rm n}$$

Comparison of measured transient torque with theoretical model for δ = 3 10^{-7}





- Squarewave modulation technique, 10^{-17} Nm transient torque resolution
- Detect loss angle δ ≈ 3 10^{-7} for 2 electrode pairs → small enough for LISA!
- Waveform and distance dependence consistent with δ independent of frequency

Force noise source: interaction of magnetic moment and B field

$$F_x = \vec{m}.\frac{\partial}{\partial x}\vec{B} \longrightarrow \vec{m} = \vec{m}_0 + \frac{\chi V \vec{B}}{\mu_0}$$

- Fluctuations in magnetic field:

$$\frac{\chi V}{\mu_0} S_{B_i}^{1/2} \frac{\partial B_{0i}}{\partial x}$$

- Fluctuations in gradient:

$$\left(m_{0i} + \frac{\chi V B_{0i}}{\mu_0} \right) S_{\partial B_i / \partial x}^{1/2}$$

- Down conversion of field / gradient interaction:

(χ frequency dependent, Faraday and skin effect)

$$\frac{\chi(t) V B_i(t)}{\mu_0} \frac{\partial B_i(t)}{\partial x} \approx -\frac{s^3}{\mu_0} \frac{i\omega'\tau}{1+i\omega'\tau} B_i(\omega') \frac{\partial B_i(\omega-\omega')}{\partial x}$$

Onset ("superconductor limit")

$$f_{ON} \approx (2\pi\tau)^{-1} \approx \left(2\pi \frac{s^2 \mu_0 \sigma}{24} \right)^{-1} \approx 450\ \mathrm{Hz}$$

Shielding cutoff from vacuum chamber:
(not including sensor)

$$f_{CUT} \approx 2\ \mathrm{kHz}$$

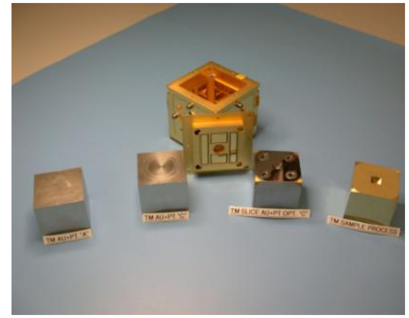
LISA Pathfinder Magnetic Measurements

Au/Pt alloy for low susceptibility, low residual moment

Measured EM TM properties

$$\vec{m}_0 \approx 10\,\mathrm{nAm}^2$$

$$\chi \approx 2\times 10^{-5}$$



Field estimates:

$$\left|\vec{B}_0\right| < 1\,\mu\mathrm{T}$$

$$\left|\frac{\partial \vec{B}_0}{\partial x}\right| < 12\,\mu\mathrm{T/m}$$

$$\left|\vec{B}_{AC}\right|_{RMS} < \mathrm{nT/Hz}^{1/2}\ \mathrm{to}\ 1\,\mathrm{kHz}$$


IABG Test facility

ASTRIUM	LISA Pathfinder	S2.ASU.TN.2523 Issue 3 Page 53 of 58

- Large field gradient due to thermistors mounted on GRS
→ Should be an order of magnitude lower with demagnetization

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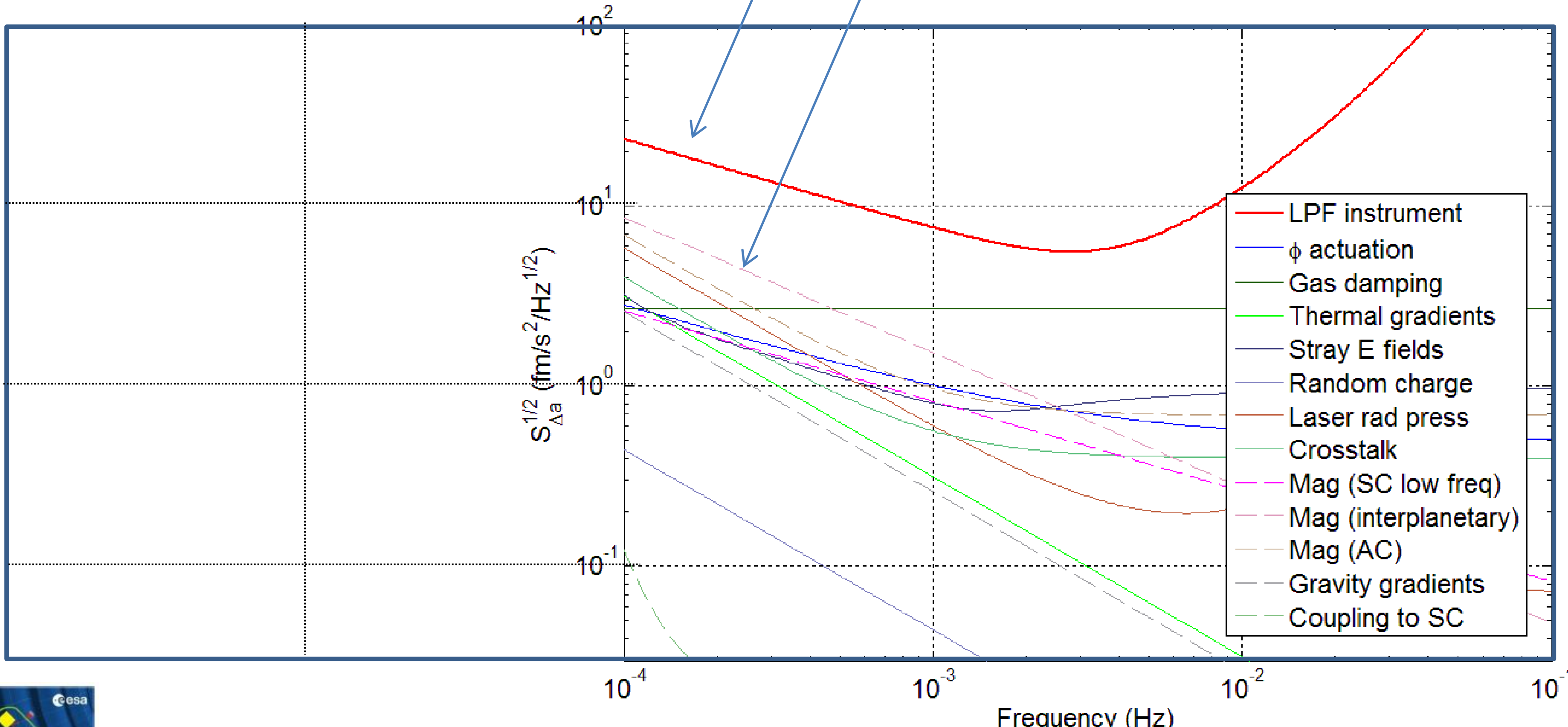
Will LPF have the resolution to see the earth-moon signal?

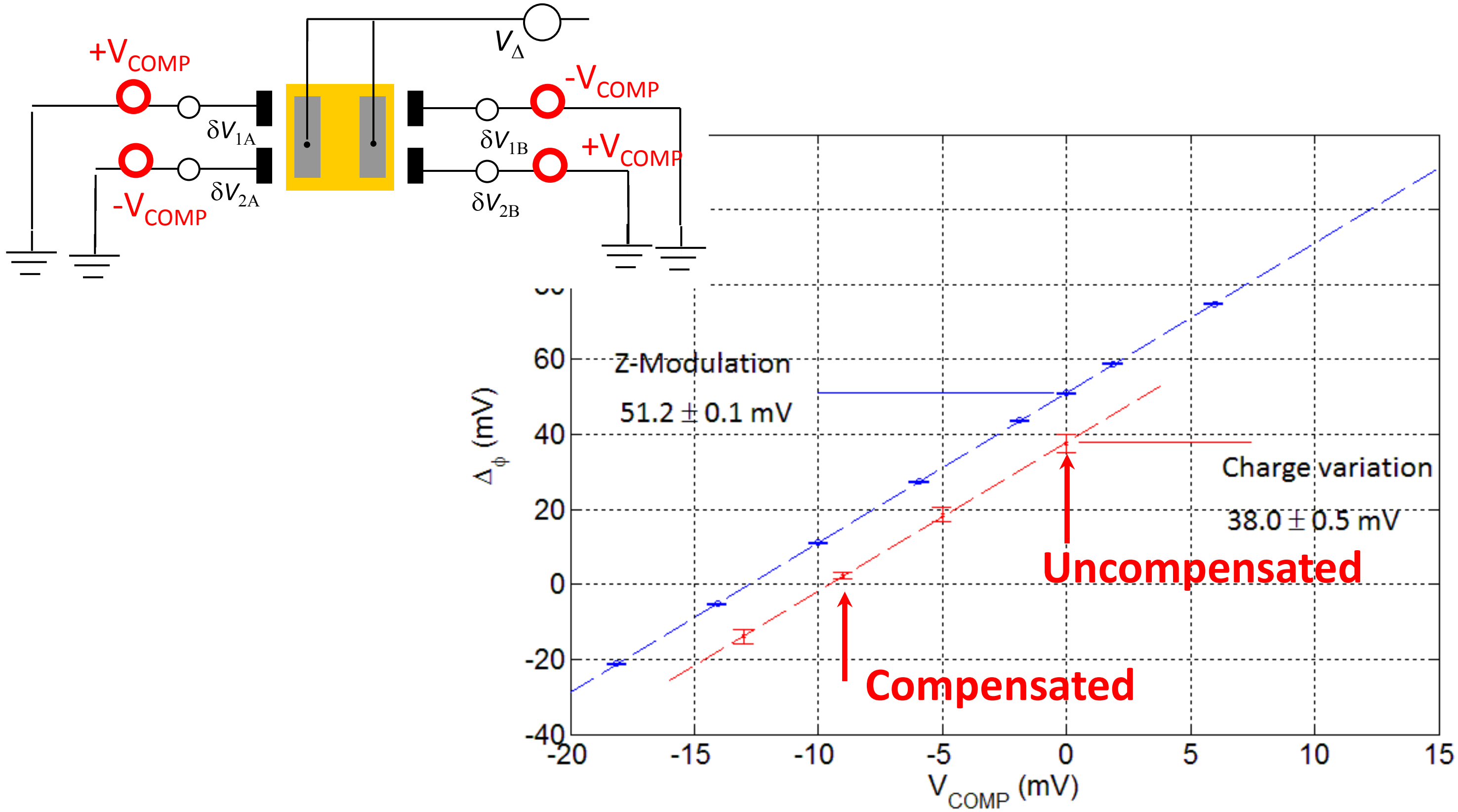
200 $fm/s^2/Hz^{1/2}$ at 1 μHz

x actuation

Interplanetary B

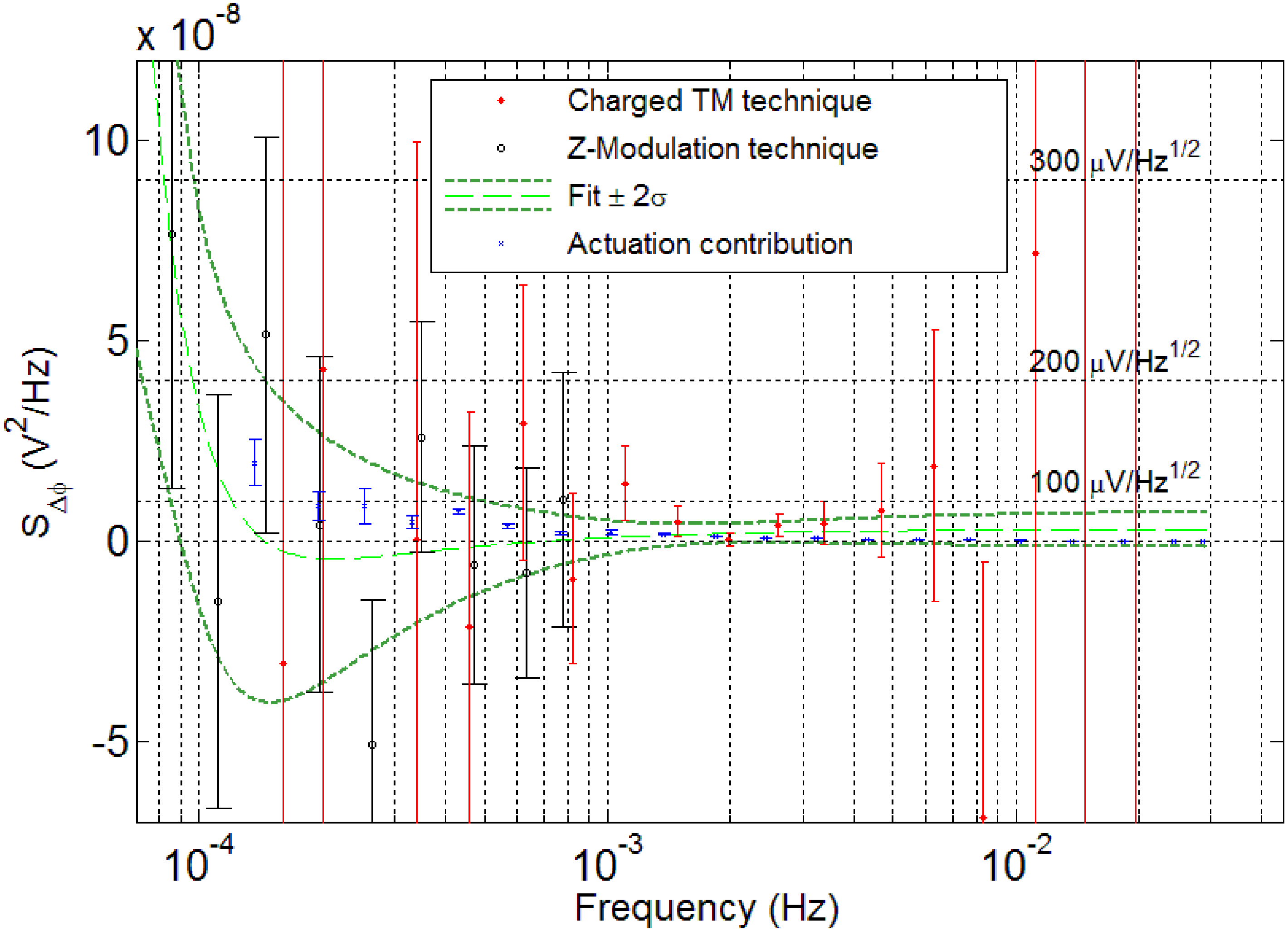


Experimental verification of stray potential compensation



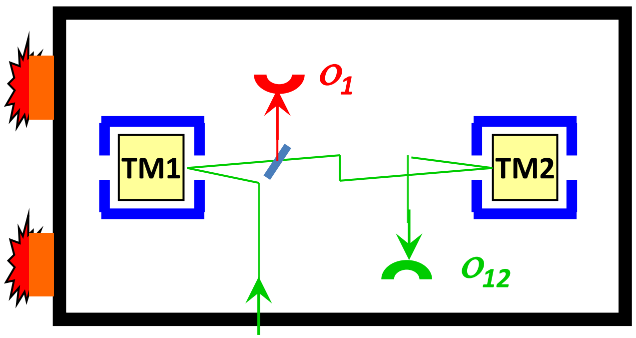
- Measurement of **dF/dq** (add charge to TM and measure change in force)
- Measure and compensate typical 100 mV imbalance to < 1 mV
- Need to measure by varying charge (not same as changing V_{TM} with applied voltages)
- Observed drifts small (order several mV in 1 month) → periodic remeasurement

Experimental upper limits on stray potential fluctuations



- consistent with sensor electronics noise fluctuations
- no excess noise from surface potential flucuations
- **upper limit for 5 cm^2 surface: <12 $\mu V/Hz^{1/2}$ at 1 mHz**

LISA Pathfinder as differential accelerometer



Closed loop noise in differential IFO signal $\boldsymbol{o_{12}}$

Differential force noise (for LISA)

Coupling to satellite "jitter" (can be tuned to zero)

Baseline stability (Zerodur)

$$o_{12}(\omega) = \frac{-1}{\omega^2 - \left(\omega_{2p}^2 + \omega_{ES}^2\right)} \left\{ \left(g_2 - g_1\right) + \left(n_1 + \frac{F_{SC}}{M\omega_{DF}^2}\right)\left[\omega_{2p}^2 - \omega_{1p}^2\right] - n_{12}\left(\omega^2 - \omega_{2p}^2\right) + \delta x \, \omega_{2p}^2 \right\}$$

IFO readout noise

LPF Instrument Noise (include x force actuation noise)

LISA

$$a_{res} = g + \omega_p^2 \left(x_n + \frac{F_{str}}{M\omega_{DF}^2}\right)$$

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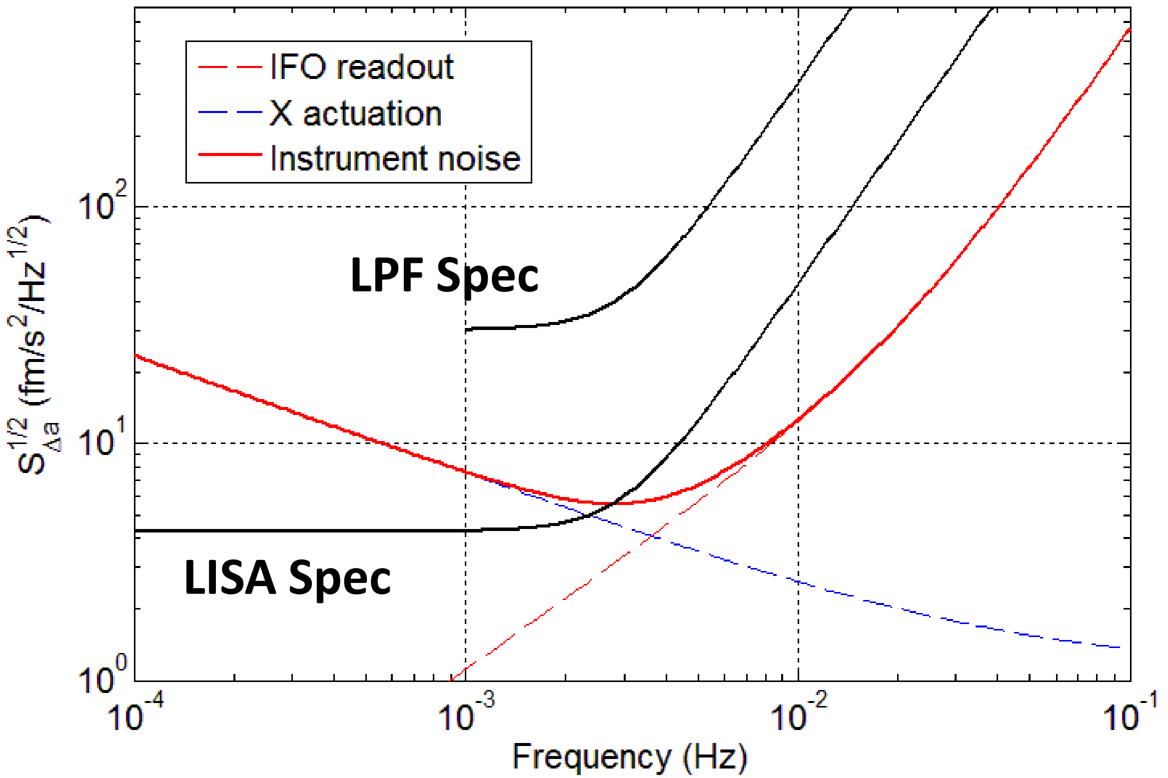
LISA Pathfinder esa

LISA Pathfinder as differential accelerometer for LISA TM acceleration noise: Instrument performance



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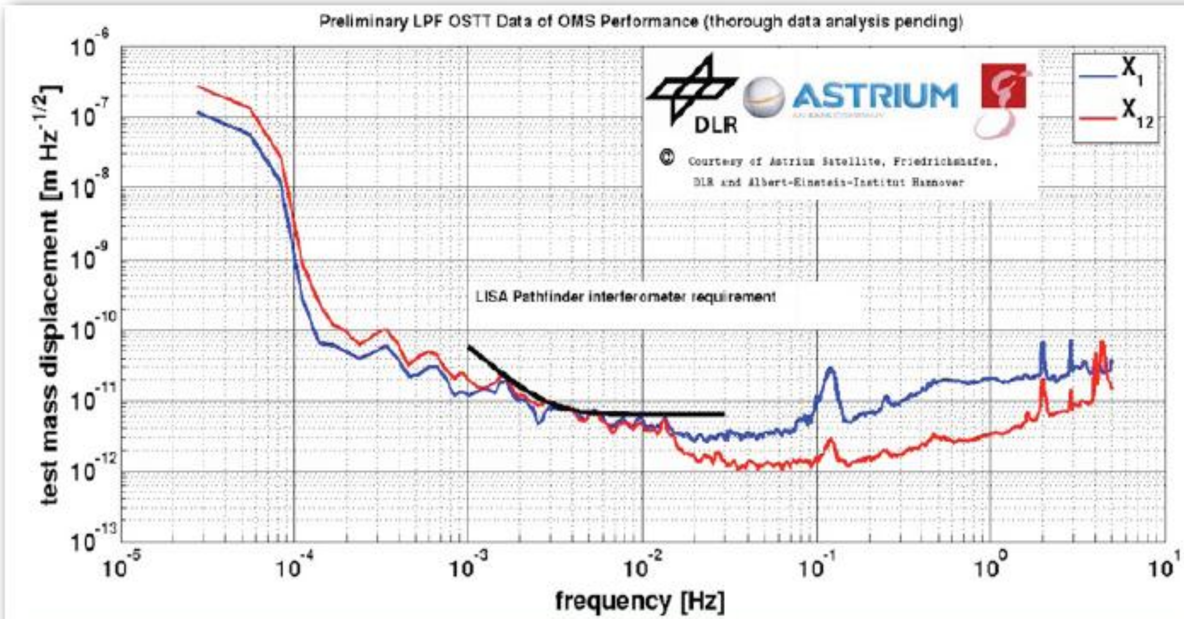
Verification of LPF Optical Metrology

OSTT - TOQM OMS longitudinal sensitivity



- Milestone: first performance demonstration of a FM OB.
- This OB is now baseline for flight (3OB).
- ASD test reports released: S2-ASD-TR-3152, TR-3155

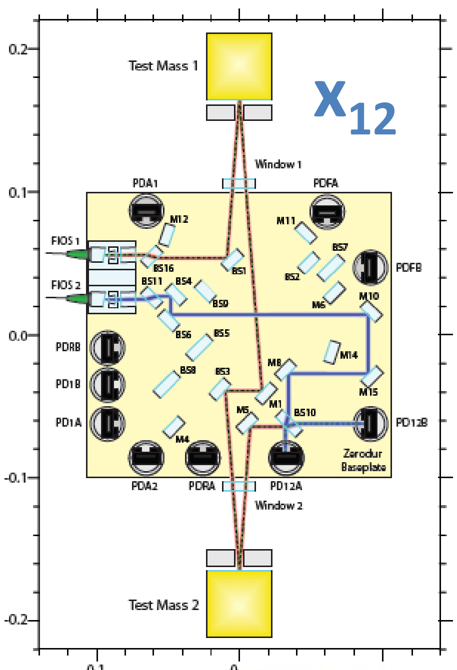
LISA Symposium 2012 | LISA Pathfinder Flight Hardware | Felipe Guzmán

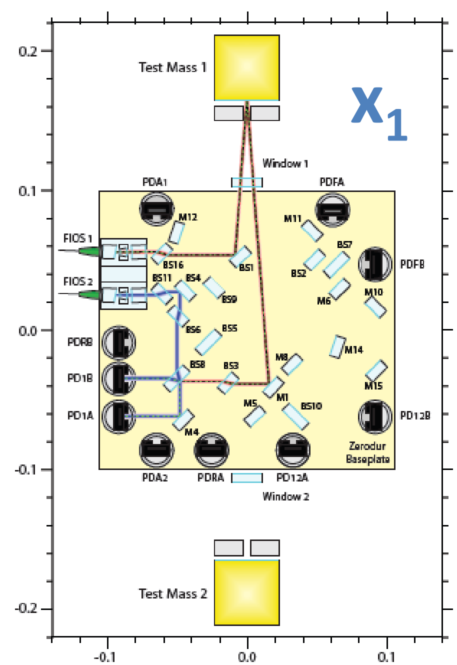
- Necessary displacement sensing achieved across whole LPF band

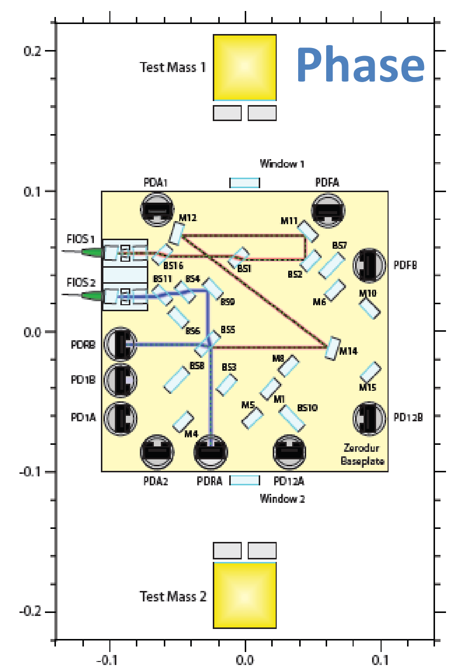
LPF Hardware for LISA: optical metrology

- (x_{12}) Differential TM displacement at 6 pm/Hz$^{1/2}$ level (3-30 mHz)
- (x_1) TM1 to spacecraft displacement – LISA local TM measurement
- Auxiliary IFO for phase and frequency noise correction

- Audio-frequency heterodyne Mach-Zehnder interferometer with waveform digitizing phasemeter
- High stability Zerodur optical bench, monolithic construction







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The micro-Newton thrusters

- Cold gas developed for Gaia better than requirements
- Now selected as baseline in place of FEEPs

Date 14/09/2012 **Ref** SRE-PN/18234-12/CGM

From C. García Marirrodriga (SRE-PN) **Visa** T. Passvogel (SRE-P)

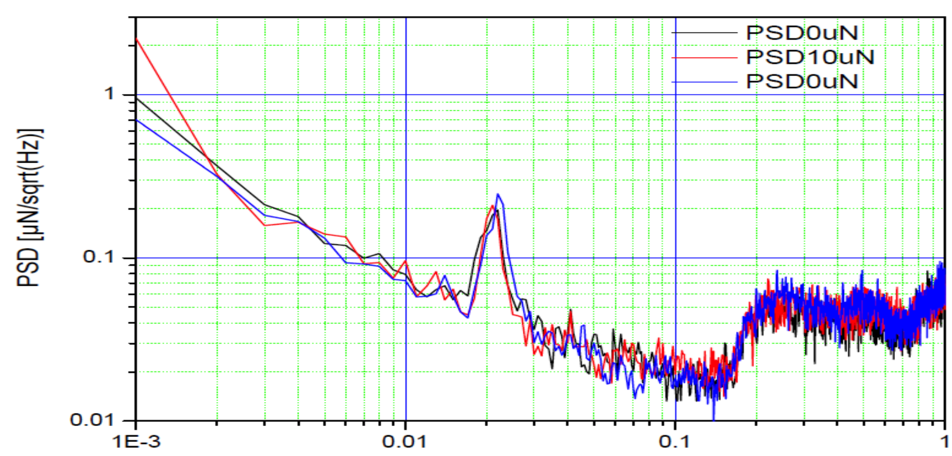
To LISA Pathfinder MPSR Board:
R. Schmidt (DG-I)
W. Veith (TEC-Q)
C. Stavrinidis (TEC-M)
A. Tobias (TEC-S)
M. McCaughrean (SRE-S)
G. Saccoccia (TEC-MP)

Copy A. Giménez Cañete (D/SRE)
P. McNamara (SRE-SA)
S. Vitale (University of Trento)
E. Bachem (DLR)
B. Sanders (TNO)
LPF Project Team & MPS support

Subject: Decision on the change of Micro-Propulsion System baseline for LISA Pathfinder

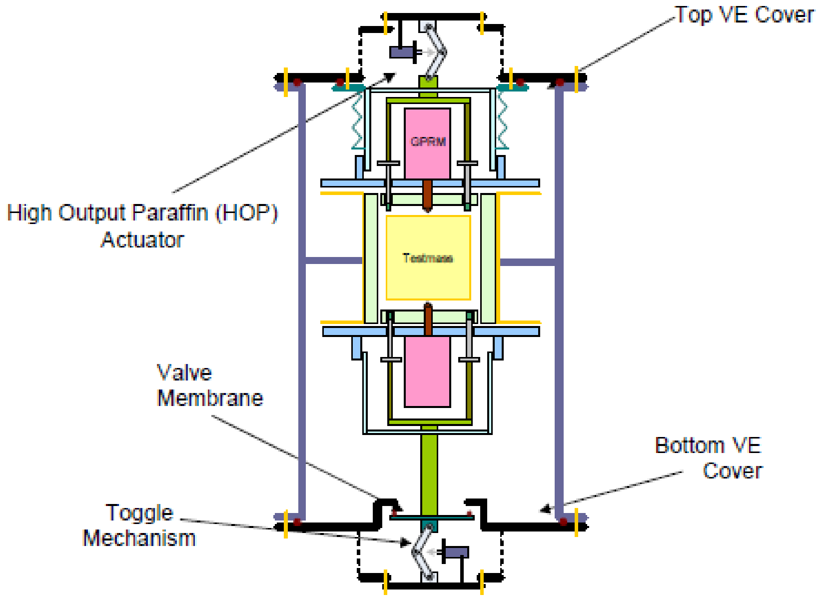
In November 2011 the LISA Pathfinder Micro-Propulsion System Review (MPSR) Board reviewed the status of the Caesium FEEP development tests and of the alternative Cold Gas system. The Board recommended (cf. Board Report DG-IR/2011/109/KL) continuing the testing of the FEEPs on unit and assembly level (TUVT and TAET respectively). In parallel, as a backup, the Board recommended to proceed with and complete the design work for the cold gas system, and to initiate the procurement of the long lead items. The overall status should be presented to the Board not later than April 2012. Such report was released in due time by the LPF Project (cf. SRE-PN/17498-12-GR), including the criteria to reach a decision on the MPS for LPF.

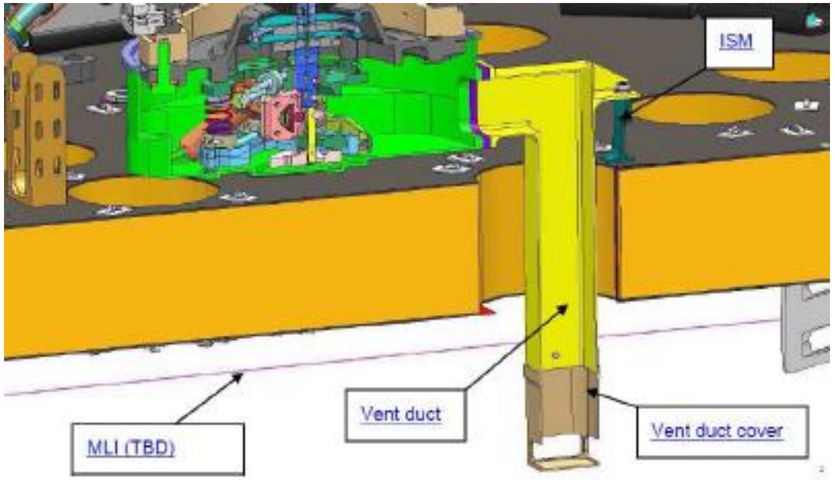
This memorandum summarizes the status reached at the present time, and introduces the LPF Project decision to select the cold gas micro-propulsion system as baseline and to discontinue further development work of the FEEP system within the context of the LISA Pathfinder project.



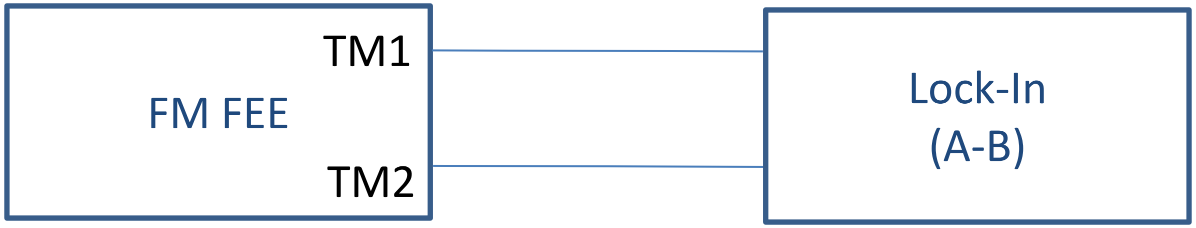
New LPF vacuum strategy: vent to space

- Replace getter pumps – low pumping speed – with high conductance (15 l/s) duct to space
- Requirement 2 μPa
- Gas load measurements indicate significantly lower





Actuation fluctuations: experimental limits with FM FEE

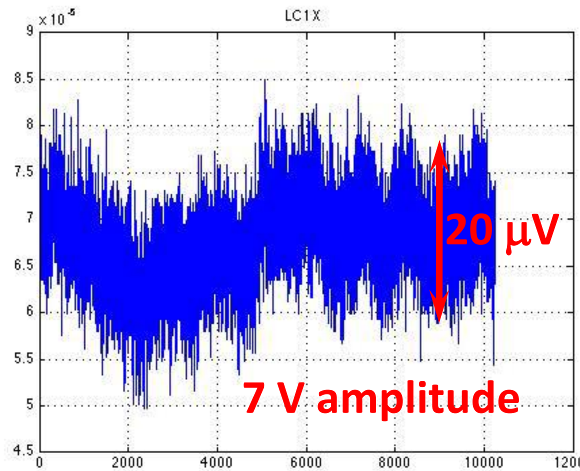


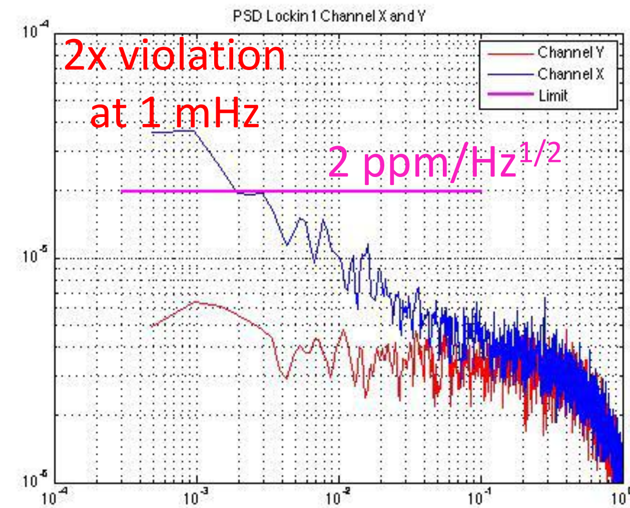
Coherent differential amplitude detection

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich Institute of Geophysics

EADS astrium

Contraves Space

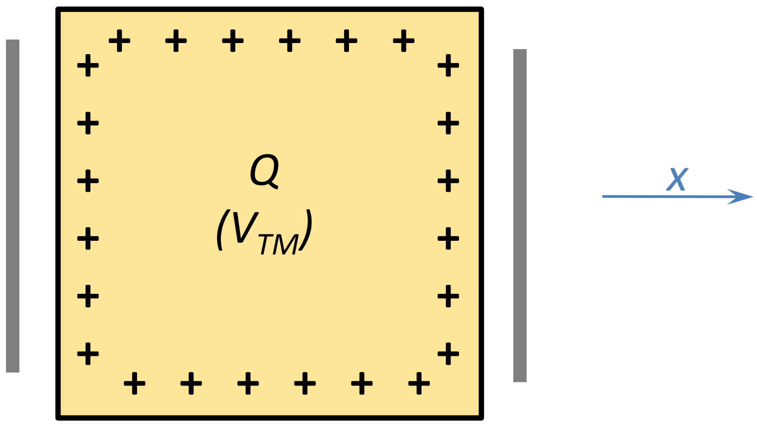




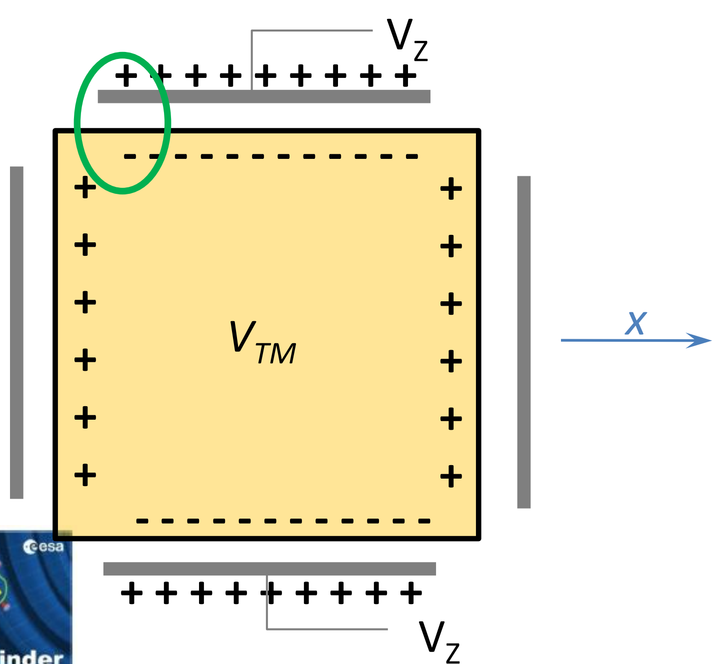
- Actuation fluctuations from 3-15 ppm/Hz$^{1/2}$ (x channels 3-7 ppm /Hz$^{1/2}$) at 1 mHz
- Typical power increase with 1/f at lower frequencies

→ Gives roughly 7 fm/s^2/Hz$^{1/2}$ at 1 mHz with 0.65 nm/s^2 grav imbalance

Difference between Q-modulation and V_Z modulation techniques



$$\frac{\partial F_x}{\partial Q} = -\frac{1}{C_{TOT}} \left| \frac{\partial C_x}{\partial x} \right| \Delta_x$$



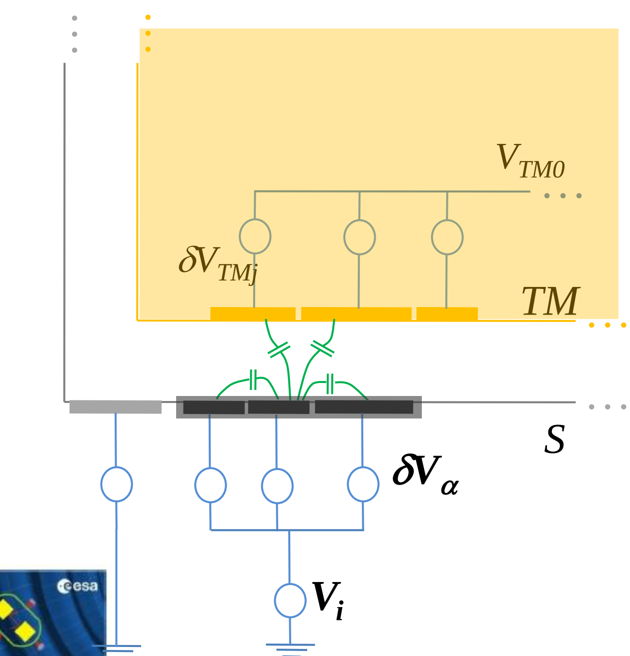
$$\frac{\partial F_x}{\partial V_z} = -\frac{4C_z}{C_{TOT}} \left| \frac{\partial C_x}{\partial x} \right| \Delta_x + \sum_{\alpha(Sz),\beta(TM)} \frac{\partial C_{\alpha,\beta}}{\partial x} \left(\delta V_\alpha - \delta V_\beta \right)$$

- In addition to modulation TM potential, introduce large field gradient at borders of z electrodes
  - amplifies shear force that is not relevant for TM charge

Electrostatic forces and possibility of compensating with applied voltages

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

$$V_{TM} = \frac{Q}{C_{TOT}} + \frac{\sum_i C_i V_i}{C_{TOT}}$$



Forces proportional to:

- $\left(\delta V_\alpha - \delta V_\beta\right)^2$ — Individual domain potential differences
- Q^2 — charge stiffness
- $\left(V_i - V_{TM}\right)^2$ — Electrode voltage fluctuation (FEE)
- $Q\Delta_x$ — Interaction charge and average field

Ideally:

- Want dF/dQ, dF/dV_i, $dF/d\delta V_\alpha = 0$
- Would require all conductors at same potential

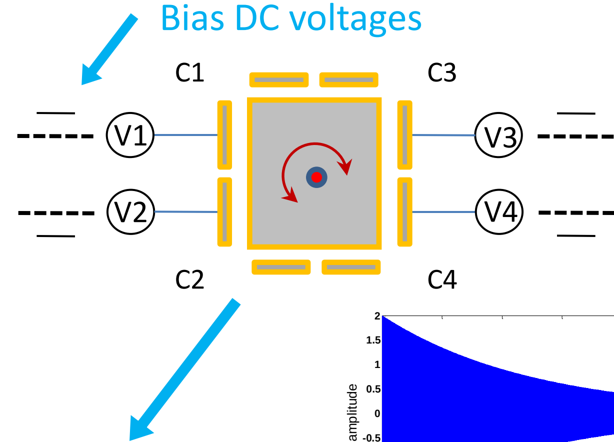
We can:

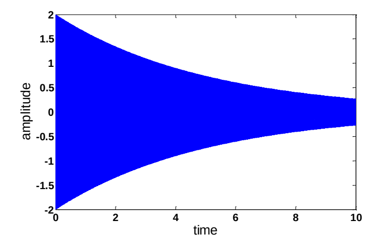
- apply DC voltages at will (up to 5 V)
- change TM charge (using UV)

2.1 Measurement with ringdown tech (2010~2012)

Object: A LPF flight model, Au-coated electrodes, 4 mm capacitive gap along x

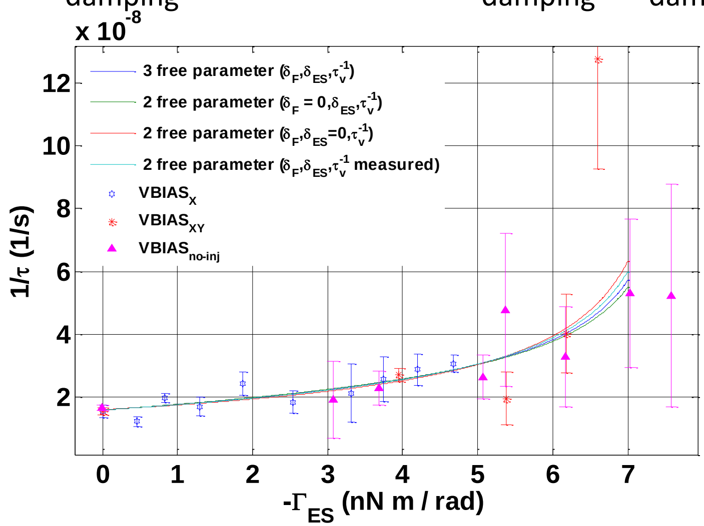
Tech1: measure pendulum amplitude decay as a function of electrode voltages





$$\frac{1}{\tau_{\mathrm{exp}}} = \frac{1}{\tau_{\mathrm{v}}} + \frac{1}{\sqrt{I}\,(\Gamma_{\mathrm{F}} + \Gamma_{\mathrm{ES}})} \cdot (\Gamma_{\mathrm{F}} \cdot \delta_{\mathrm{F}} - \Gamma_{\mathrm{ES}} \cdot \delta_{\mathrm{ES}})$$

Viscous damping — fiber damping — Electrostatic damping

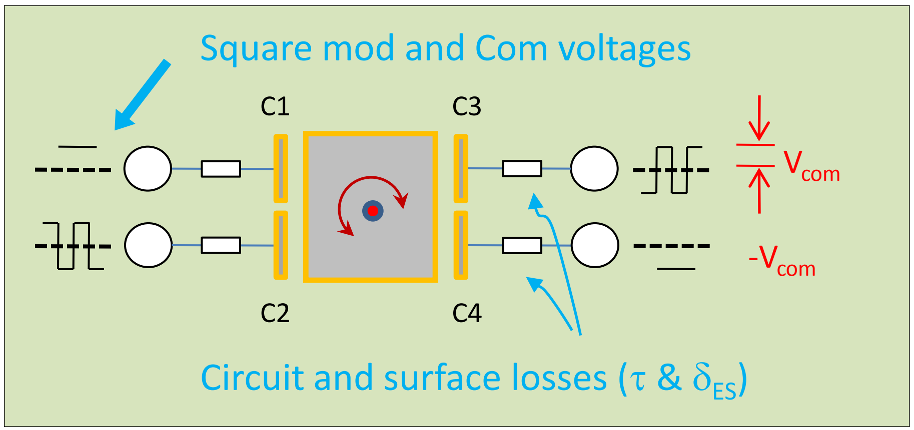


Fit condition	δ_{ES} (10^{-7})	δ_F (10^{-7})	$1/\tau_v$ (10^{-8} /s)	χ^2	Remark
3 free parameters	7.6 (7.5)	-4 (12)	1.1 (1.6)	1.2 (20 DOF)	Physical
Assuming $1/\tau_v$ only from gas	4.5 (1.3)	8.7 (.4)	0.43	1.2 (21 DOF)	Physical
Assuming δ_{ES} =0	--	16 (.03)	-.5 (.3)	1.2 (21 DOF)	Not physical

Result: upper limit of δ_{ES} $1.5*10^{-6}$.

2.2 Measurement with modulation tech (2011~2012)

Tech2: Perfect Square Wave modulation, which gives constant torque proportional to V^2. However delays due to lossy elements cause force transients proportional to delta at every square wave transition *



Ideal SW to one diagonal pair

$$V_{MOD} = \sum_{j,odd} \frac{4V_M}{j\pi} \sin(\omega_M t)$$

Compensation voltages to the other pair

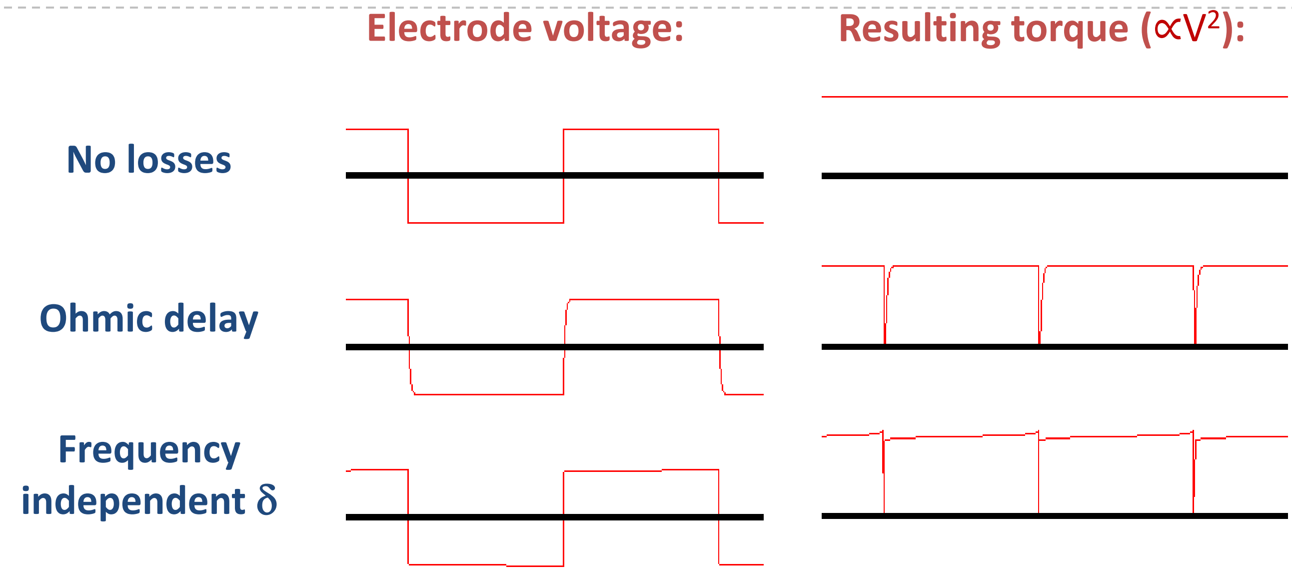
$$N_{DC} \equiv \frac{\partial C}{\partial \varphi} V_{COM}^2$$

Huge DC torque cancelled
Small transient torque left

- +/- V_{com} and out of phase square wave applied to diagonal pairs, to avoid the change of TM potential
- enable to measure circuit loss and surface loss τ & δ_{ES} together
- Huge DC torque (~10^{-10} N m) cancelled, small transient torque left (~10^{-17} N m ↔ δ_{ES}~10^{-7}) for losses extraction

* L. Carbone et al, 6th Amaldi, Japan, 2005

2.3 Illustration of measured signal



- 2f signal (+ other even harmonics)
- Nearly "Dirac δ-function" for ohmic delay (all cosine)
- Longer lived signal for frequency independent δ_{ES} (both sine and cosine)

$$\frac{-N_{2f}}{N_{DC}} \approx \left[\delta_{\mathrm{ES}} \cdot \left(\frac{4}{\pi}\right)^2 \underbrace{\frac{2}{\pi}\left(\sum_{j,\mathrm{odd}} \frac{\ln j(j+2)}{j(j+2)}\right)}_{\approx 0.681} + 8 f_{\mathrm{M}}\tau\right]\cos(2\omega_M t) + \left[\delta_{\mathrm{ES}} \cdot \underbrace{1}_{=1}\left(\frac{4}{\pi}\right)^2\right]\sin(2\omega_M t)$$

$$\frac{-N_{4f}}{N_{DC}} \approx \left[\delta_{\mathrm{ES}} \cdot \left(\frac{4}{\pi}\right)^2 \underbrace{\frac{2}{\pi}\left(\sum_{j,\mathrm{odd}} \frac{\ln j(j+4)}{j(j+4)} - \frac{\ln 3}{3}\right)}_{\approx 0.574} + 8 f_{\mathrm{M}}\tau\right]\cos(4\omega_M t) + \left[\delta_{\mathrm{ES}} \cdot \underbrace{\frac{2}{3}}_{\approx 0.67}\left(\frac{4}{\pi}\right)^2\right]\sin(4\omega_M t)$$