Ground testing of free-fall for LISA Pathfinder, LISA, and future space missions

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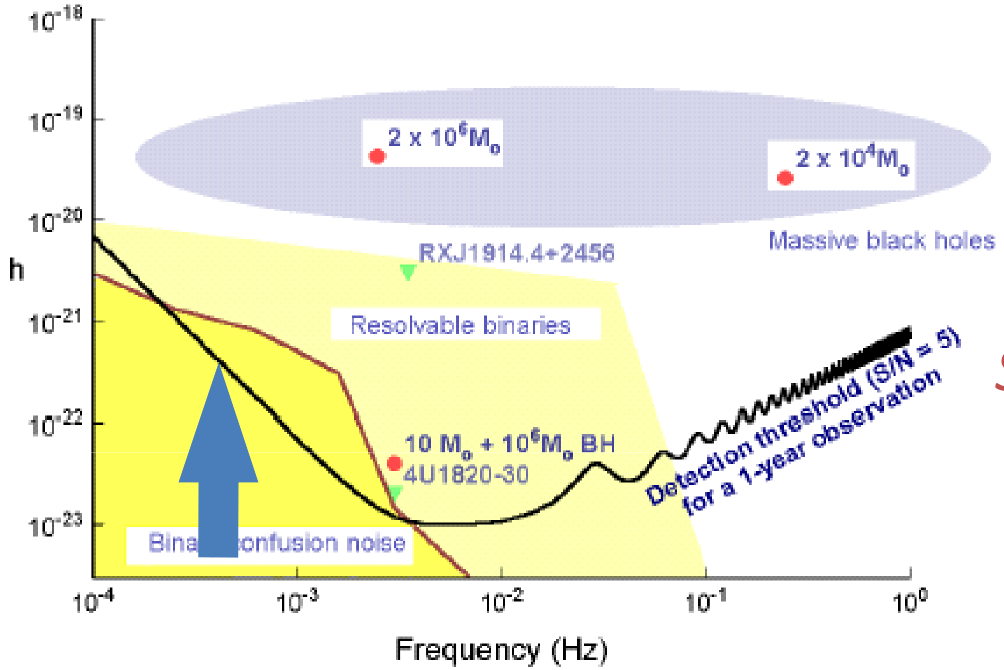
LISA / LISA Pathfinder Project

Quantum to Cosmos Workshop

Warrenton, Virginia, 7 July 2008

Purity of free-fall critical to low frequency LISA sensitivity and LISA science



LISA goal:

$S_a^{1/2} < 3$ fm/s^2/Hz$^{1/2}$ at 0.1 mHz

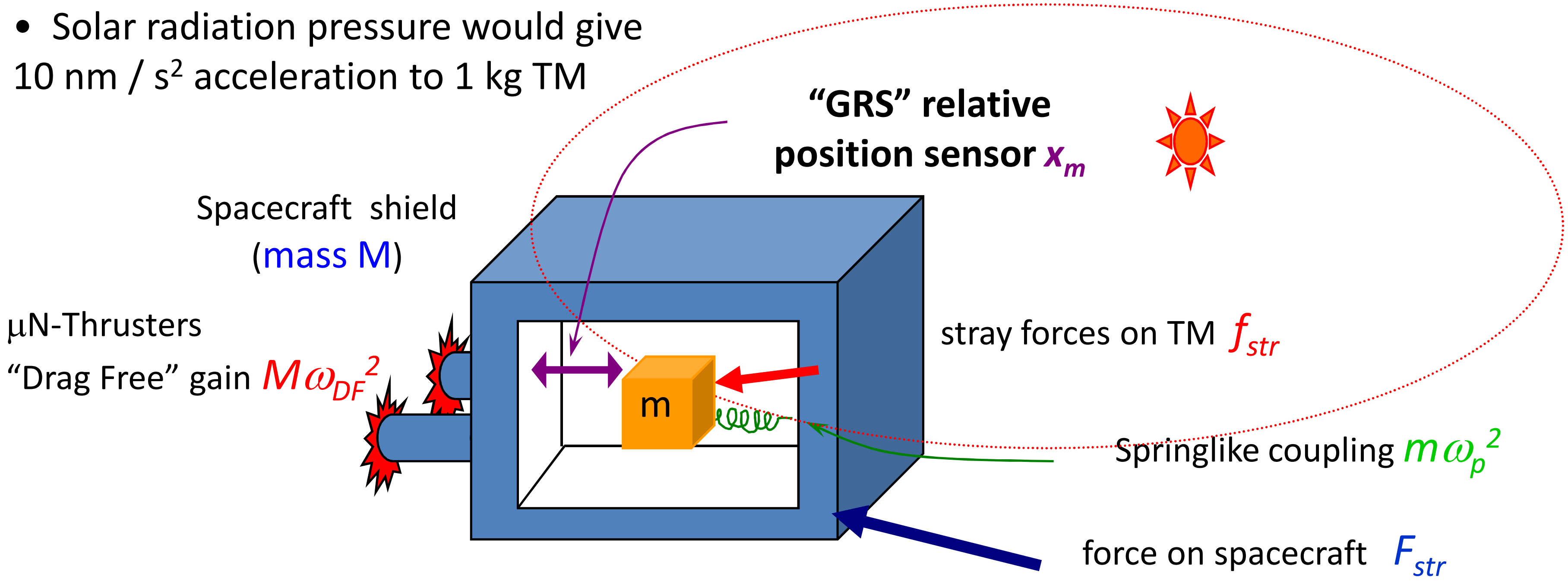
Low frequency acceleration noise determines how well, how far, and how early we will observe black hole mergers.

- do we see the merger for long enough to pinpoint it and to search with optical telescopes (1 degree)?

Stray forces and drag-free control

- Solar radiation pressure would give

10 nm / s^2 acceleration to 1 kg TM



Residual acceleration noise:

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

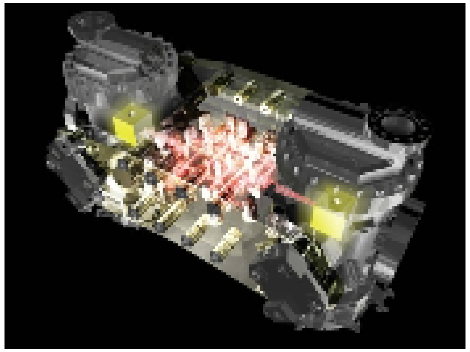
Spacecraft itself – and particularly GRS – potentially dominant source of force noise

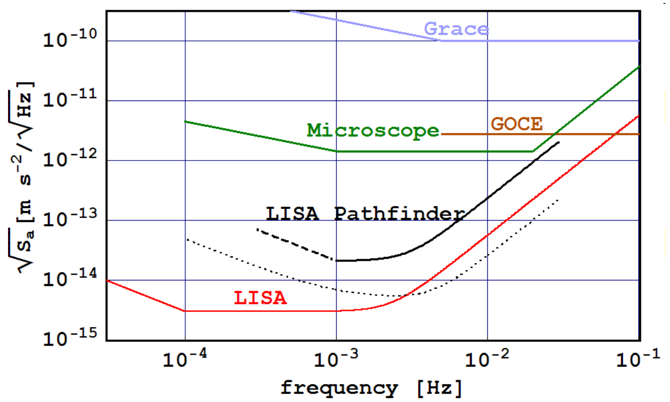
- TM charge, stray electrostatic fields, sensor back-action, thermal gradient effects

The "path" to LISA free-fall

LISA Pathfinder (2010)

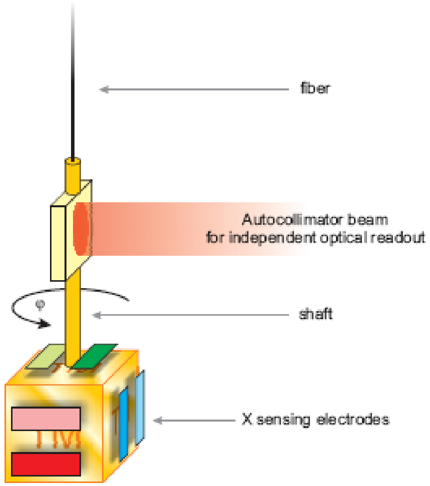
- 30 cm arm with 2 TM and 1 SC
- Test free-fall to 30 fm/s^2/$Hz^{1/2}$ at 1mHz
- true pathfinder for space experiments demanding free-fall (EP, time delay, geodesy)





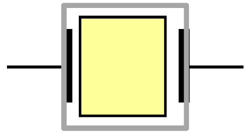
Ground testing of small forces on TM inside GRS (torsion pendulum)

- pre-mission verification of noise model
- testing of in-flight noise mitigation / calibration / measurement techniques
- current upper limits on unknown surface forces below 100 fm/s^2/$Hz^{1/2}$ at 1 mHz
- dedicated tests of known noise sources



TM suspended as torsion element inside GRS

Gravitational Reference Sensor Design



- **Defines TM environment**
- **Provide nm/Hz$^{1/2}$ measurement on all axes**
  - **10 pm/Hz$^{1/2}$ interferometer used on *x* axis**
- **Provides electrostatic voltages (force, measurement)**

Capacive GRS design for LISA PF / LISA

- 46 mm cubic Au / Pt test mass (1-2 kg)
- 6 DOF "gap sensing" capacitive sensor
- Contact free sensing bias injection
- Resonant inductive bridge readout (100 kHz)
- ~ 1 nm/Hz$^{1/2}$ thermal noise floor
- Audio frequency electrostatic force actuation

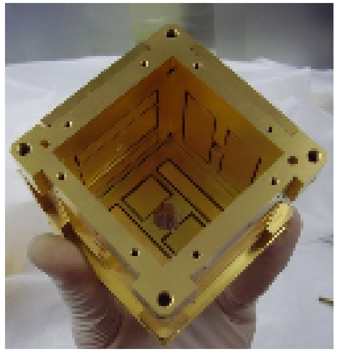
  → avoid DC voltages

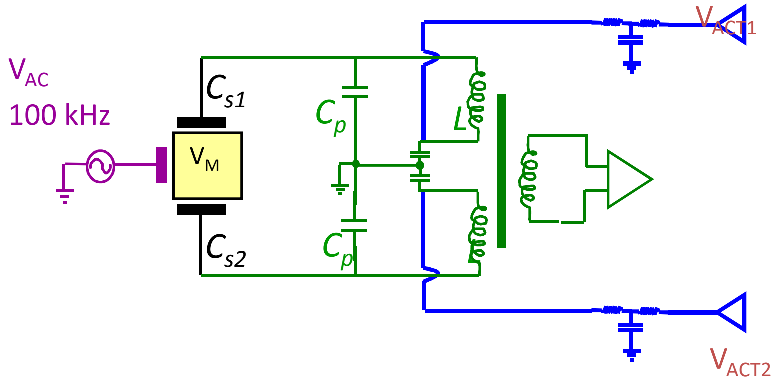
- Large gaps (2 – 4 mm)

  → limit electrostatic disturbances

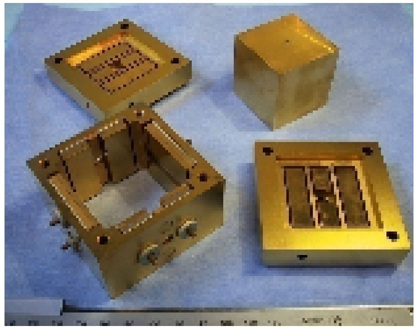
- High thermal conductivity metal (Mo) / sapphire construction

  → limit thermal gradients

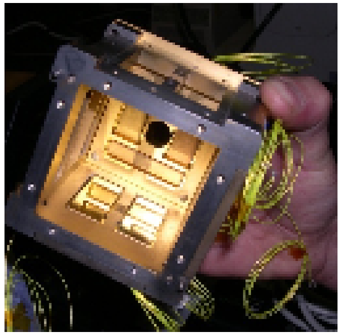




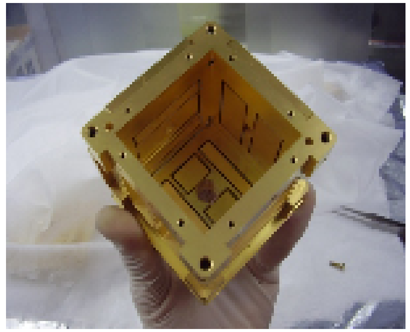
Ground testing of free-fall with LISA / LISA PF GRS



Mo / Shapal (2 mm)

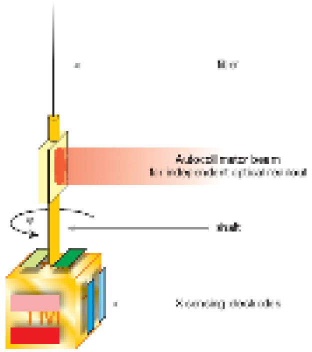


Mo / Shapal EM (4 mm)

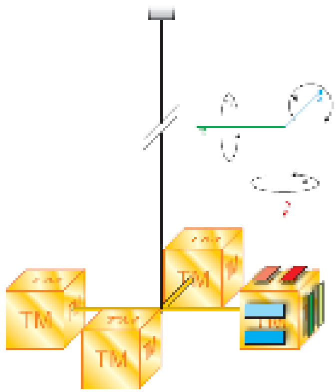


Mo / Sapphire LPF EM (4 mm)

LISA PF design!



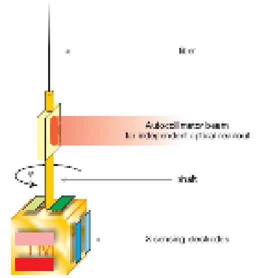
1-mass torsion pendulum (torques)



4-mass torsion pendulum (direct force sensitivity)

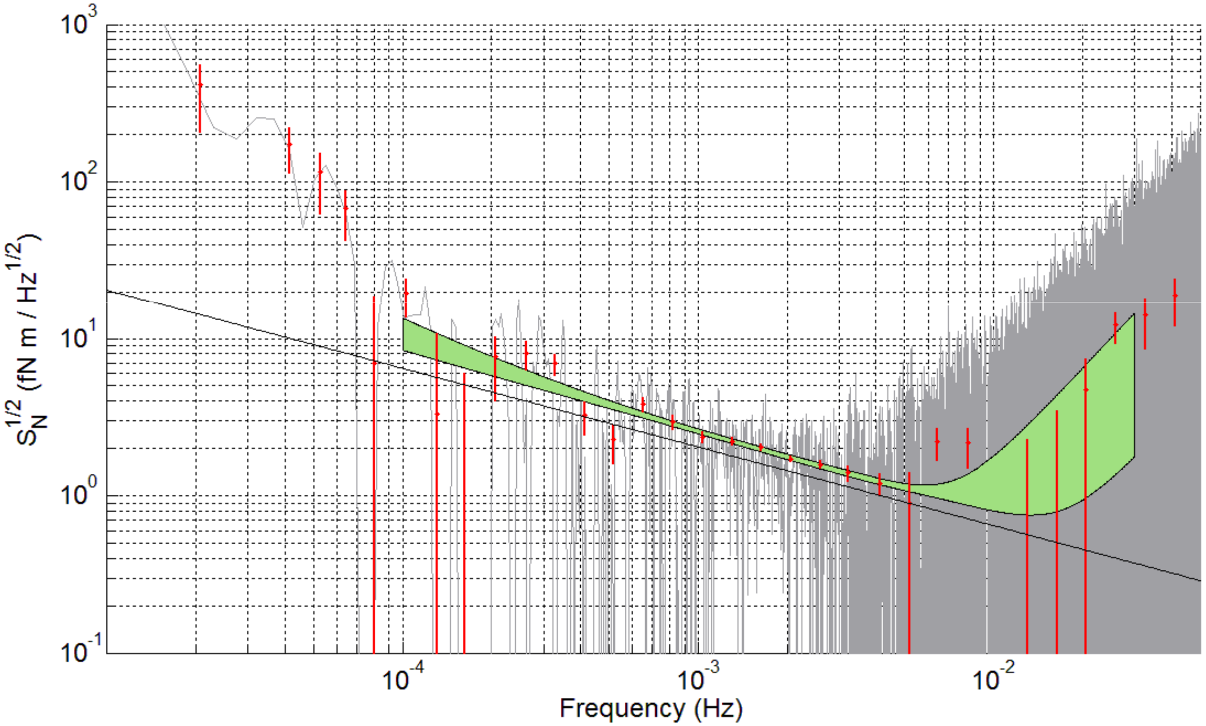
Torsion pendulum upper limits on GRS force noise: Mo / sapphire sensor and 1 TM pendulum

Angular deflection measurement with two readouts (GRS and autocollimator)
→ distinguish true torque noise floor from background readout noise



$$S_N = \Re\left\{ S_{N_{AC}, N_S} \right\}$$

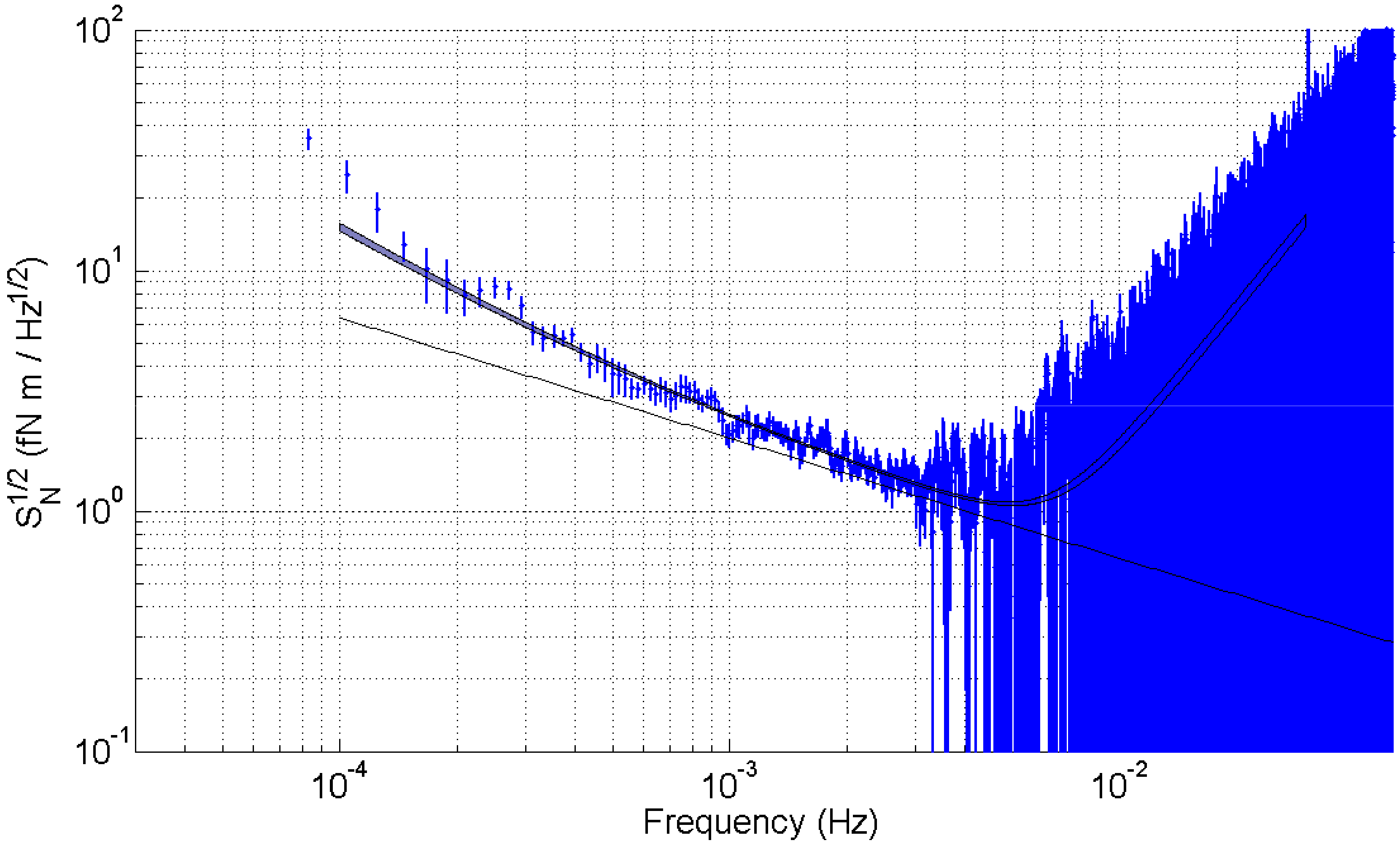
Single “best” run
(220000 s)



- near (< 2 in power) Brownian noise for frequency decade around 1 mHz → true excess?
- excess at lower frequencies (coupling to environment? Sensor itself?)
- excess at higher frequencies – rotational motion of apparatus (order 10 nrad/Hz$^{1/2}$)

Upper limits on GRS force noise: averaged data for Mo / Sapphire

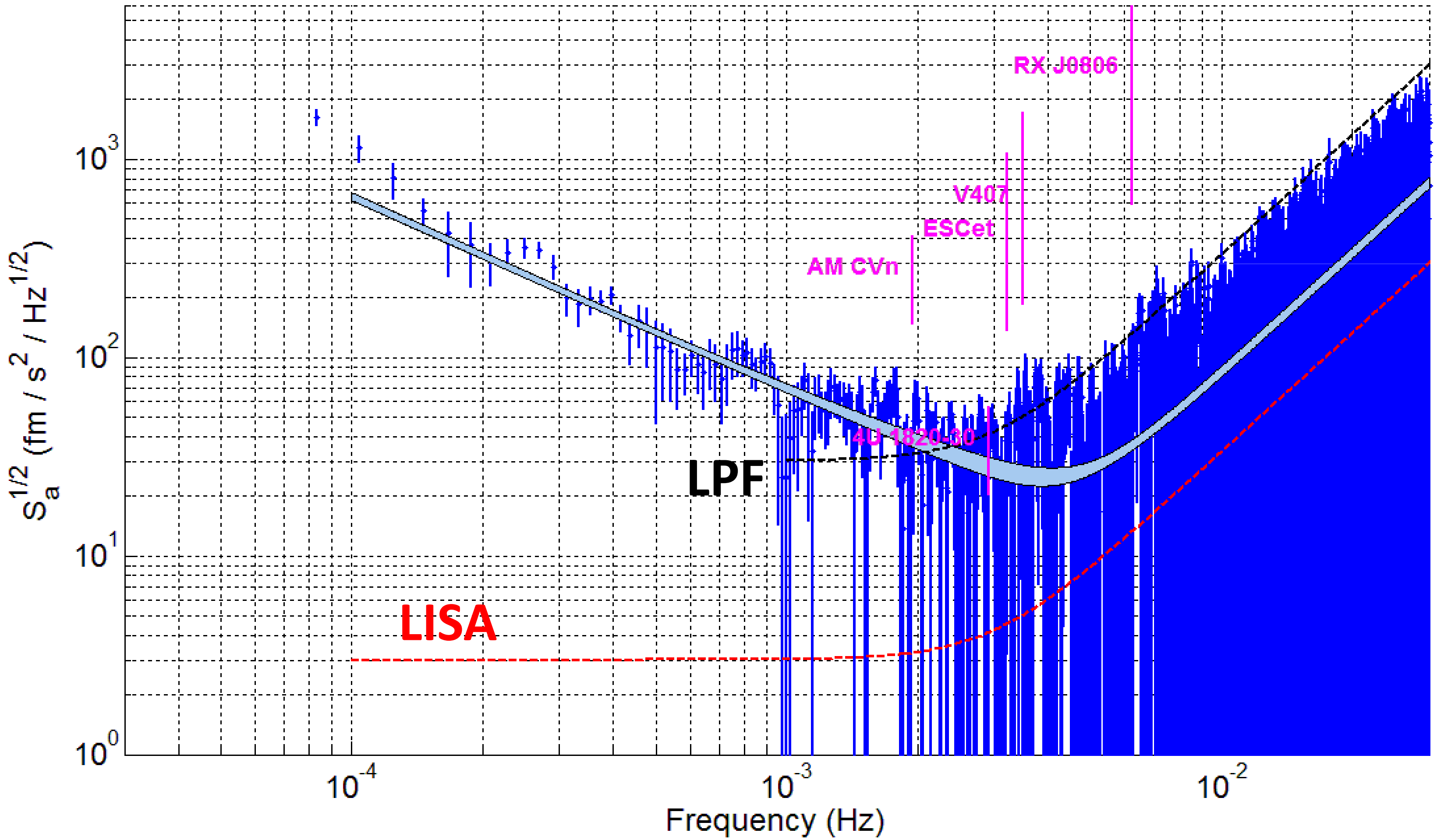
Average of 32 48000 s windows (6 weekends of data)



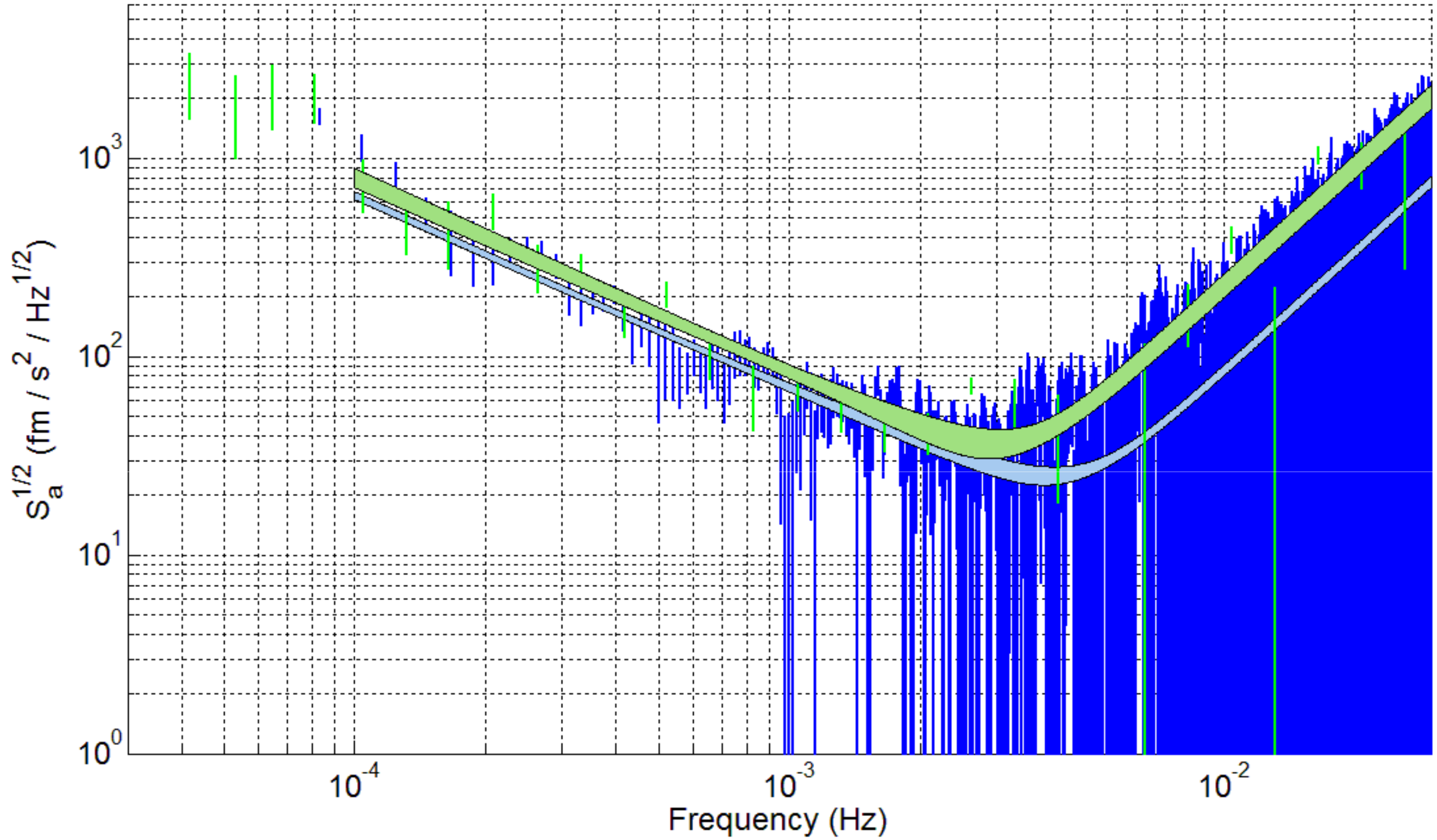
Average confirms slight excess torque noise around 1 mHz → roughly 50 % in power

Upper limits on GRS force noise:
conversion from torque → force (acceleration)

Division by armlength 10.75 mm → ½ separation electrodes (electronics back-action)
For uniformly distributed forces on all TM faces → would use 23 mm



Upper limits on GRS force noise:
Comparison Mo/Shapal sensor (green) and Mo/sapphire (blue)

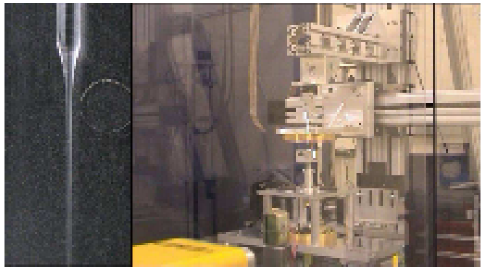


Observe roughly same force excess with:

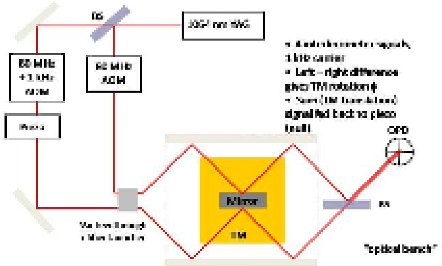
- Different sensor materials, coating
- Different electronics (ETHZ EM for LPF / homemade UTN)
- Same fiber

Current force noise and electrostatic noise measurements limited by force resolution…

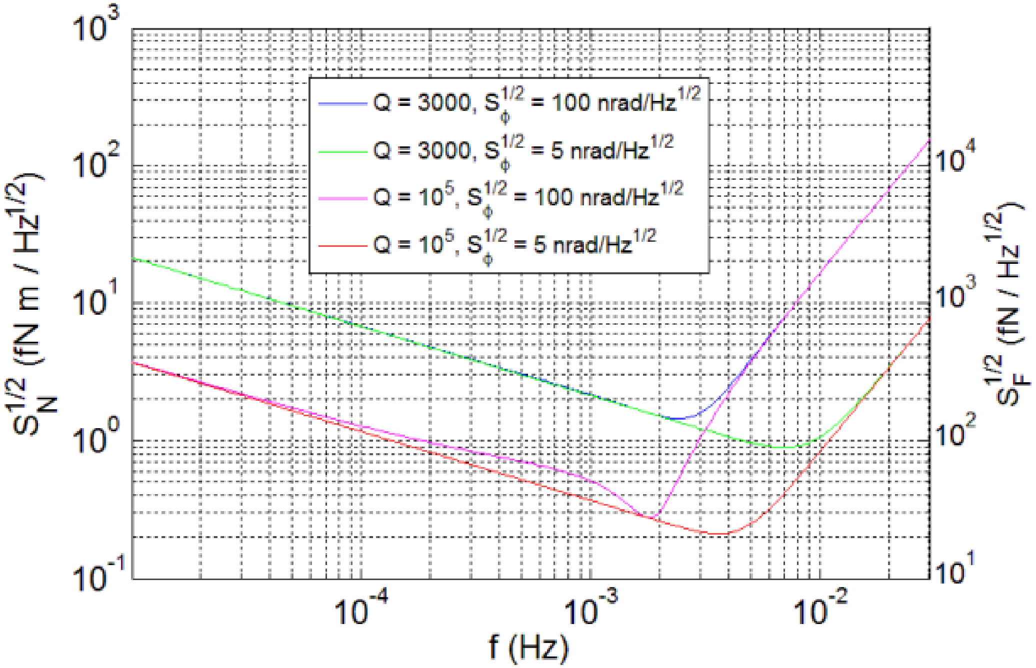
An improved torsion pendulum for higher sensitivity force measurement



High Q fused silica fiber
(35-40 micron diameter)
Collaboration with U. Glasgow
(S. Rowan, A. Hepstonstall)



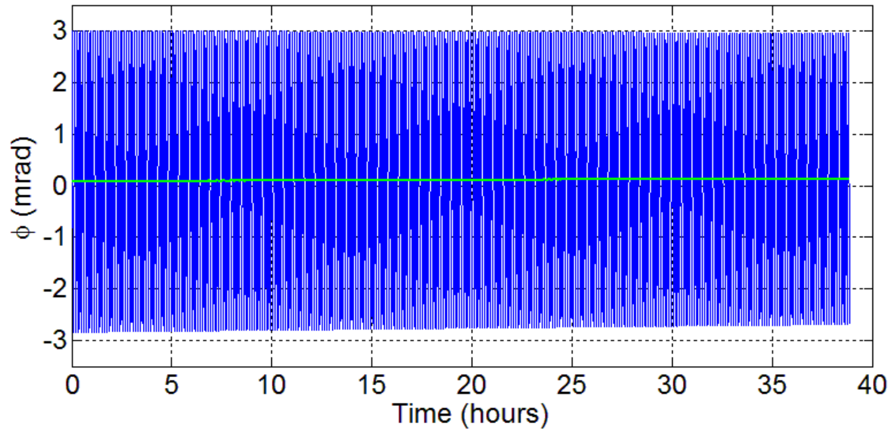
Wavefront sensing
interferometric readout



Possible improved sensitivity → factor 10

Torsion pendulum with fused silica: preliminary results

40 μm diameter



Ringdown:

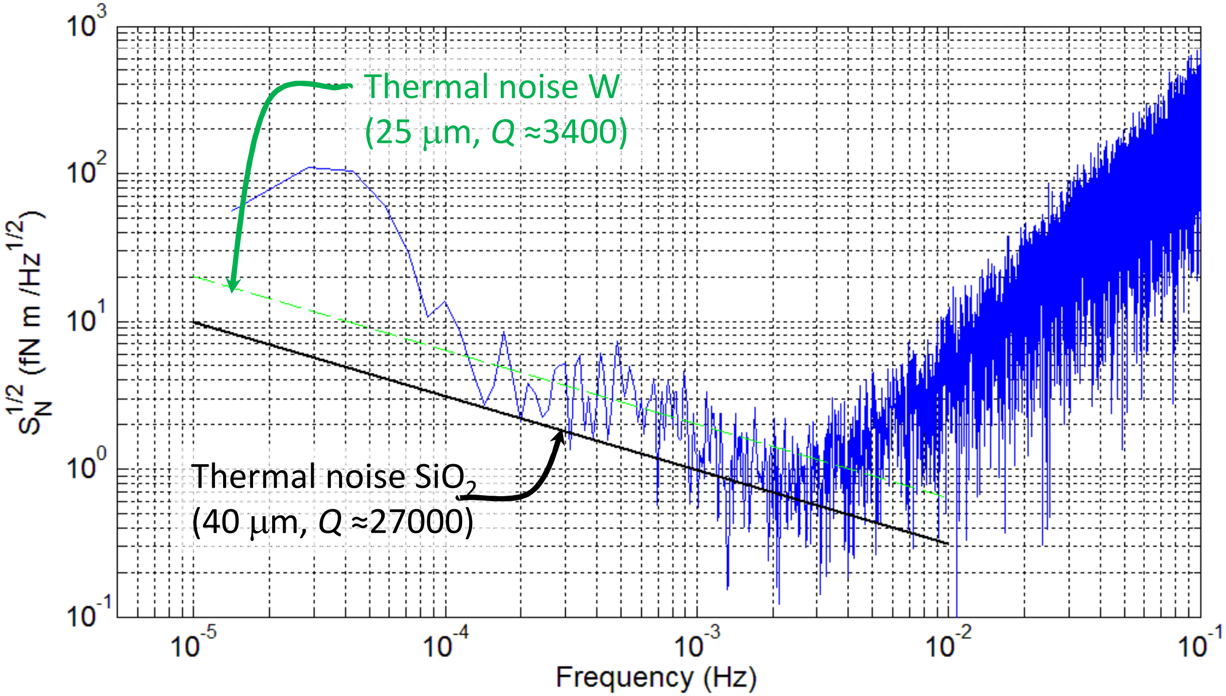
T_0 = 466 s (Γ≈8 nN m / rad)

τ≈ 2.10^6 s (Q ≈27000)

Unwinding ≈ 1.3 μrad / hour

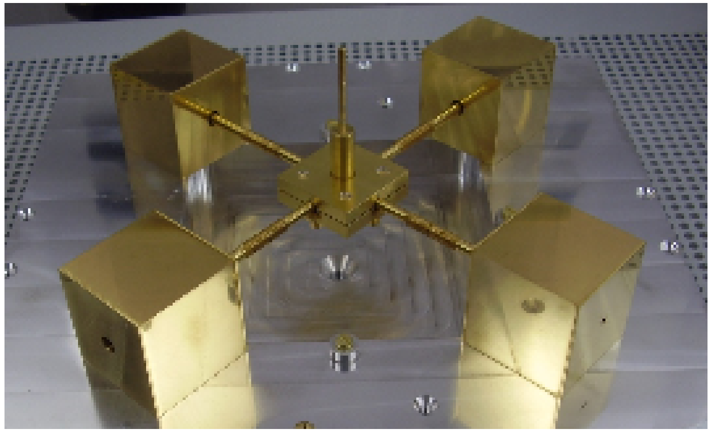
Torque noise

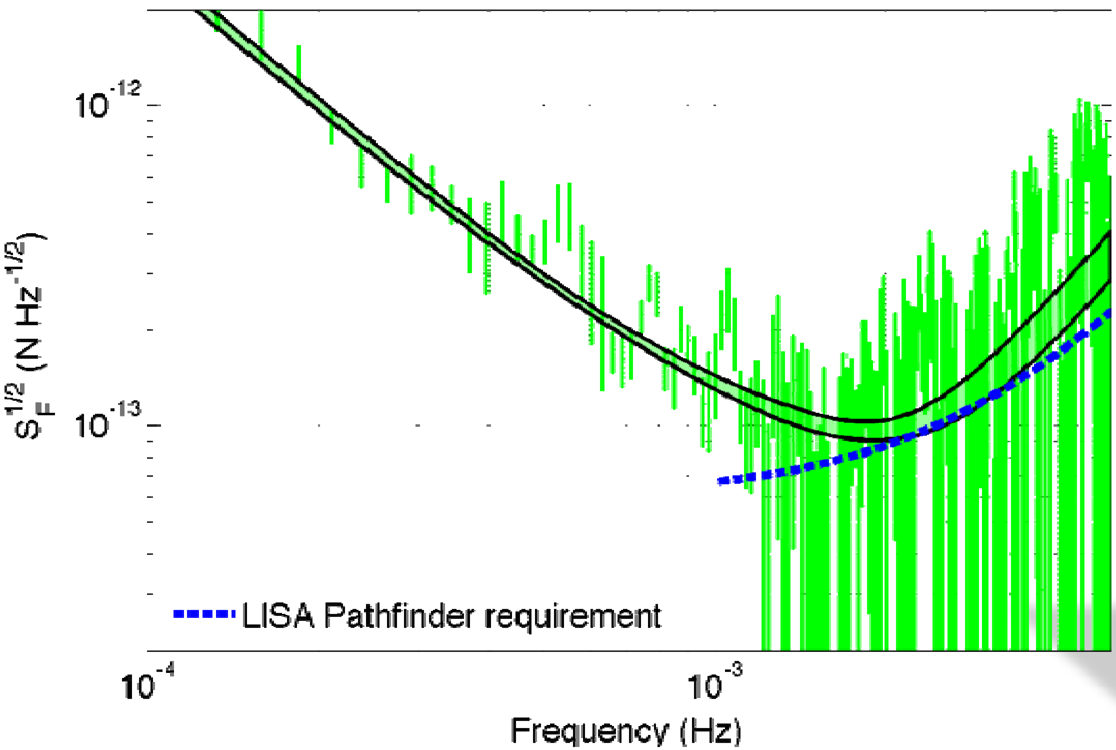
Prelimary data already at "old" tungsten thermal noise limit



Direct force noise upper limits with 4-TM pendulum

100 fN /$Hz^{1/2}$ level near 1 mHz

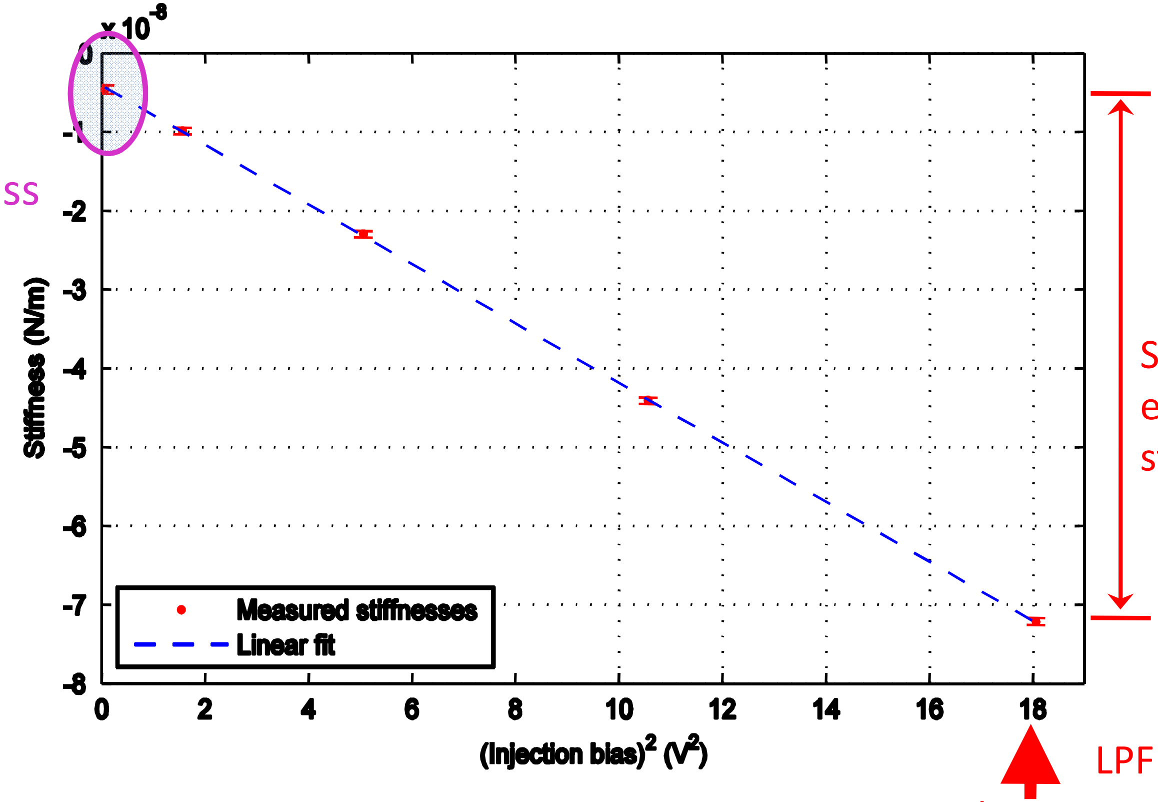


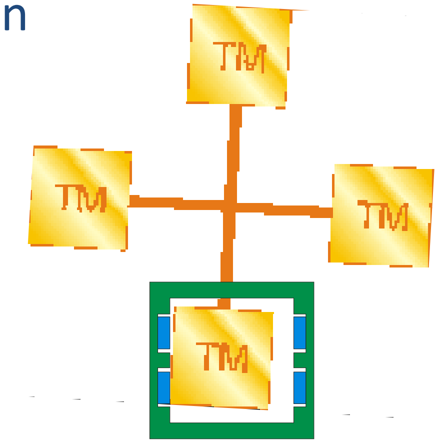


Satellite coupling: Direct measurement of sensor translational stiffness

Detect coherent pendulum deflection for small sensor translation

Sensor OFF
stray stiffness





Sensing
electrostatic
stiffness

LPF sensor bias

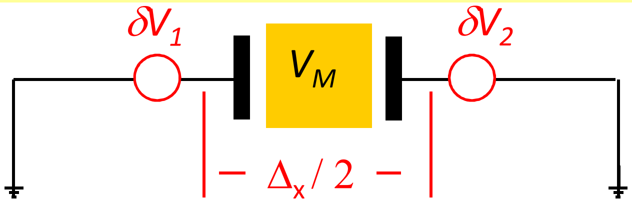
Sensor stiffness (modeled): ~ 100 nN / m

Measured "stray" stiffness (sensor OFF) ~ 5 nN / m (DC bias? δV_{RMS} ~ 90 mV)

Total LISA stiffness budget: ~ 1000 nN / m

- Unexpected stiffness likely not an issue for LISA (4 mm gaps!)
- LISA Pathfinder will perform full stiffness measurement (including gravity gradients)

Noise source: stray low frequency electrostatics



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

$$k = -\frac{\partial F}{\partial x} = -\frac{1}{2}\sum_i \frac{\partial^2 C_i}{\partial x^2}\left(V_i - V_{TM}\right)^2 \quad \begin{cases} \propto Q^2 \\ \propto \left\langle \delta V^2 \right\rangle \end{cases}$$

Electrostatic stiffness

$$F = \frac{Q}{C_{TOT}}\sum \frac{\partial C_i}{\partial x}\delta V_i \quad \begin{cases} S_F^{1/2} = \dfrac{\sqrt{2e^2\lambda_{EFF}}}{\omega C_T}\left|\dfrac{\partial C}{\partial x}\right|\Delta_x \\ S_F^{1/2} = \dfrac{\langle Q\rangle}{C_T}\left|\dfrac{\partial C}{\partial x}\right| S_{\Delta_x}^{1/2} \end{cases}$$

Random charge noise mixing with DC bias (Δ_x)

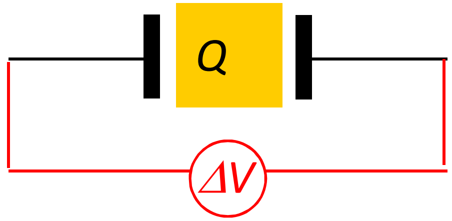
Noisy average "DC" bias ($S_{\Delta x}$) mixing with mean charge

$$S_F^{1/2} = \sqrt{\sum \left|\frac{\partial C_i}{\partial x}\right|^2 \delta V_i^{\,2} S_{\delta V_i}}$$

Noisy "DC" biases interacting with themselves

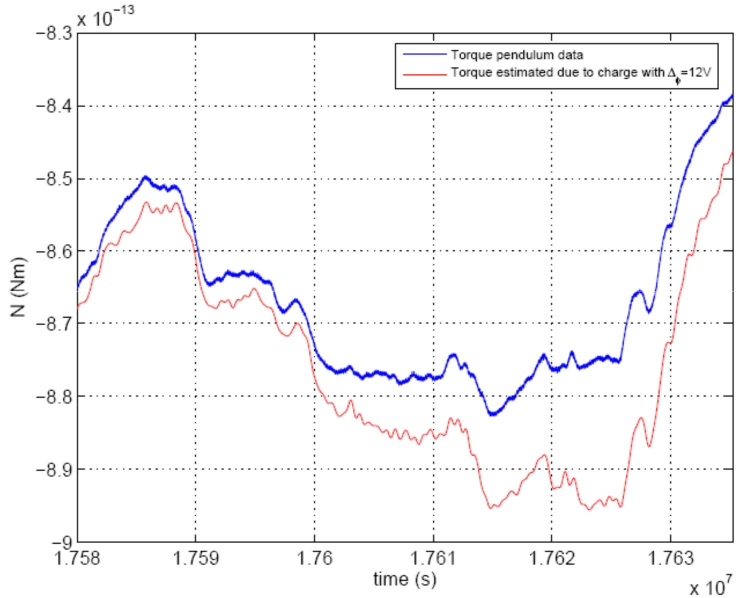
Noise source: Cosmic ray charging

- Randomly arriving charged particles interact with any net field to produce force noise

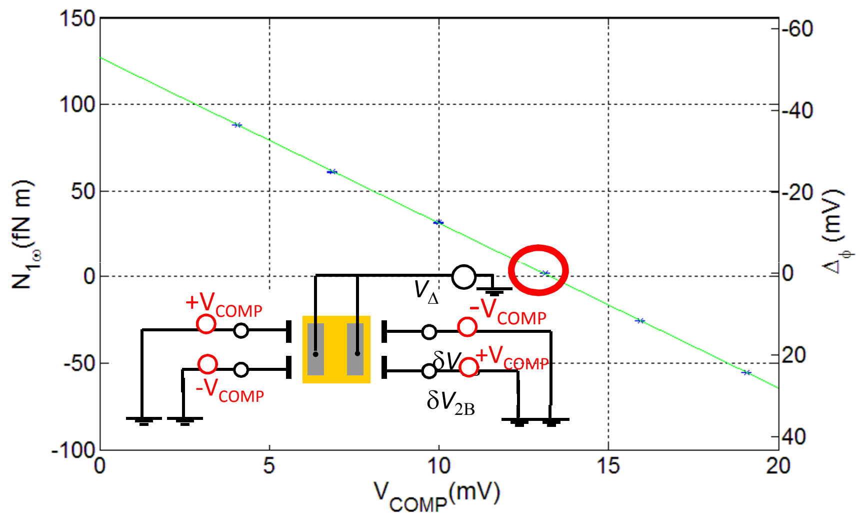


$$F_Q \propto -Q\,\Delta V$$

- Expect λ_{EFF} ~ 1000 +*e*/s [Araujo, 2004]



- Calculated and measured force noise with **large** photoelectric currents (+/- 12000 e / s) and **large** applied field (Δ_ϕ = 12 V)

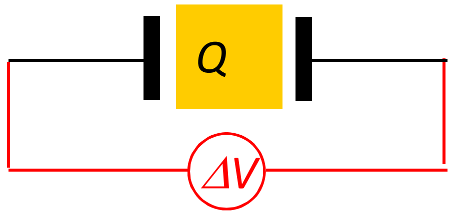


- Measurement and compensation of DC bias to within Δ_ϕ < 1 mV
- uncompensated 50 mV, Mo/sapphire sensor

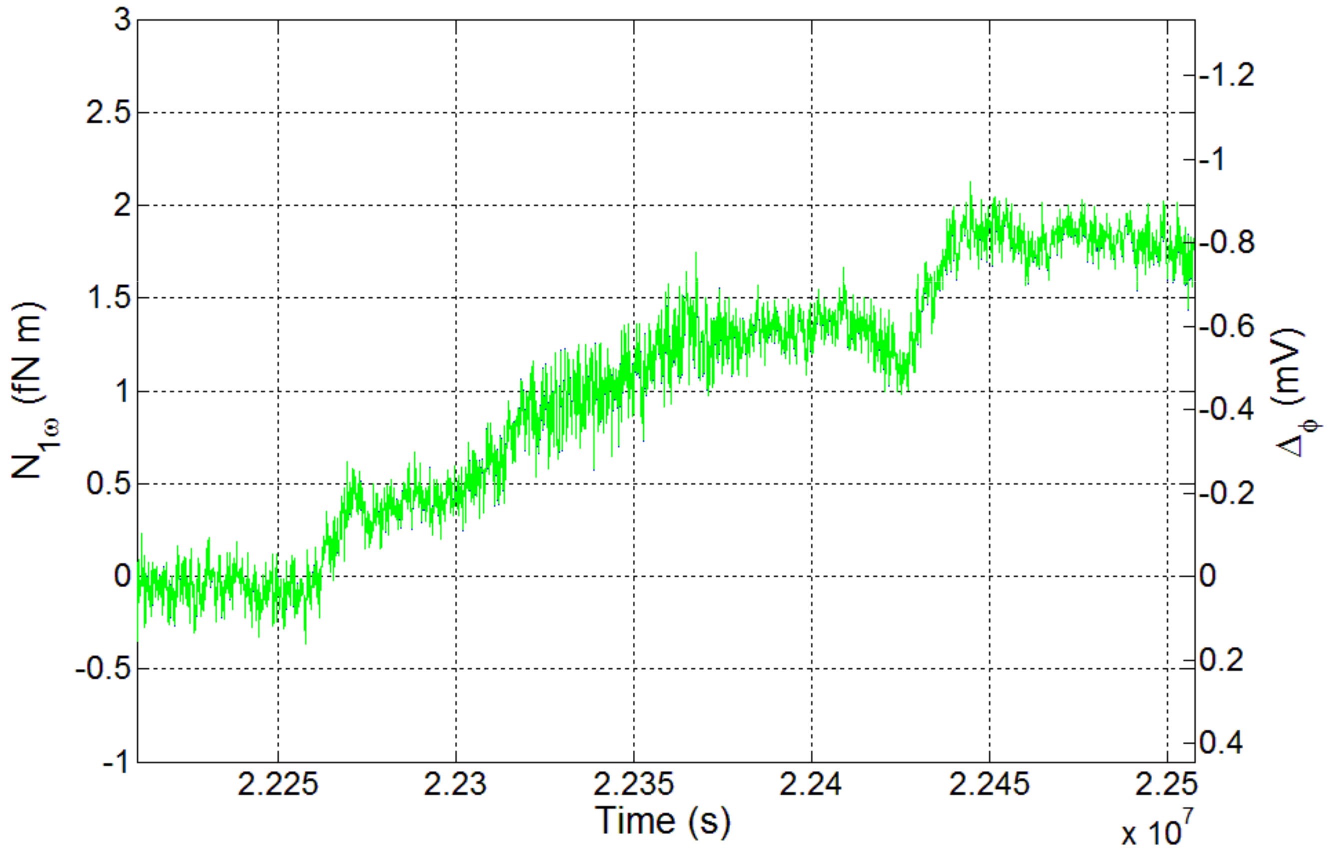
Still needed: test of compensation at mV level with true TM charge modulation (not TM potential modulation)

Noisy DC bias interacting with TM charge

- Even steady charge can create force noise mixing with a noisy stray electrostatic field



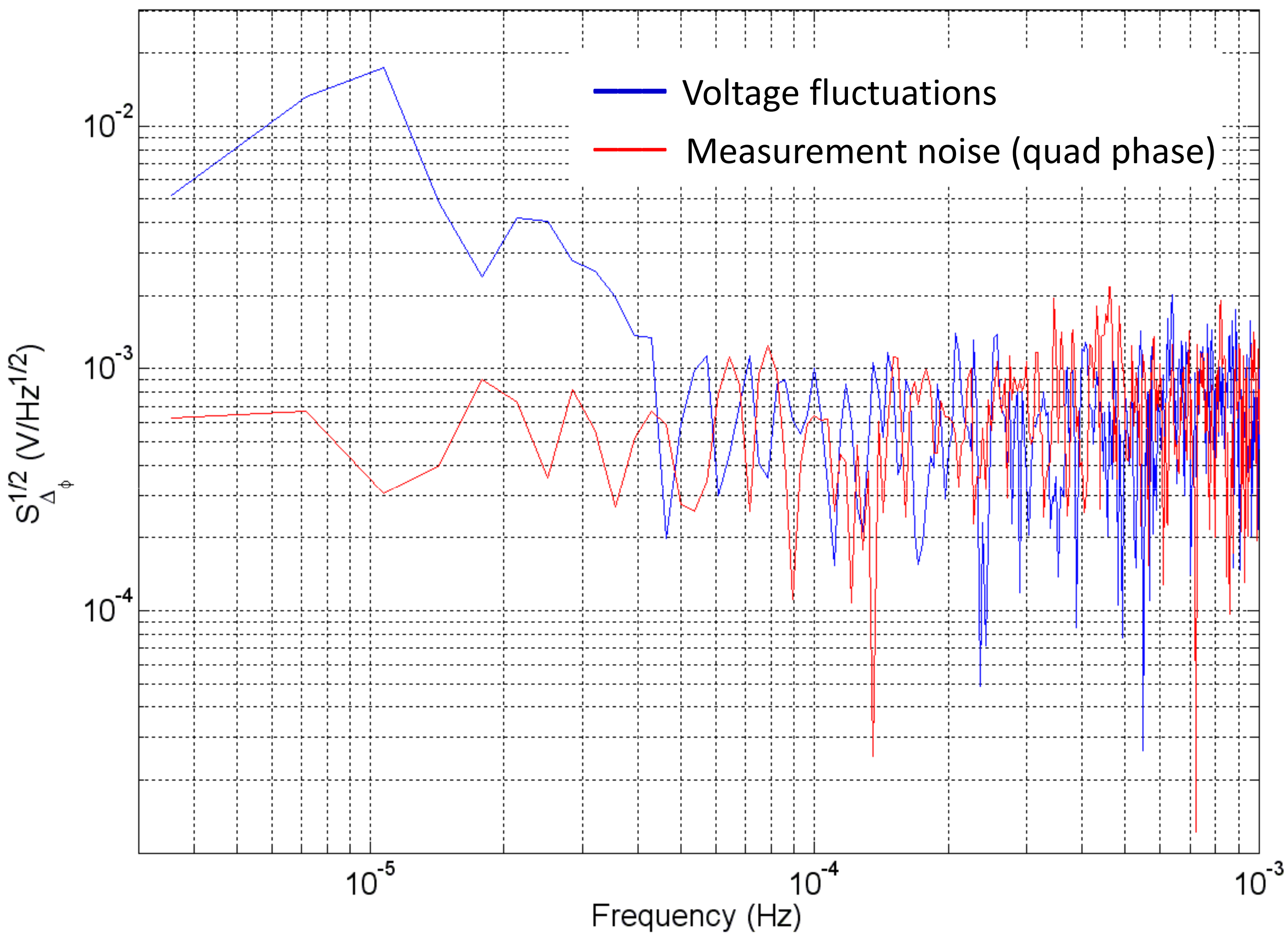
$$F_Q \propto -Q\,\Delta V$$



$$\Delta_\phi \equiv \frac{\sum_i \frac{\partial C_i}{\partial \phi}\delta V_i}{\left|\frac{\partial C_x}{\partial \phi}\right|}$$

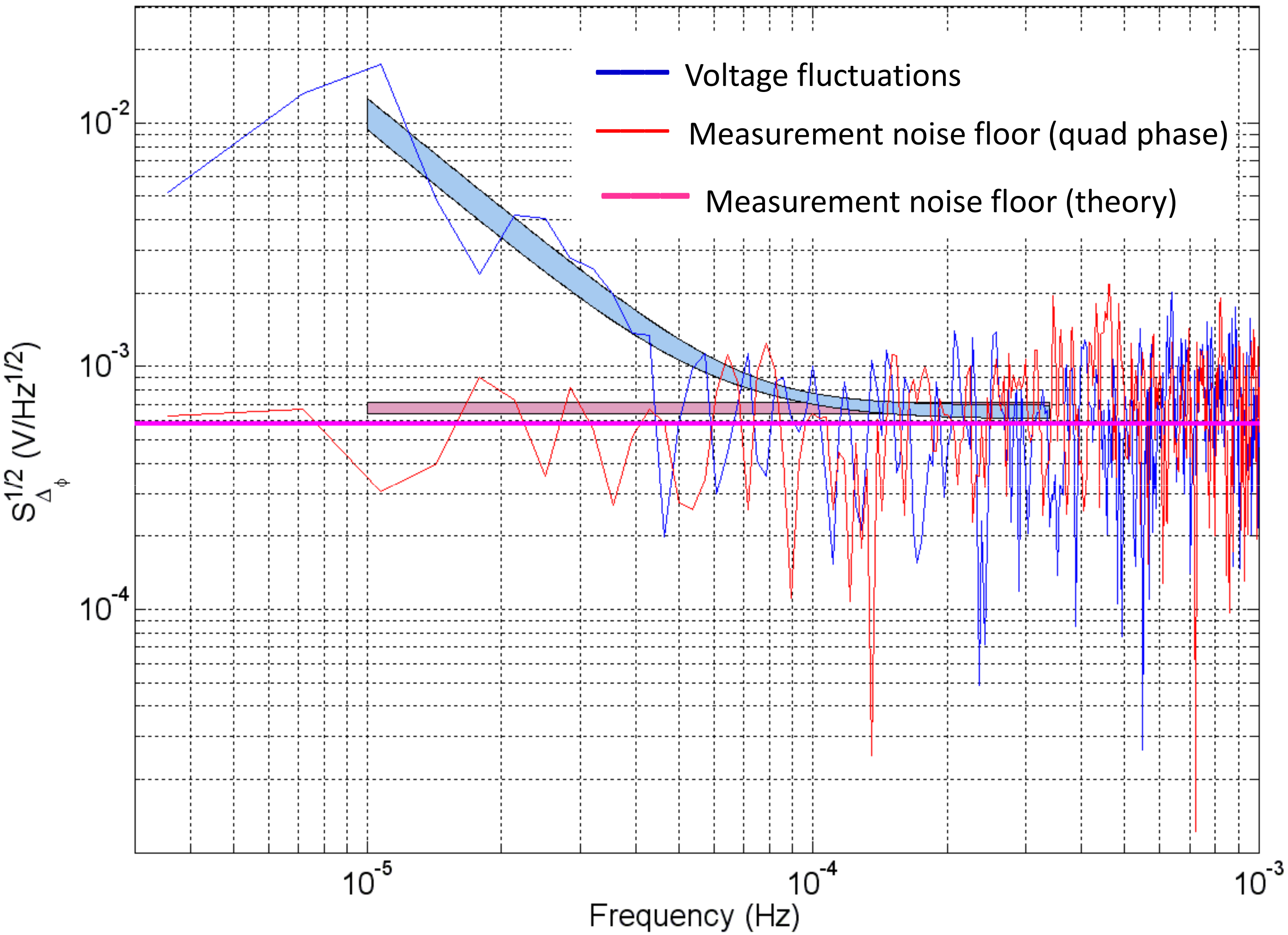
Rotational measurement of DC bias fluctuations with Mo – sapphire sensor over 3 days

Measured noise in stray "DC" biases

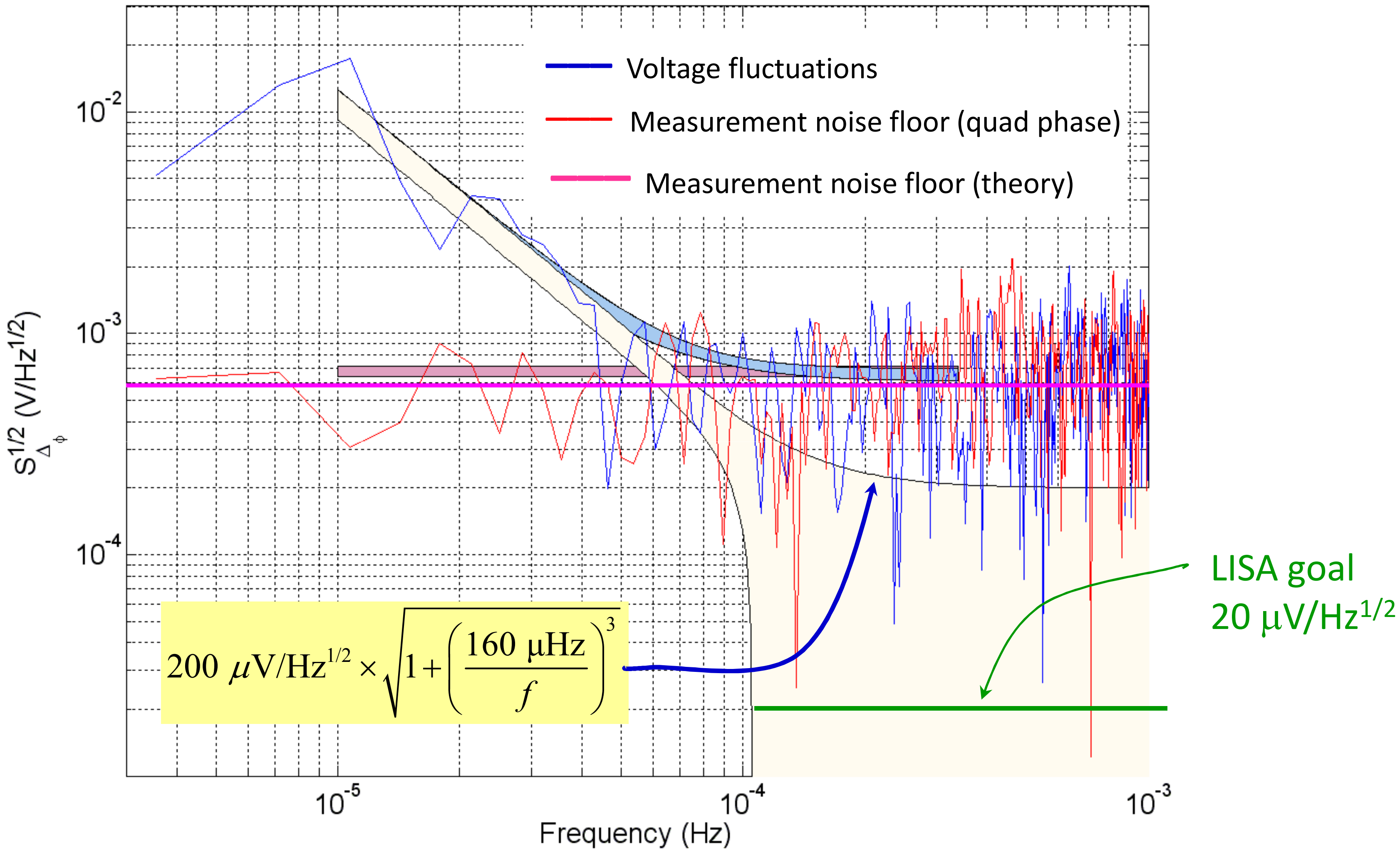


(Mo – shapal sensor)

Measured noise in stray "DC" biases

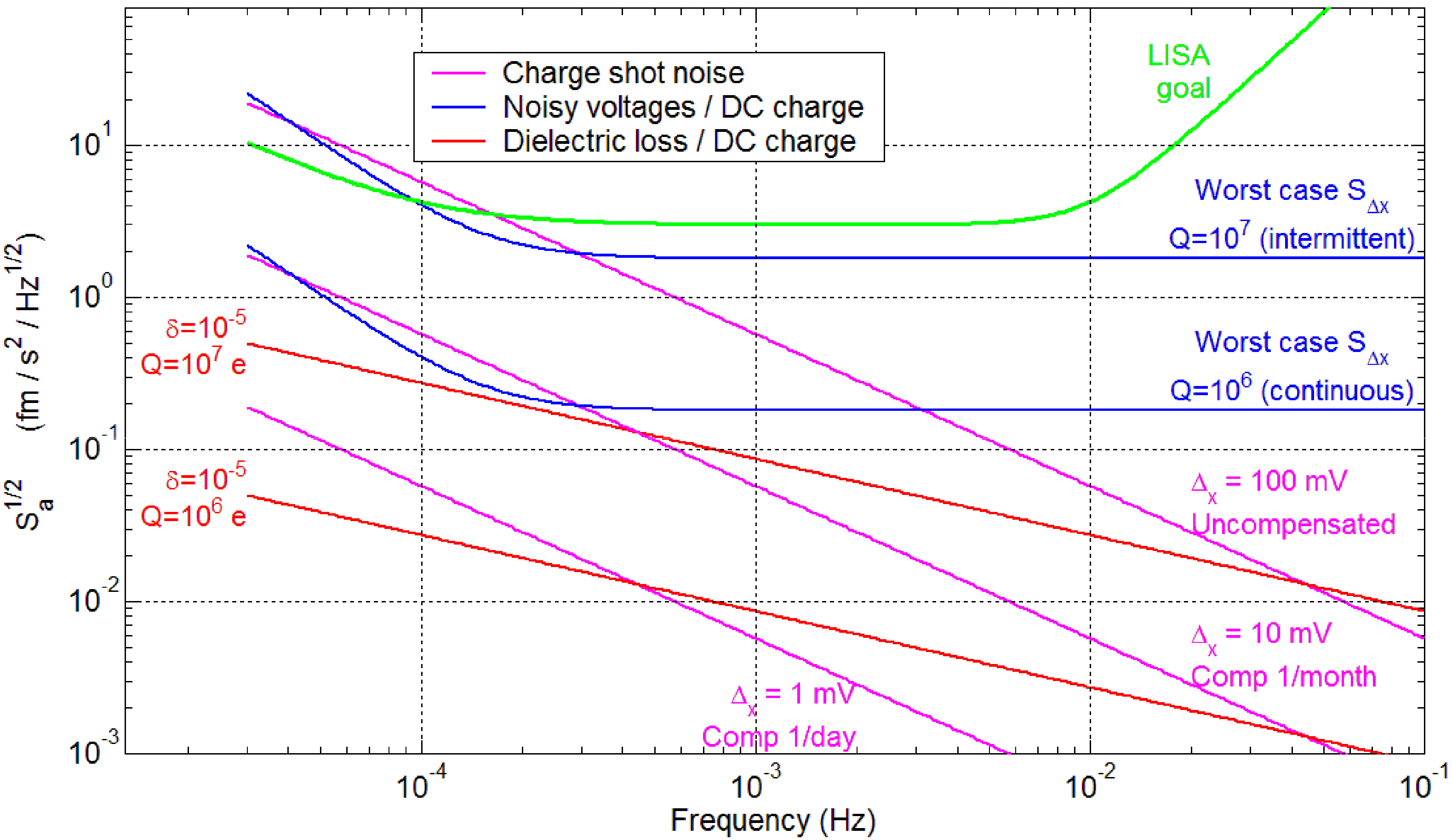


Measured noise in stray "DC" biases



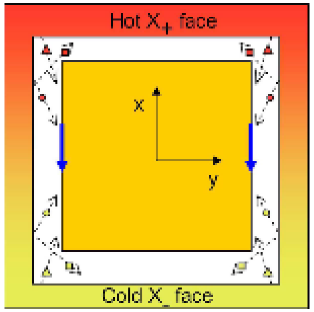
- No excess voltage fluctuation noise observed above 0.1 mHz
- 1σ-limit of measurement: 200 μV/ Hz$^{1/2}$ white noise near 0.2 mHz
- fit to $1/f^{\,3/2}$ excess at lower frequencies

Noise budget for charge – stray voltage interaction



NB: “worst case” for stray voltage fluctuations is measurement limited (true noise likely falls off with increasing frequency)

Thermal gradient-induced forces



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radiometric

$$F_{radiom} = AP\frac{\Delta T}{4T}\times\kappa_{RAD} \approx 18\ \mathrm{pN/K}\times\kappa_{RAD}$$

$$\kappa_{RAD} \approx 1.25$$

radiation pressure

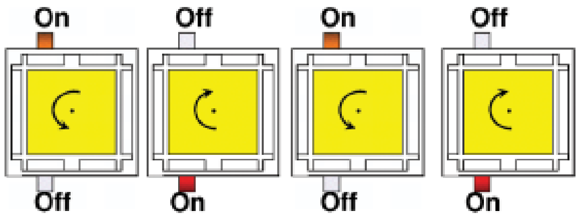
$$F_{rad\ press} = \frac{8}{3}\frac{\sigma A T^3}{c}\Delta T\times\kappa_{RP} \approx 27\ \mathrm{pN/K}\times\kappa_{RP}$$

$$\kappa_{RP} \approx 0.3\ (r{=}95\%)$$

outgassing

$$F_{outgas} \propto \frac{\Delta T}{T^2}\Theta Q_{outgas} \qquad ???$$

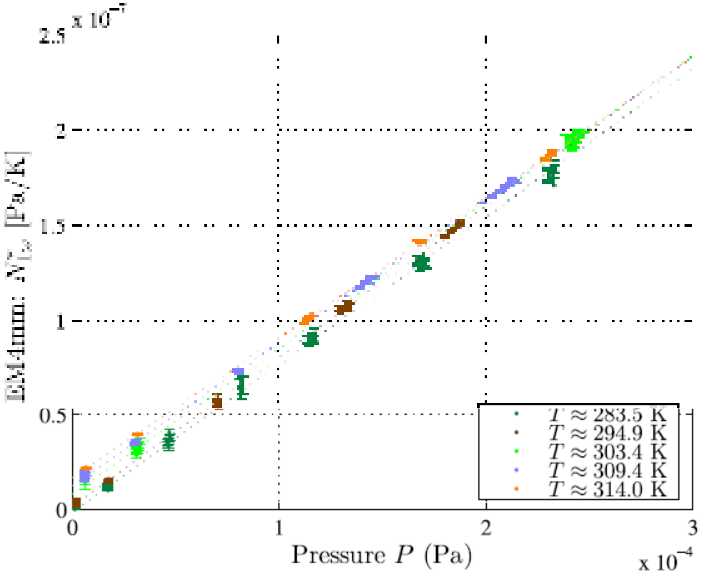
Numerical simulations for "finite size" calculations

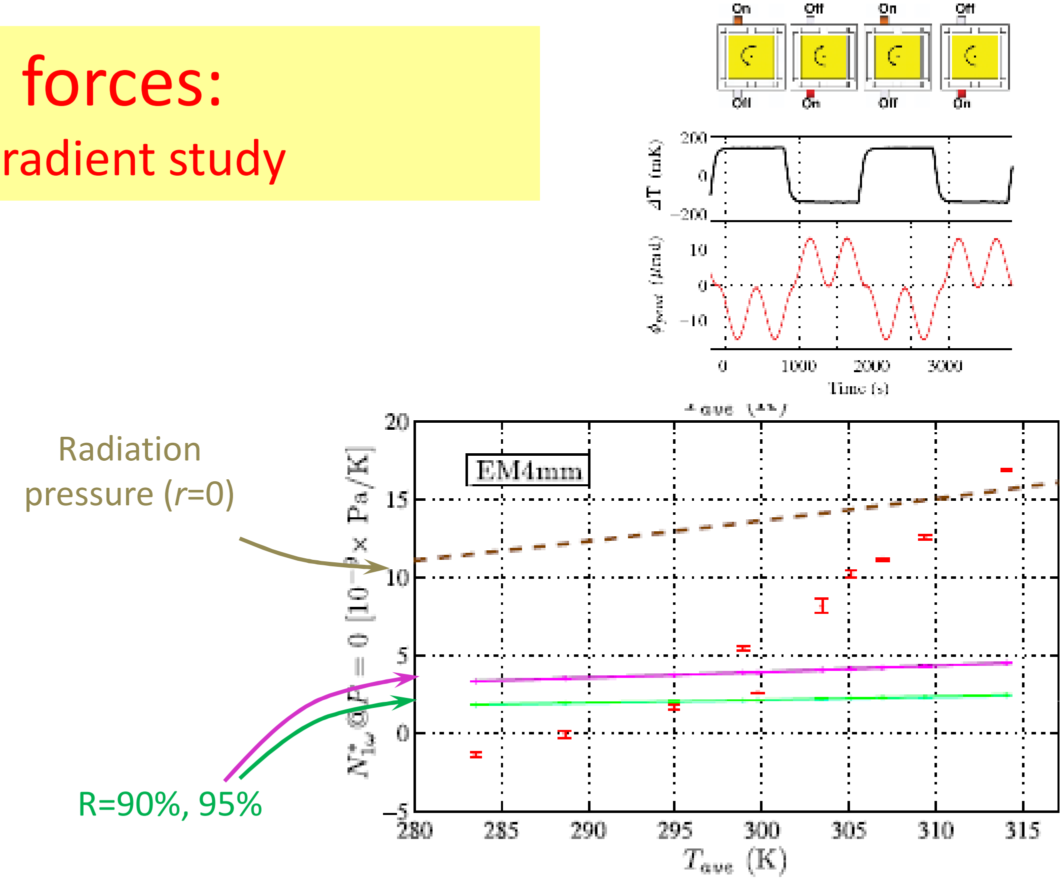


- dF/dΔT ~ 100 pN / K
  → need $S_{\Delta T}^{1/2}$ < 10 μK / $Hz^{1/2}$
- outgassing hard to predict → need a measurement

Thermal gradient-induced forces:

1-mass “rotational” temperature gradient study





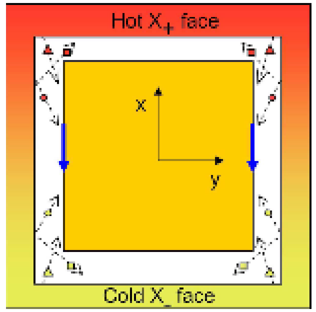
- verify *(p/T)* dependence of radiometric effect
  - ➢quantitative agreement with model (30% uncertainty in temperature distribution)

- Observe small outgassing effect
  - ➢radiation pressure and outgassing not threatening to LISA goals

- 100 pN / K remains conservative estimate
  - ➢need 10^{-5} K/Hz$^{1/2}$ temperature difference stability

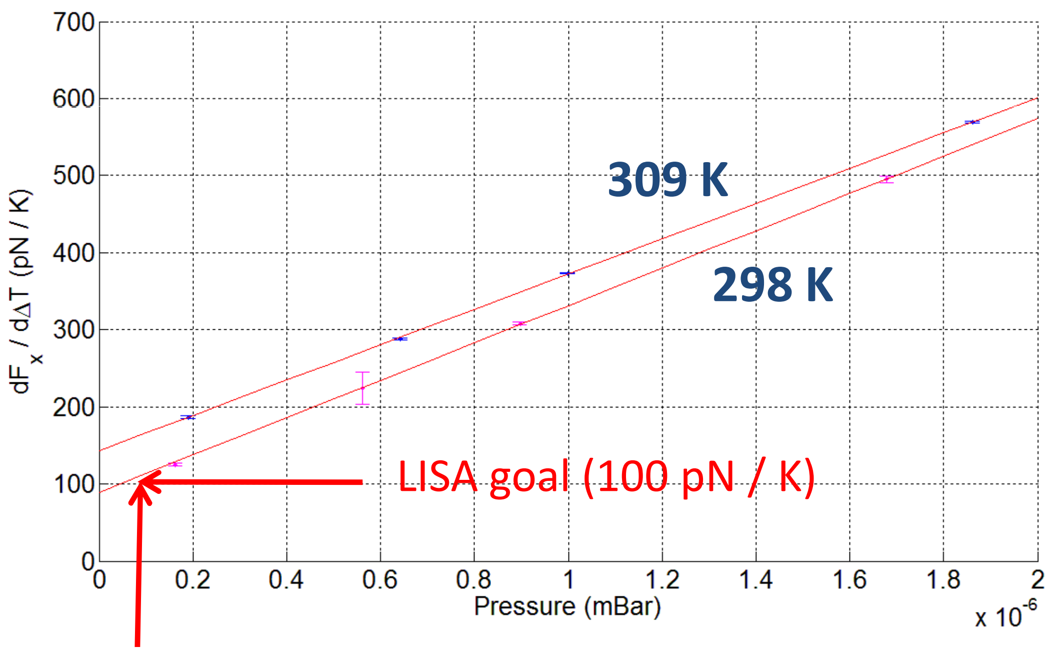
Thermal gradient-induced forces:

4-mass torsion pendulum translational force measurement (preliminary results)



→ Direct measurement of force coupling $dF_x/d\Delta T$ relevant to LISA force noise

→ Much easier analysis of temperature distribution



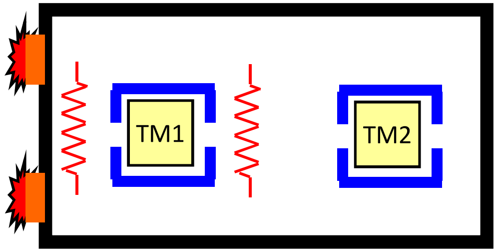
LISA pressure
10^{-5} Pa

Preliminary results:

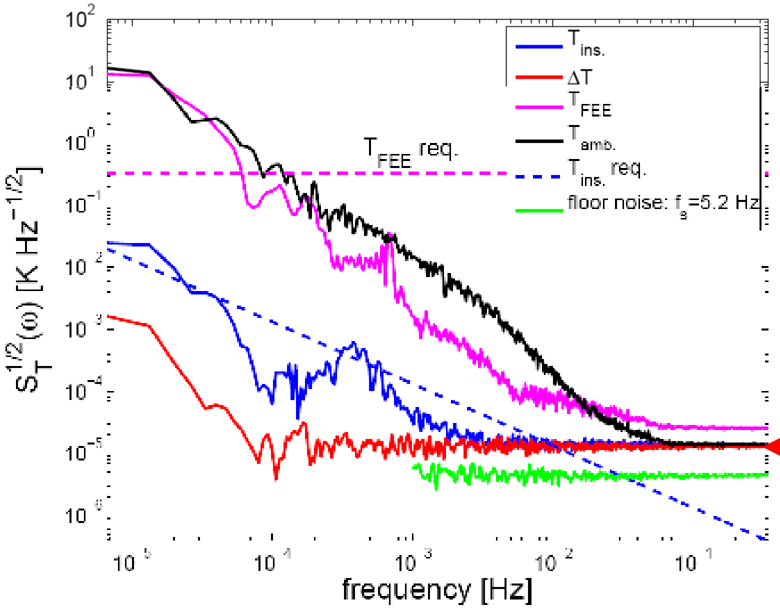
- Verify radiometric model (10%)
- Outgassing observed (pre-bake)
  → Zero pressure data increase faster than radiation pressure's T^3
- Measure roughly 100 pN/K at 10^{-5} Pa / 25 C

→ LPF will allow an in-flight measurement of thermal gradient effects

Measurement of coupling with thermometers and heaters



→ LPF will characterize spacecraft thermal environment



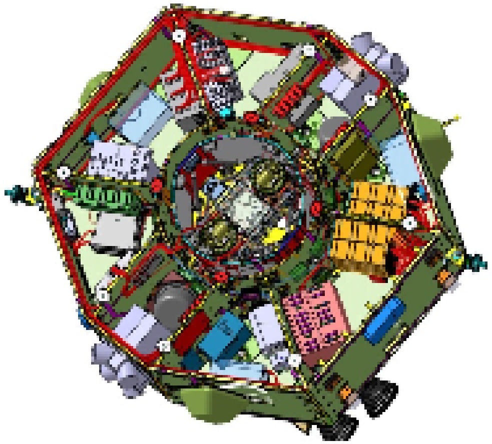
- Discrimination/subtraction of possible thermal effects
- **Can characterize SC thermal environment at LISA's 10 $\mu K/Hz^{1/2}$ level**
- Thermometers can be re-used for LISA

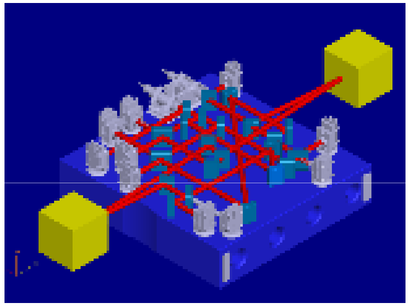
LISA Pathfinder: Performance limited by 2 TM in 1 SC → applied forces

- SC can only follow 1 TM along x (2 TM, 1 SC)
- Any differential DC acceleration must be balanced by applied (electrostatic) forces
- Noise in applied voltage gives noisy force

$$F \propto V^2$$

$$S_F^{1/2} = 2FS_{\delta V/V}^{1/2}$$

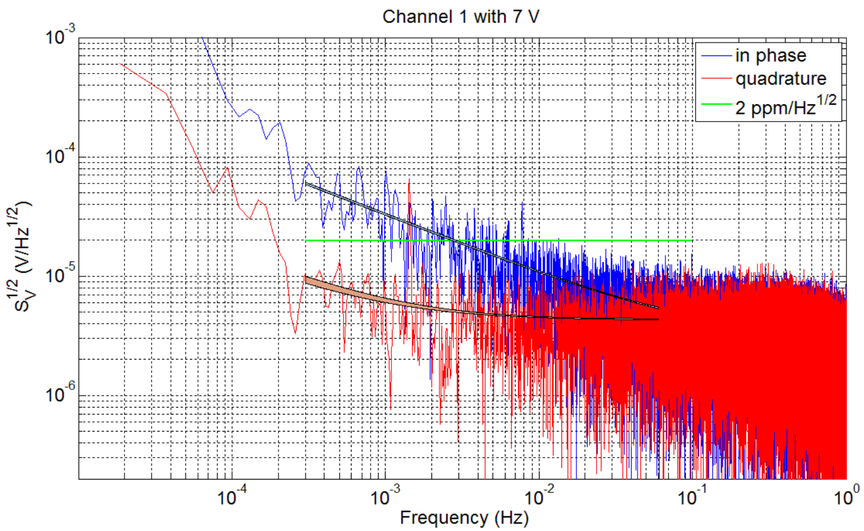




- Local SC gravity modelled and balanced to 100 pico-g level

- Actuation voltage carrier amplitude stable to 3 ppm/Hz$^{1/2}$

(electronics Contraves Space, test U. Trento / ETH Zurich)



ESA LTP Collaboration

Trento LISA Team

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