Torsion Pendulum Ground Testing Results for LISA Gravitational Reference Sensors

Mauro Hueller

and the LISA team at Trento University:

L. Carbone, A. Cavalleri, R. Dolesi, C.D. Hoyle, S. Vitale, and W.J. Weber

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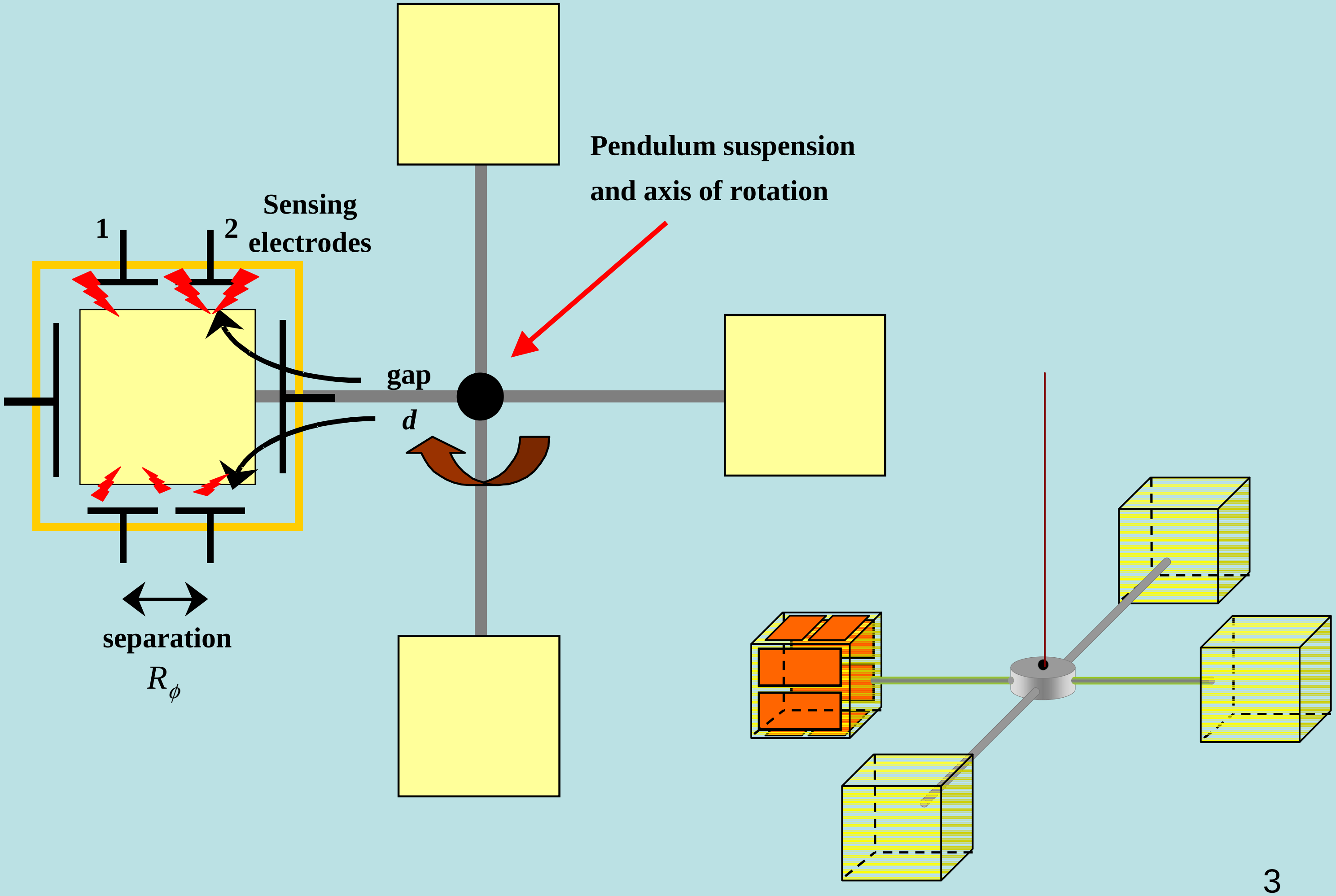
Talk summary

- Scheme of the experiment
- Random force noise measurements
- Sensor disturbances characterization:
    - stray DC bias measurements and compensation
    - electric charge measurements
    - electrostatic coupling (stiffness)
- Status and future of the facility

Testing LISA gravitational sensors with torsion pendulum

- Light weight test mass suspended as part of the inertial member of a low frequency torsion pendulum, surrounded by representative LISA sensor housing

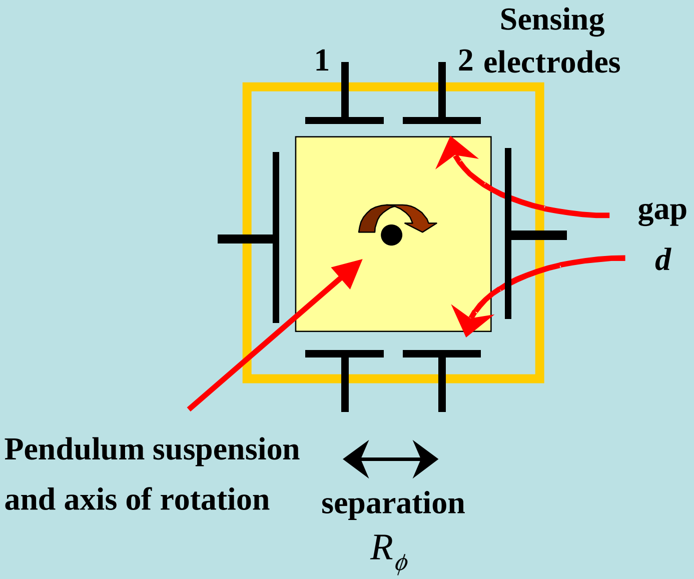


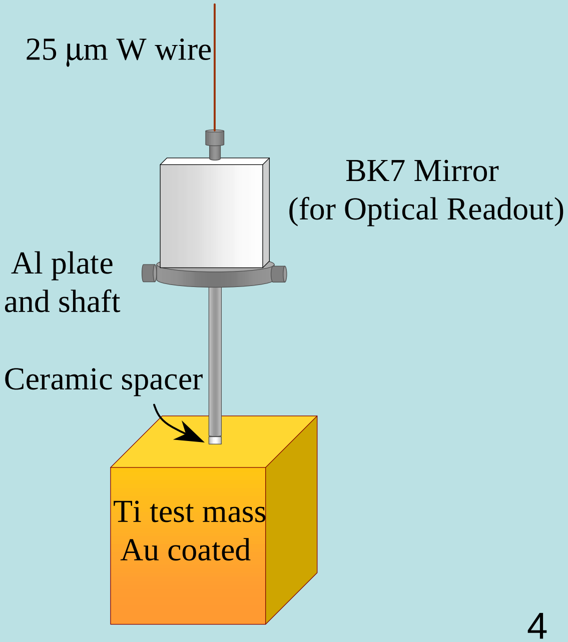
- Measure surface stray forces and coupling to sensor as deflections of pendulum rotation

- Upper limit to differential force noise along 1 rotational dof

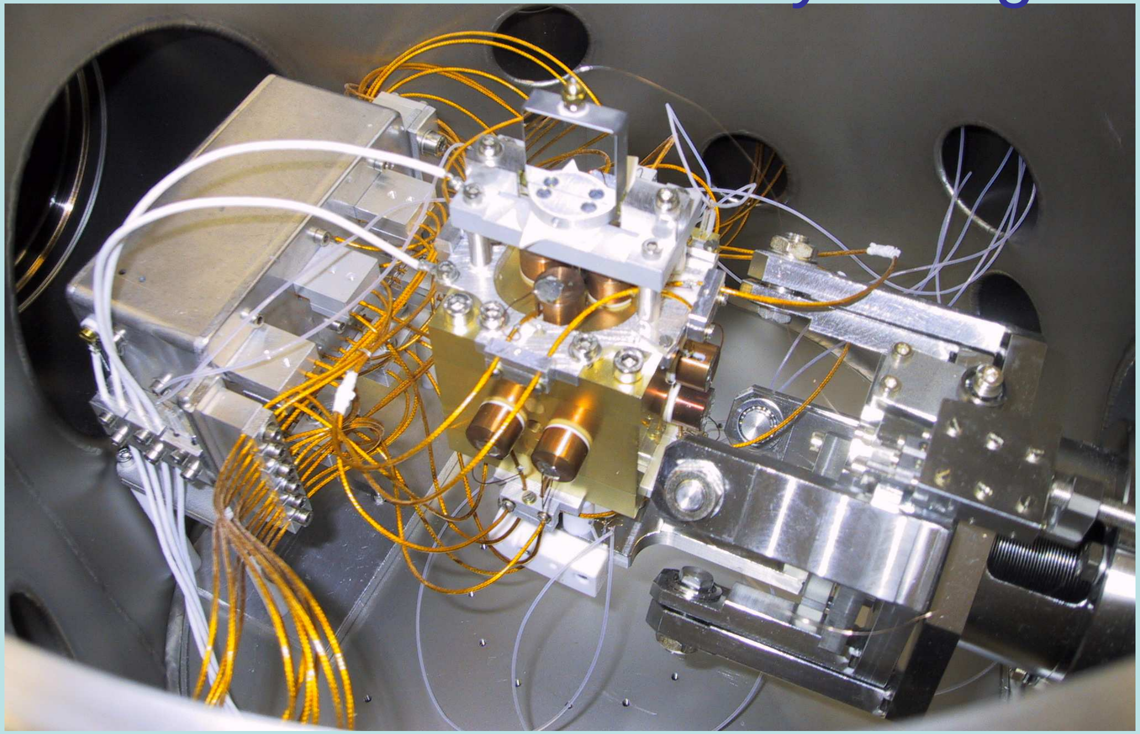
- Precise measurements of residual coupling to sensor (electrostatic, gravitational)

- Disturbance sources study: stray DC voltages (charge, patch fields)



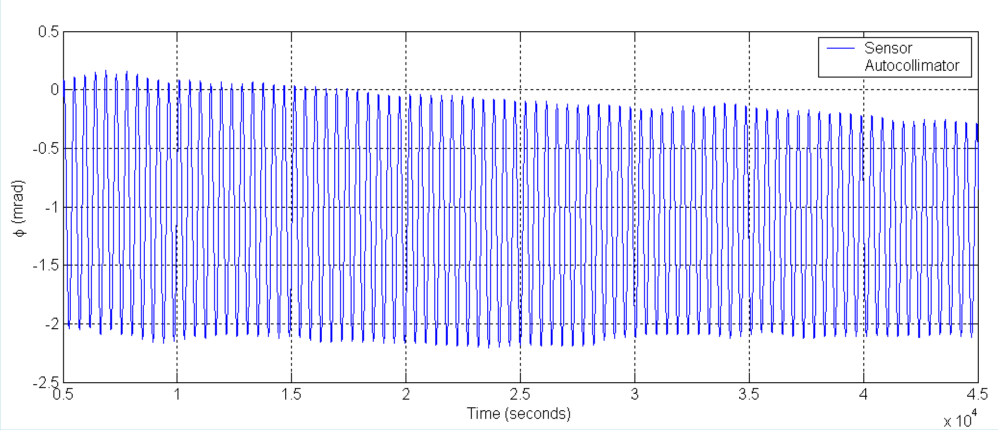


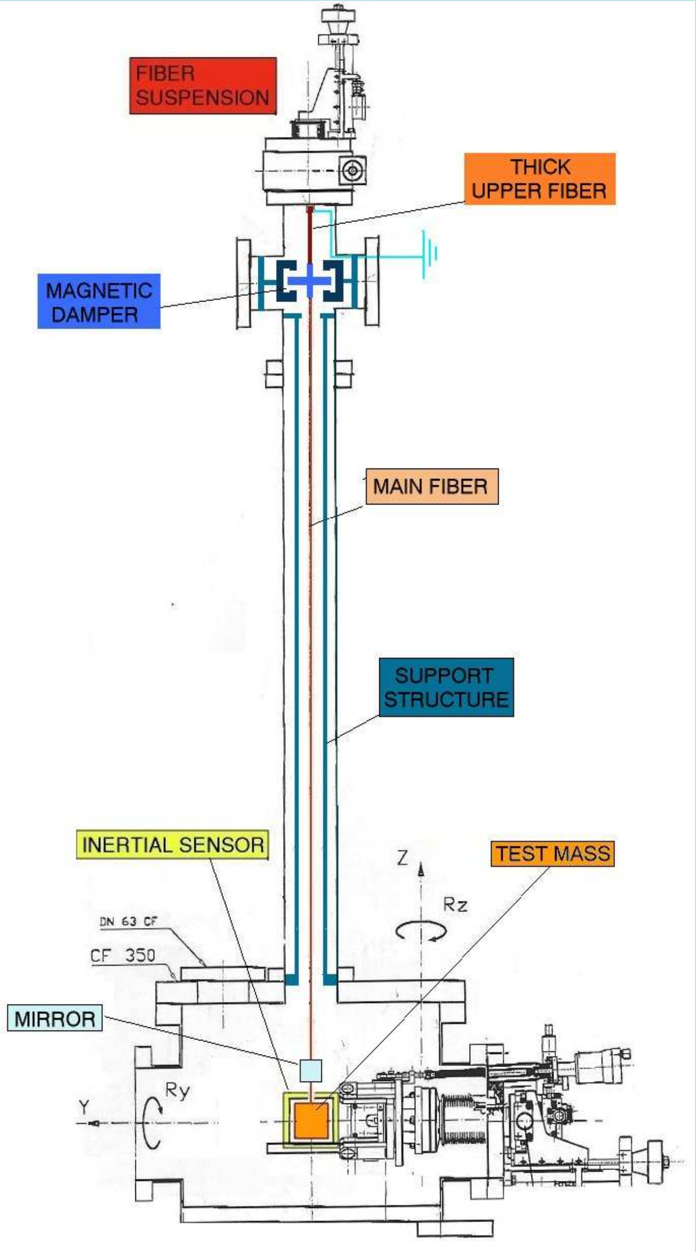
The facility at a glance



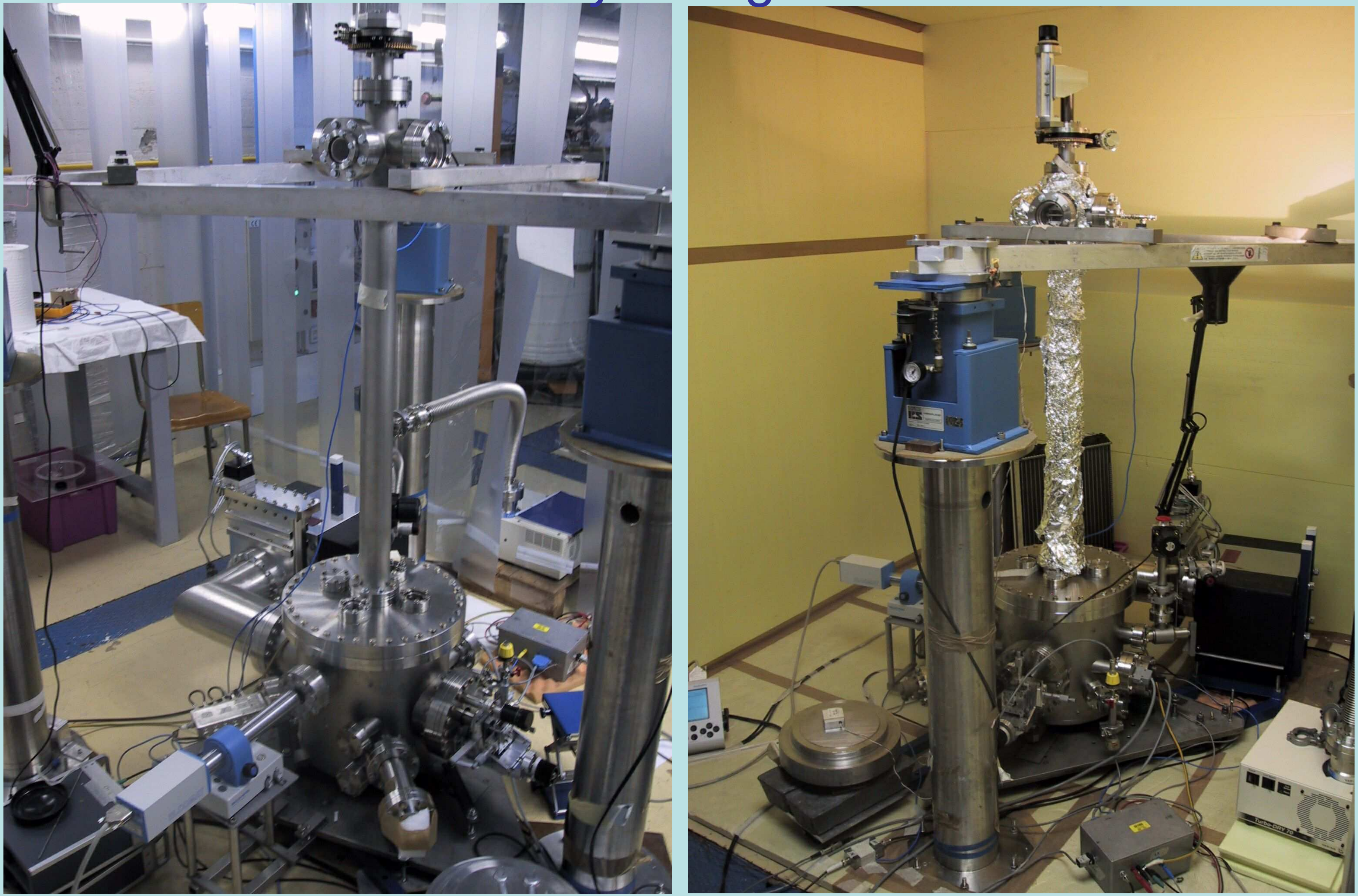
25 μm
1m W fiber

T_0 = 513 s
Q = 1750



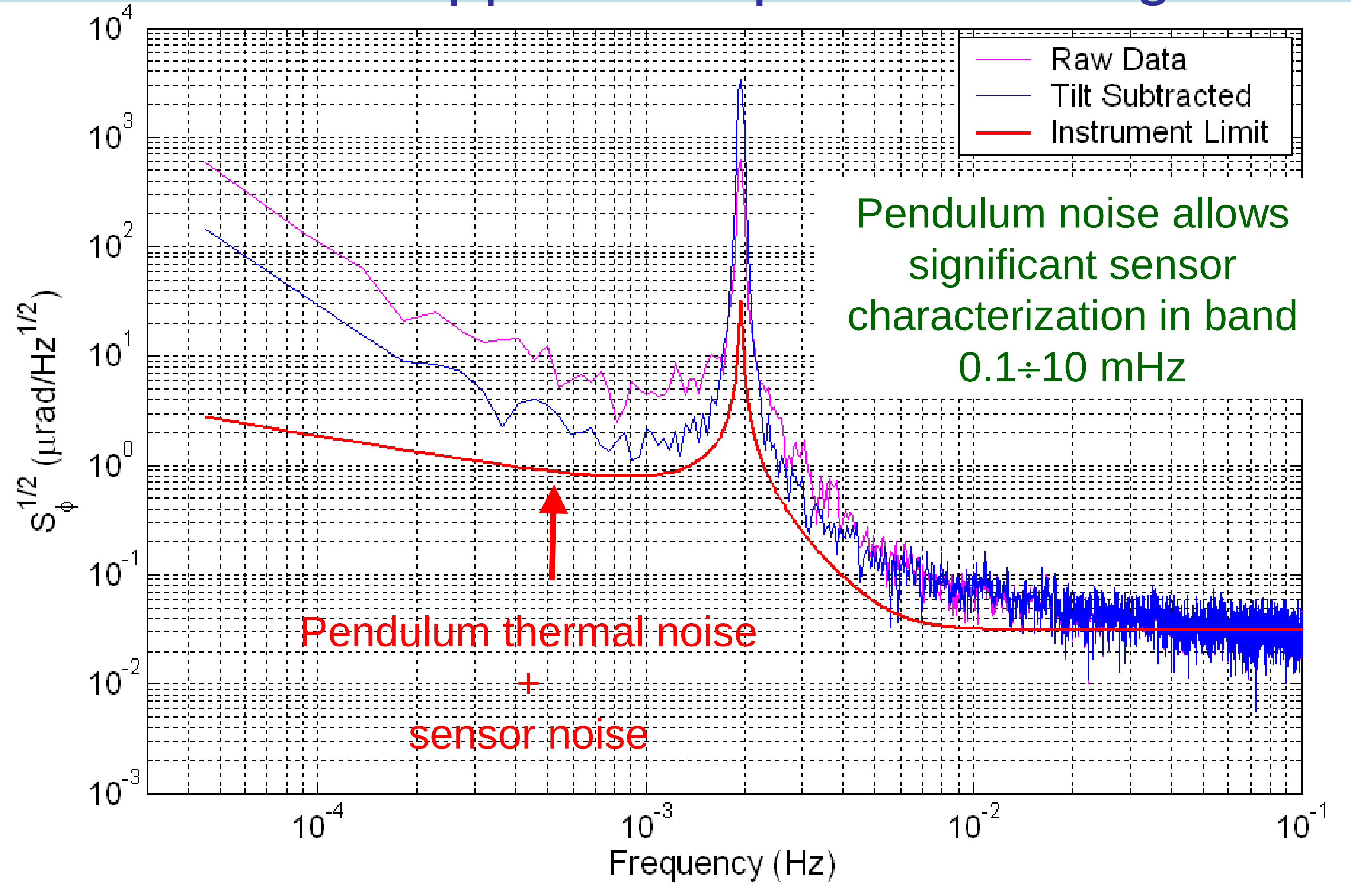


The facility at a glance



Many more details in poster by L.Carbone *et al*

Random forces upper limit: pendulum angular noise



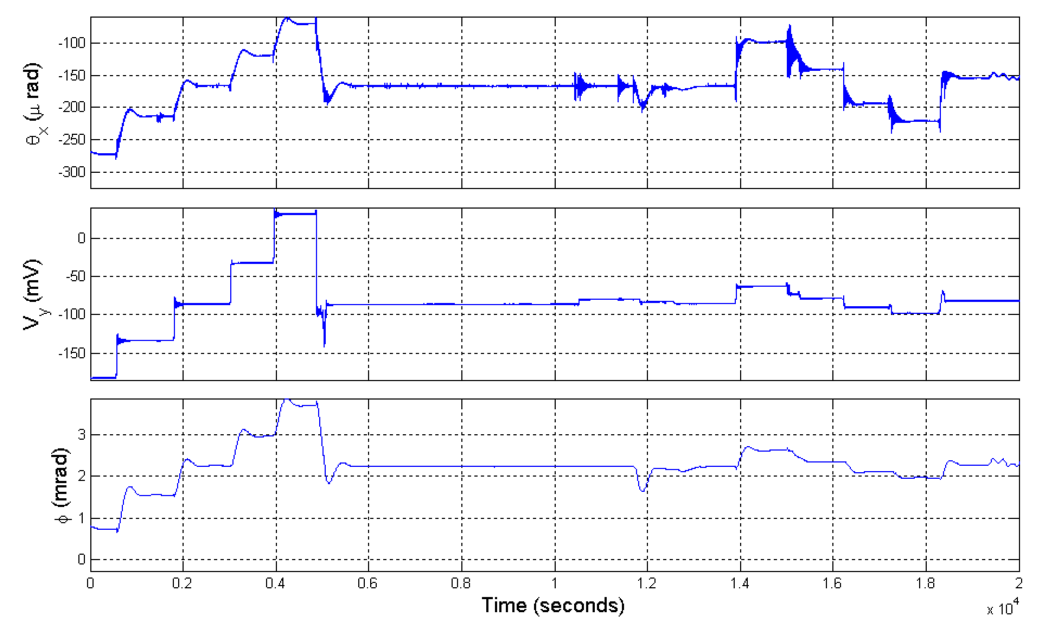
Pendulum noise allows significant sensor characterization in band 0.1÷10 mHz

Pendulum thermal noise + sensor noise

- Angular noise of roughly 6 times the thermal limit at 1 mHz
- Tilt-subtracted data by measured coupling coefficients: roughly 2-3 times the thermal limit

Pendulum tilt noise

- “Tilt-twist” feedthrough couples tilt into torsional mode
- Measured: ~ 300 nrad/Hz$^{1/2}$ at 1 mHz



Pendulum *x* tilt

Pendulum *y* tilt (uncalibrated sensor, 2000 mV ~ 1 mrad)

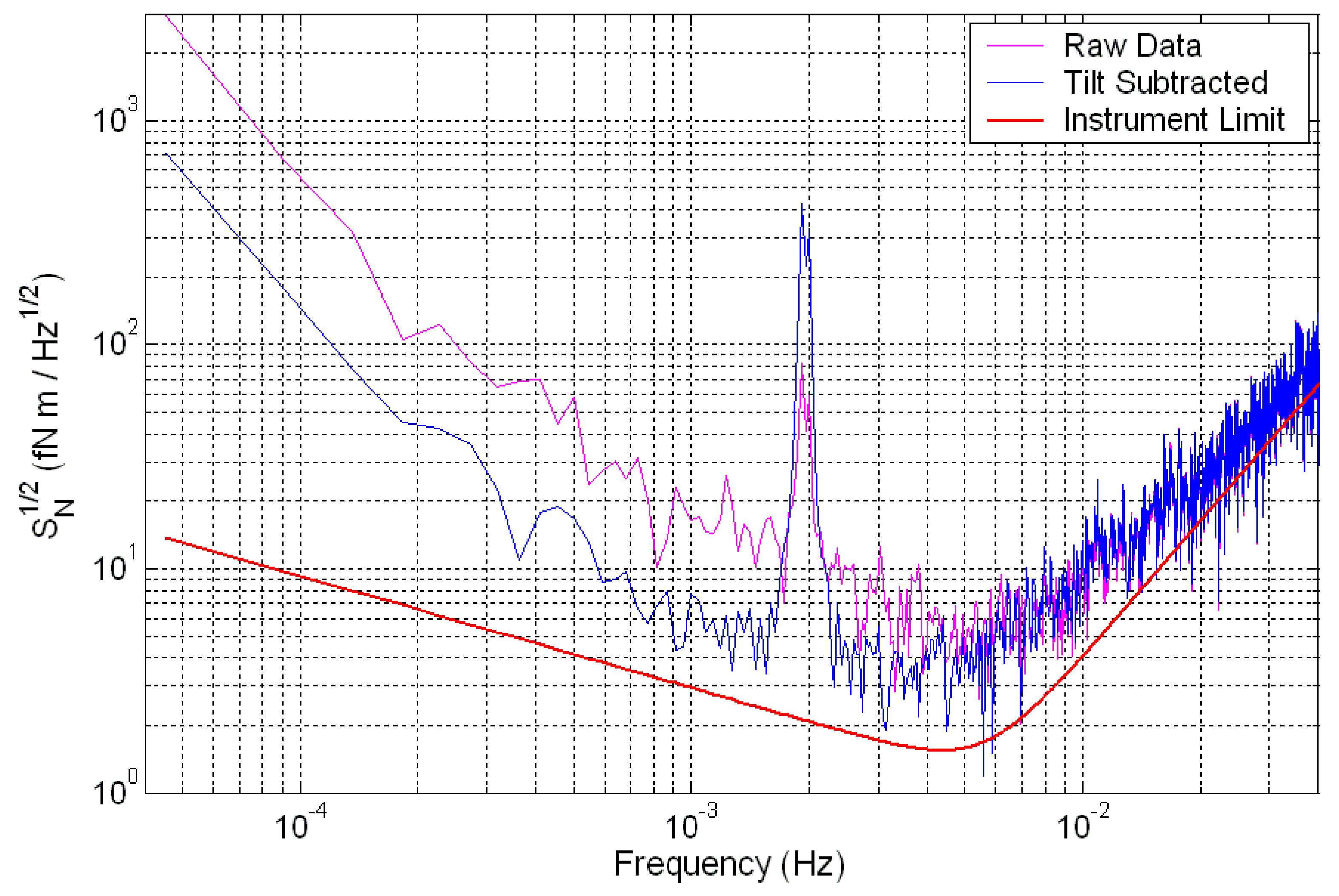
Pendulum twist

- Tilt pendulum platform, measure tilt and resulting pendulum rotation
- Time series subtraction of effect of floor tilt, with sensor θ_x,θ_y data and measured coefficients

$$\Delta\phi(t)=\boxed{T_{\theta_x}}\Delta\theta_x(t)+\boxed{T_{\theta_y}}\Delta V_Y(t)$$

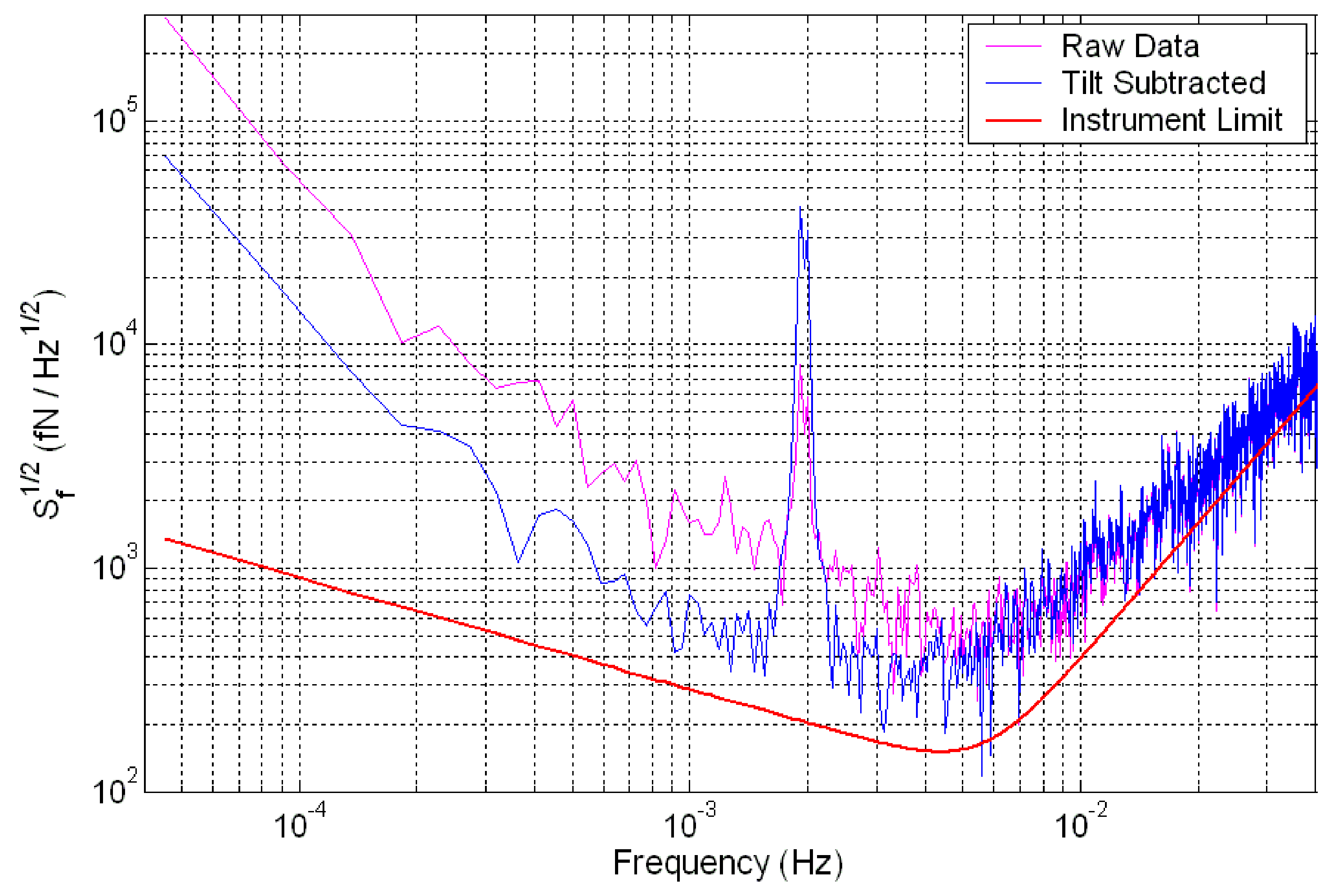
$$\phi(t)=\phi_{raw}(t)-\Delta\phi(t)$$

Random forces upper limit: torque noise



- Torque noise <10 fN m/Hz$^{1/2}$ between 0.6 and 10 mHz

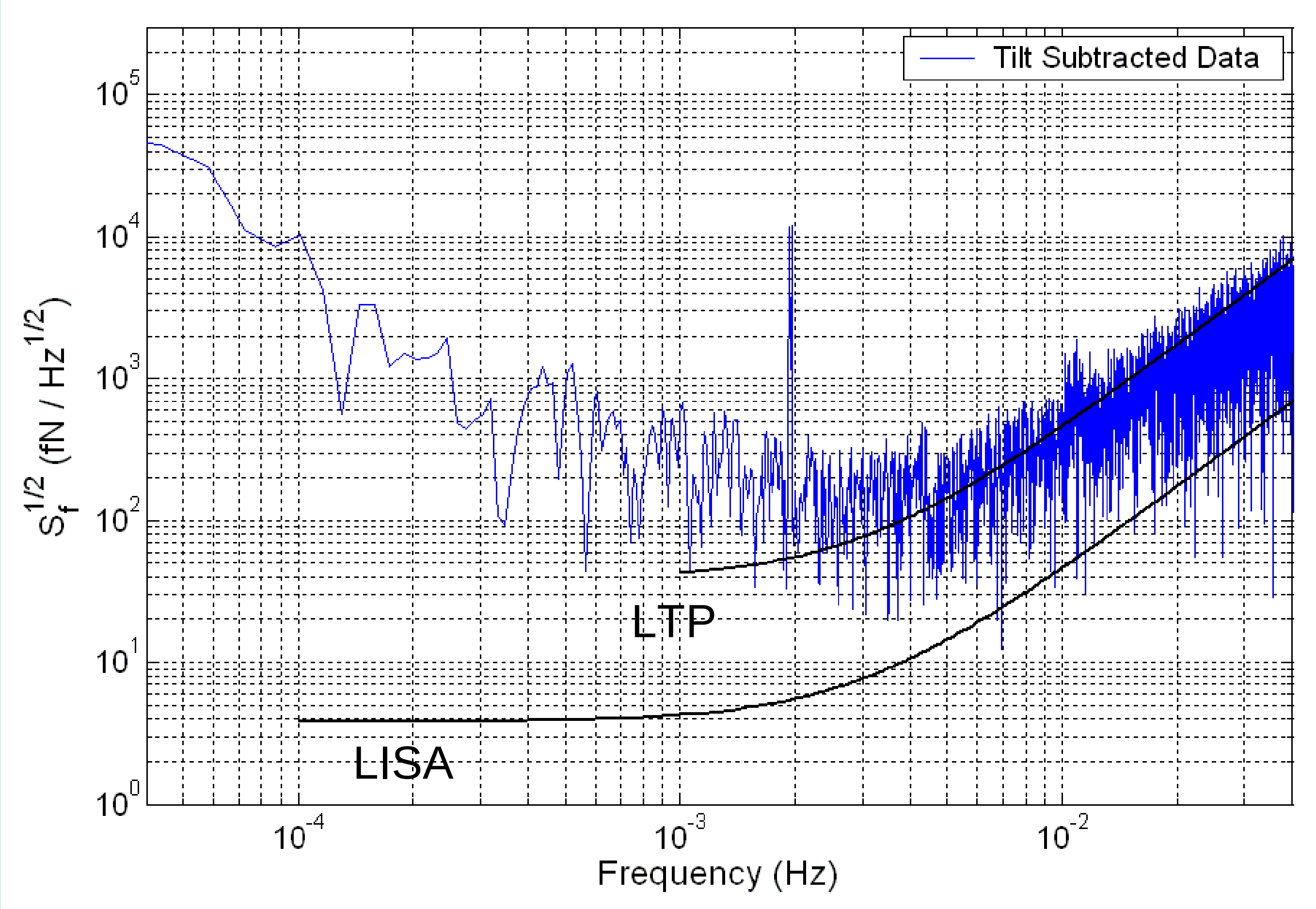
Random forces upper limit



Conversion from torque noise to differential force noise:

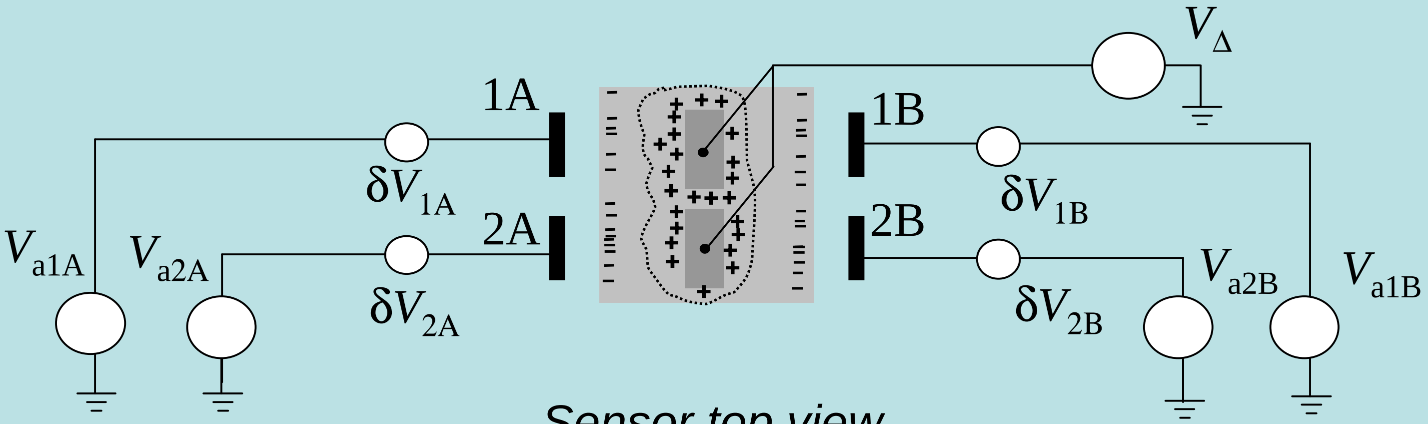
- Sensor back-action: arm length $L = R_\phi \approx 10$ mm
- Randomly distributed surface effects: $L \approx 20$ mm

Impact for LISA



- Upper limit on random surface forces:
molecular collisions, homogeneusly distributed patch charges
- Relatively insensitive to bulk gravitational/magnetic disturbances
and to net forces

Electrostatic torque measurements: modulated DC biases



Sensor top view

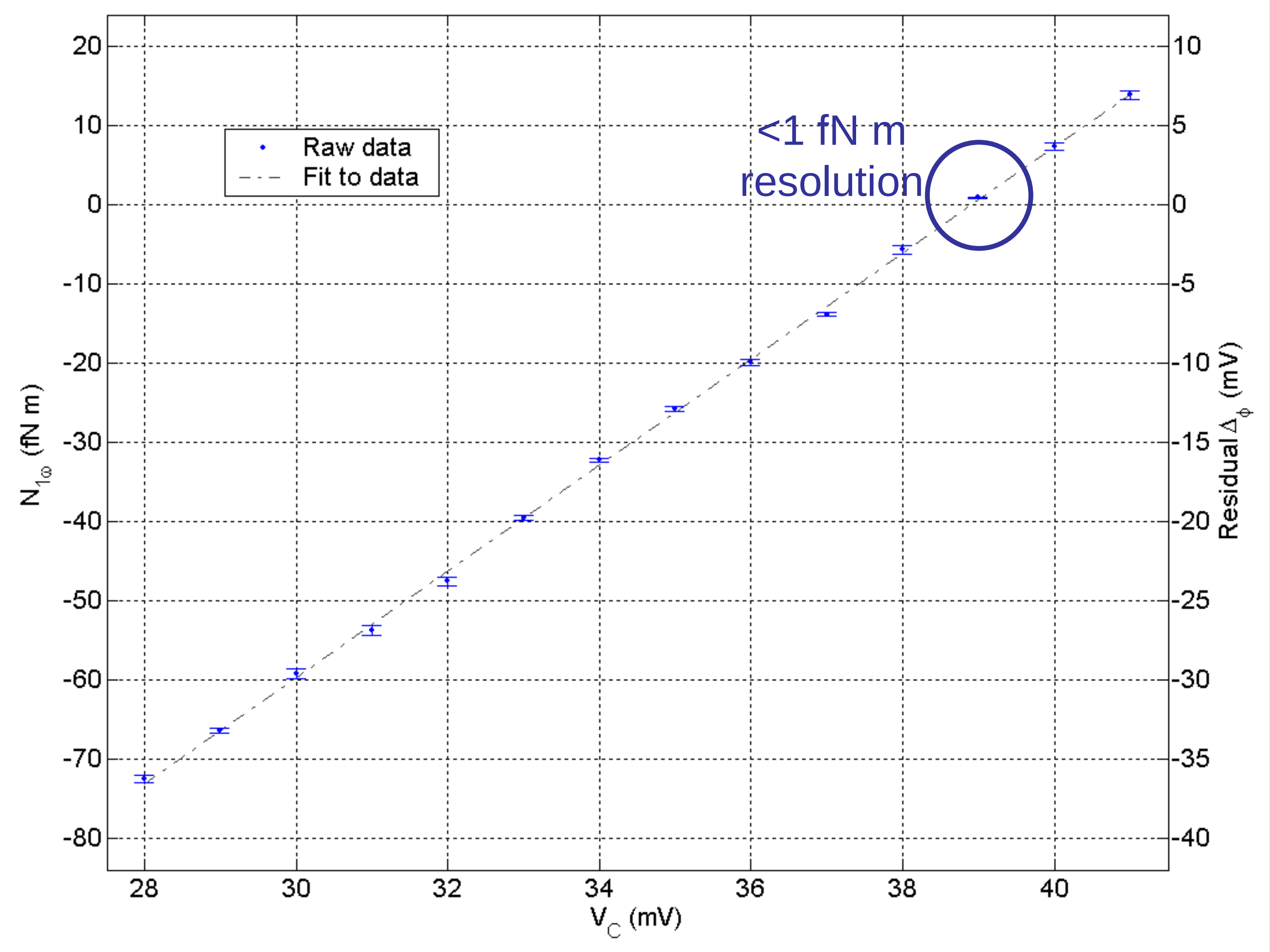
- Modulate test mass voltage with V_Δ = 3V amp at f_0 = 5 mHz on injection electrodes
- Charge and DC biases produce torques at voltage driving frequency
- Measured $1\omega_0$ torque sensitive to “diagonal” DC bias imbalance

$$\Delta_\phi = \delta V_{1A} + \delta V_{2B} - \delta V_{1B} - \delta V_{2A}$$

- Compensate with applied voltages:

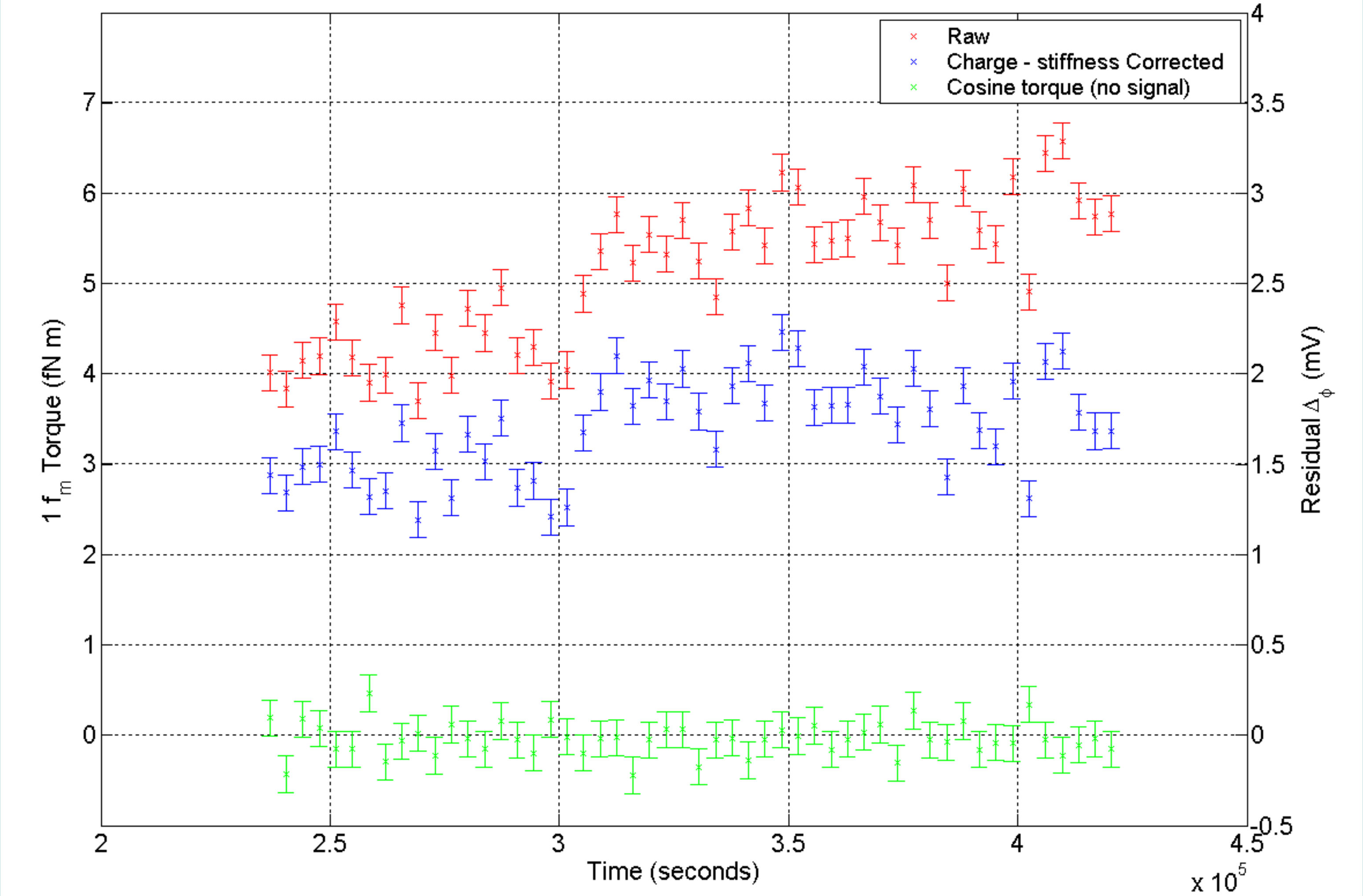
$$V_{a1A} = V_{a2B} = -V_{a1B} = -V_{a2A} \equiv V_{COMP} = -\Delta_\phi / 4$$

DC Bias measurement and compensation



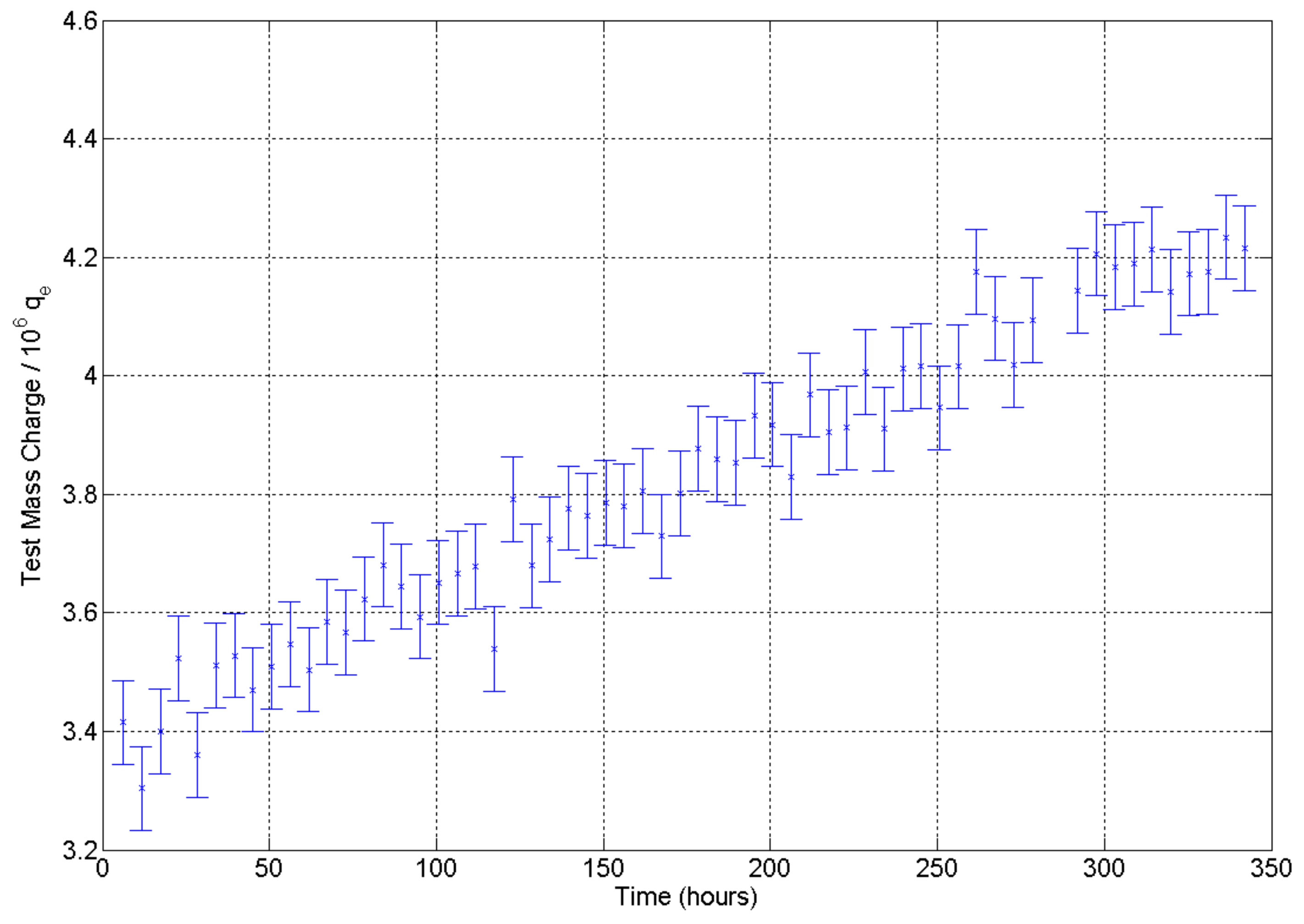
- DC Bias imbalance measured and compensated within 1 mV
- Problem for LISA: 10 mV level

Measurement of DC Bias Stability



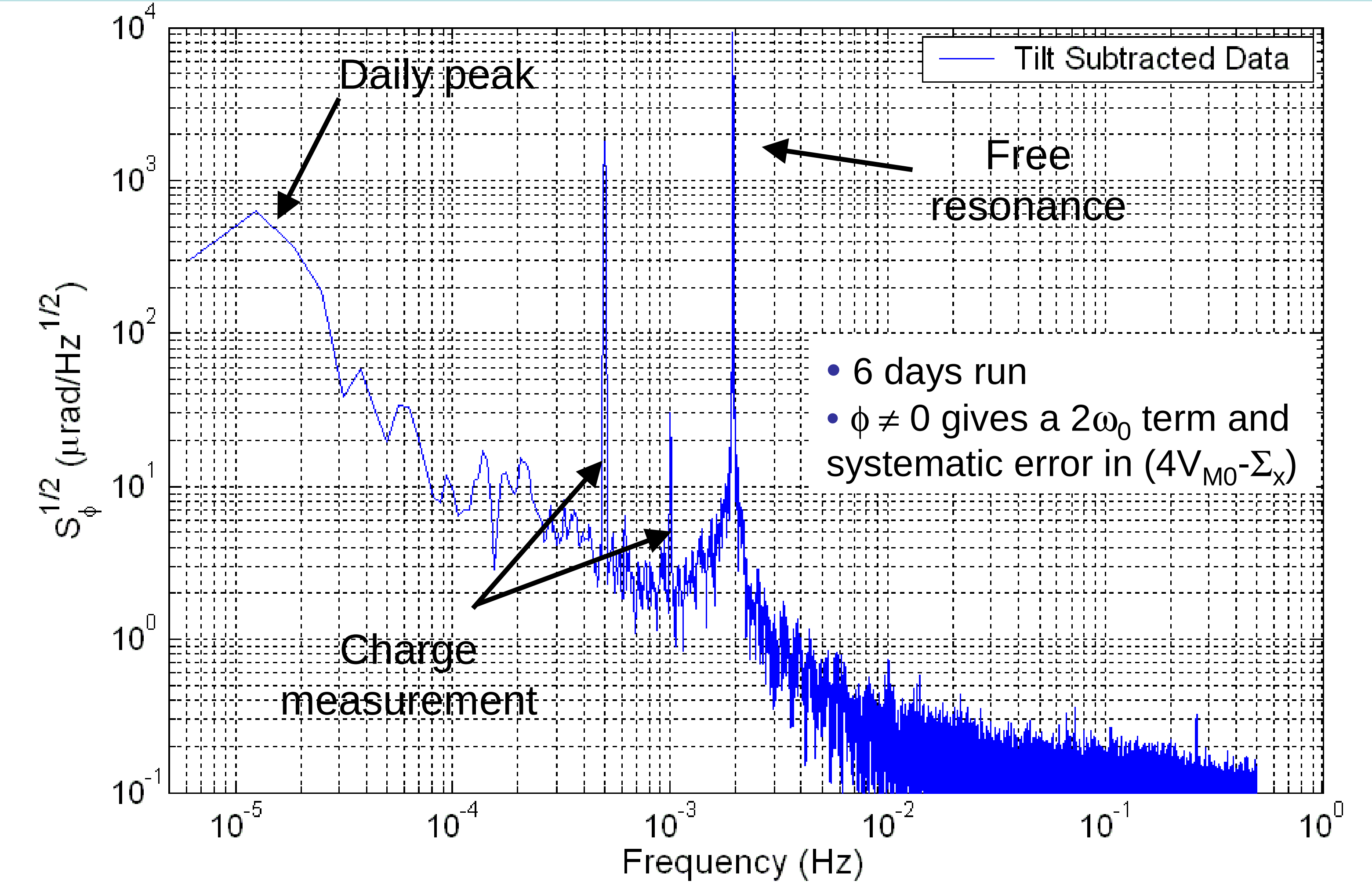
- DC bias imbalance stable to within 1 mV over 50 hour run
- Measurement noise (cosine phase) is below the observed scatter in the electrostatic signal

Long term charge measurement



- Roughly +1 e/s charging
- Measurement error of $5 \cdot 10^4$ charges in a 6 hour measurement with 50 mV measurement bias

Test mass charge measurement



- 6 days run
- $\phi \neq 0$ gives a $2\omega_0$ term and systematic error in ($4V_{M0}-\Sigma_x$)

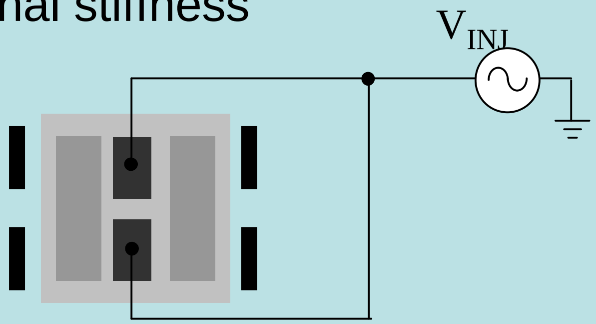
Ground-based demonstration of the technique to be used in flight for:

- Stray DC fields
- Test mass charge

Measurement of electrostatic sensing stiffness

- Sensor bias voltage produces electrostatic rotational stiffness

$$N_0 = \frac{1}{4}\left(V_{in0}\frac{C_{in}}{C_{TOT}}\right)^2 \sum \frac{\partial^2 C}{\partial \phi^2}\left(\phi-\phi_0\right) = -\Gamma_{sens}\left(\phi-\phi_0\right)$$



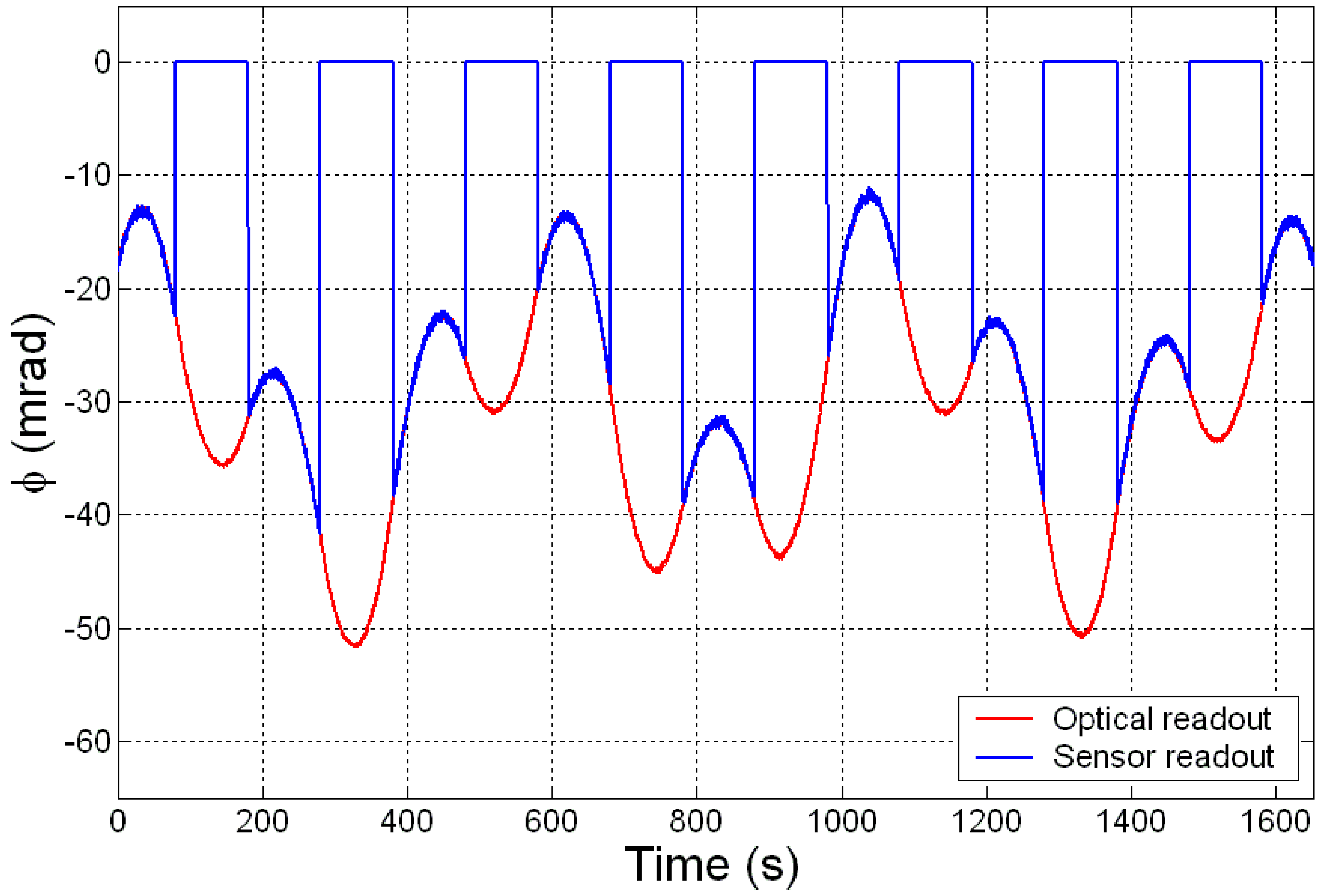
- Squarewave modulation of 100 kHz sensor bias amplitude produces squarewave torque *N(t)*

$$N(t) = N_0 \times \left\{\frac{1}{2} + \frac{2}{\pi}\sin\omega_0 t + \frac{2}{3\pi}\sin 3\omega_0 t + \frac{2}{5\pi}\sin 5\omega_0 t + \ldots\right\}$$

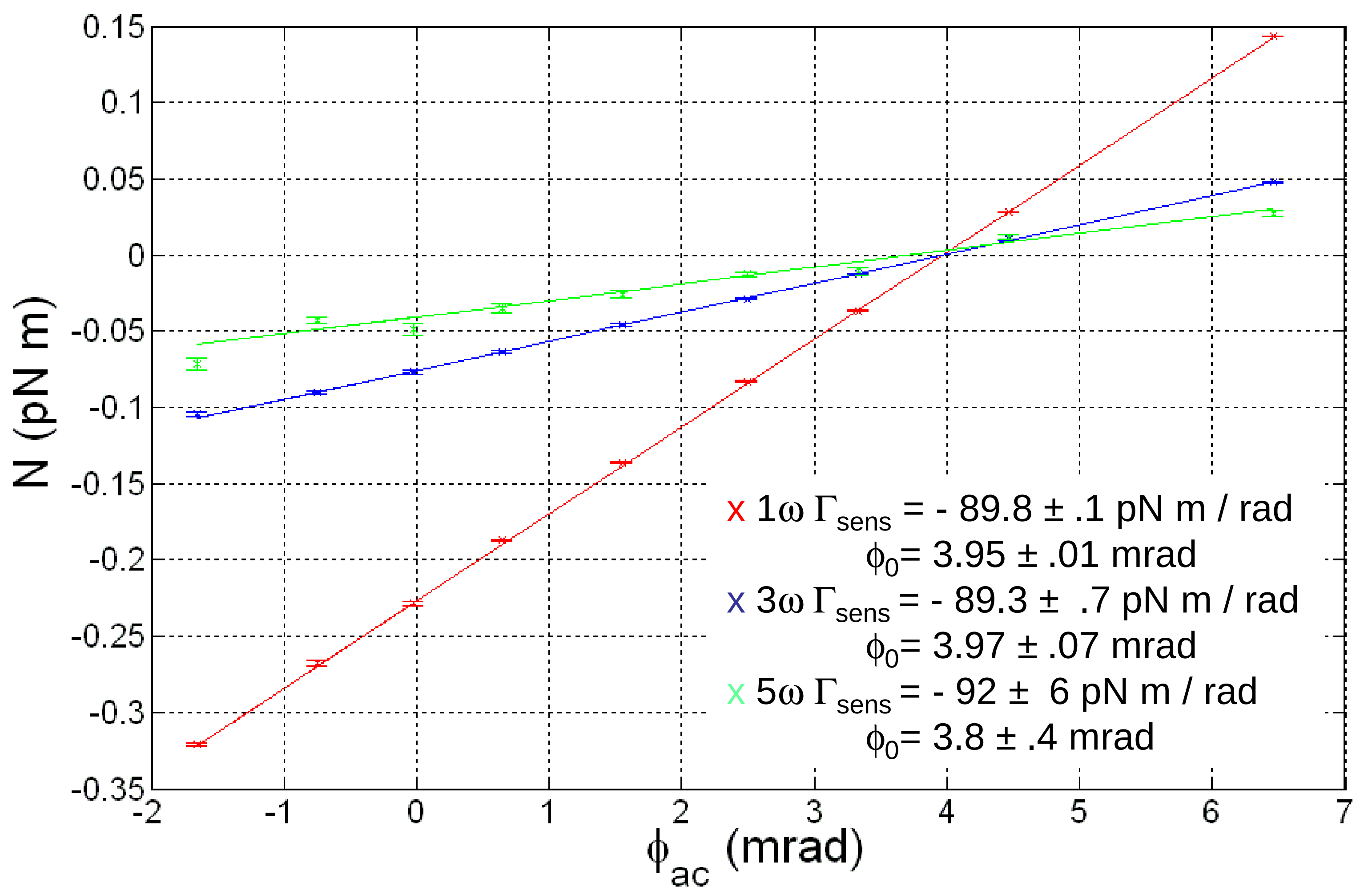
- Coherent detection of $1\omega_0$, $3\omega_0$ torques … each give independent estimate of squarewave torque amplitude

- Measure torque *N*(ϕ) as function of position to get the torque gradient or angular stiffness: $\Gamma_{sens} = -\partial N_0 / \partial \phi$

Electrostatic stiffness measurements: coherent torque scheme



Electrostatic stiffness measurements: position dependence



Infinite wedge capacitor: $$\Gamma_{sens} = -\frac{1}{4}\left(V_{in0}\frac{C_{in}}{C_{TOT}}\right)^2 \sum \frac{\partial^2 C}{\partial \phi^2} \approx -96 \text{ pN m / rad}$$

For LISA: known with **5%** (or better) precision

Status of the facility:

- “natural end” of the experiment due to fiber detaching from pendulum
- 6 months continuous operation

Next future:

- mirror and inertial member Au coating to reduce chargig effects
- automated micropositioning system for sensor ϕ for total stiffness measurement
- charge management system device for LTP (breadboard)

Future:

- multiple mass configuration to study translational forces
- improved tilt immunity
- …

Expermental results in submitted paper, on line at:

http://xxx.lanl.gov/PS_cache/gr-qc/pdf/0307/0307008.pdf