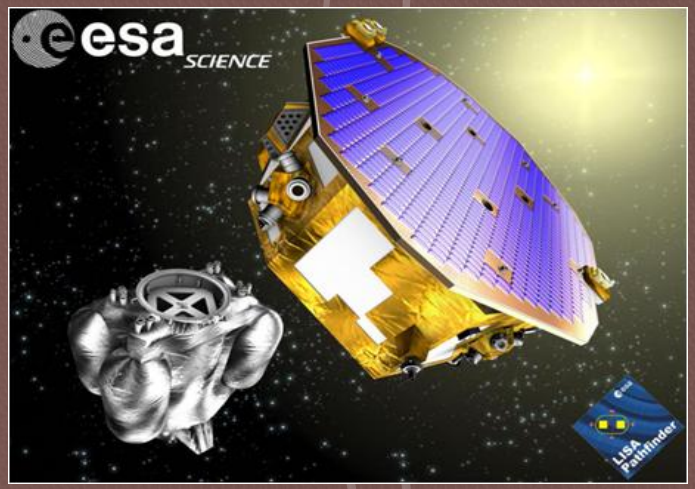

A **TORSION PENDULUM** TEST OF THE ***LISA PATHFINDER*** **FREE-FALL MODE**

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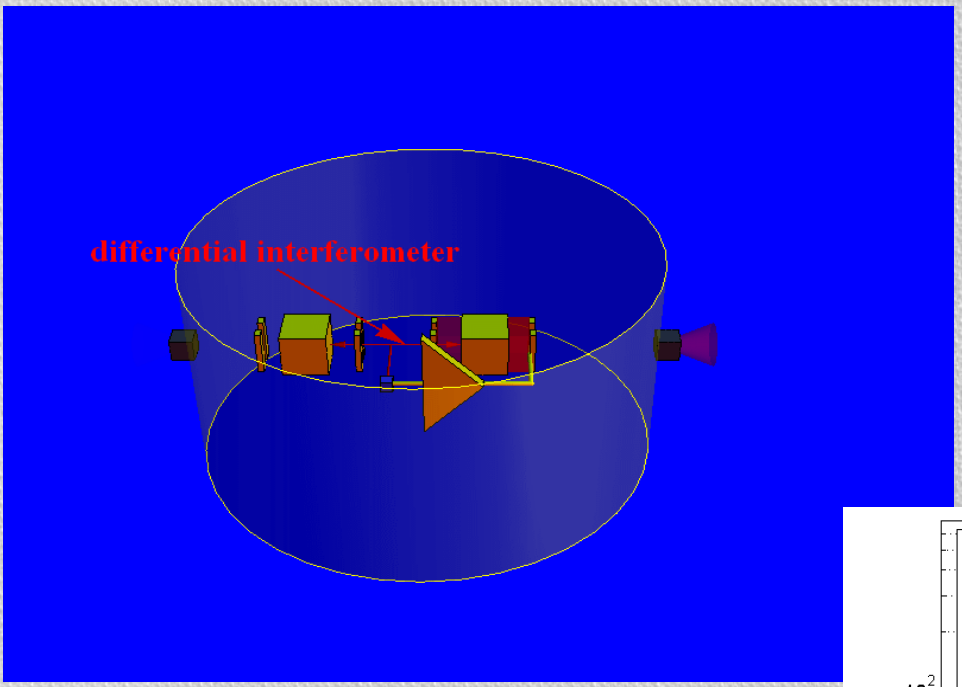
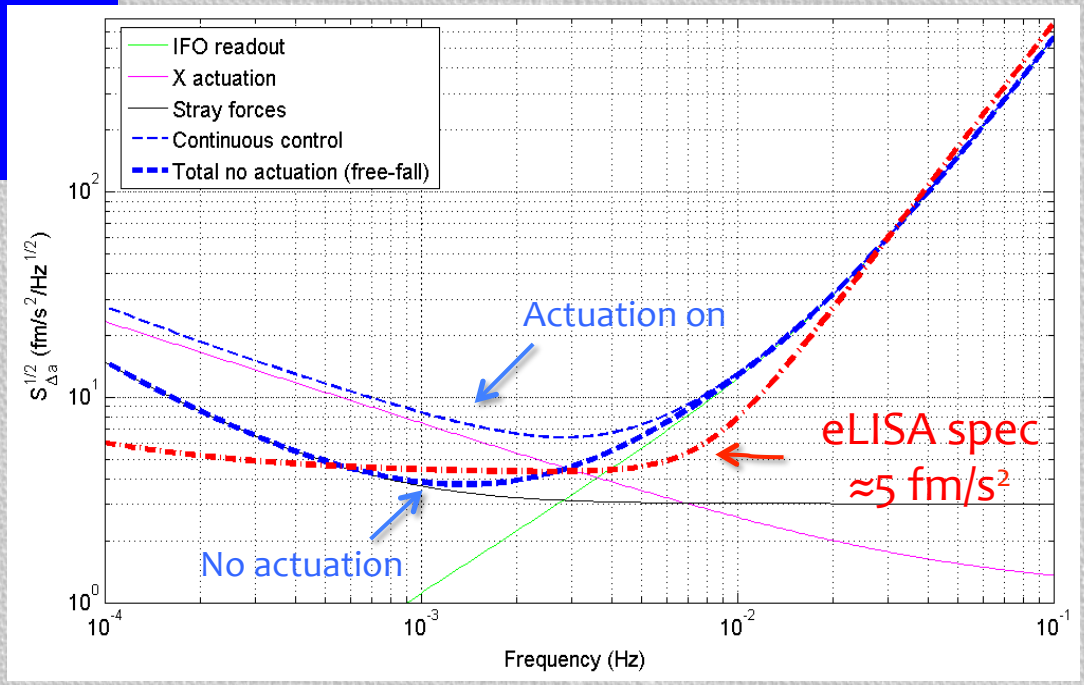
UNIVERSITÀ DEGLI STUDI DI TRENTO

INFN

Free-fall control strategies



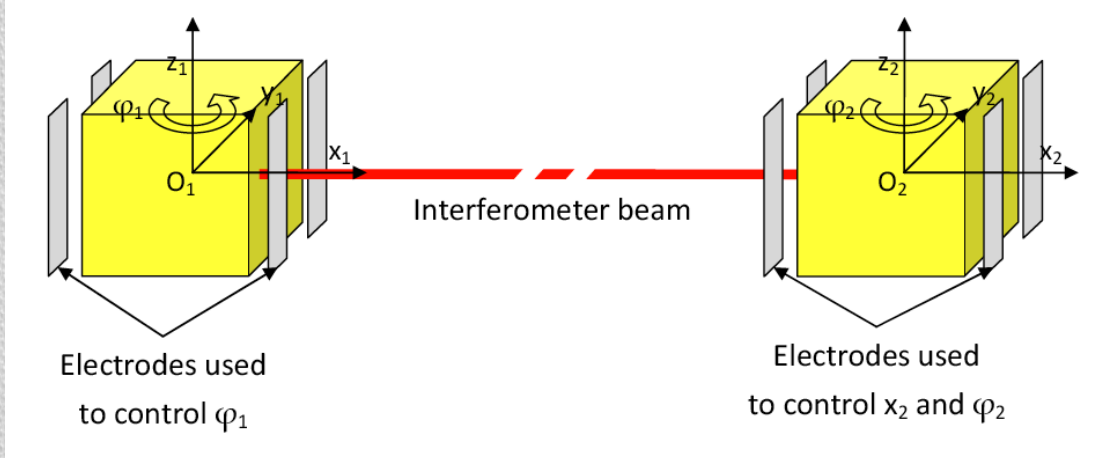
- Drag free control loop
- Continuous control
- Drift mode



Ground testing objectives:

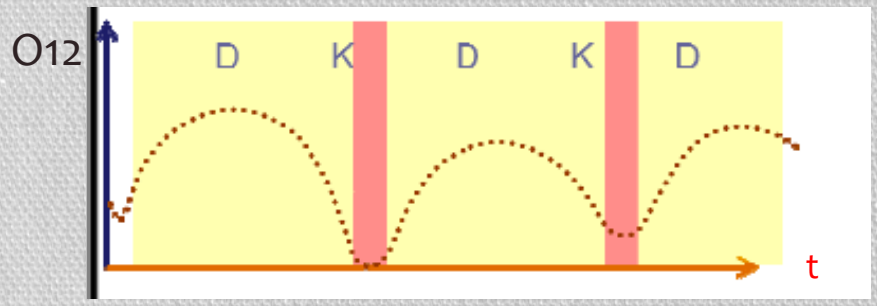
- Investigate different measurements conditions to remove actuation noise
- Data analysis techniques

Drift Mode for LISA Pathfinder



- TM motion between two kicks is a free parabolic flight
- Allows measurement of acceleration noise without applied actuation forces

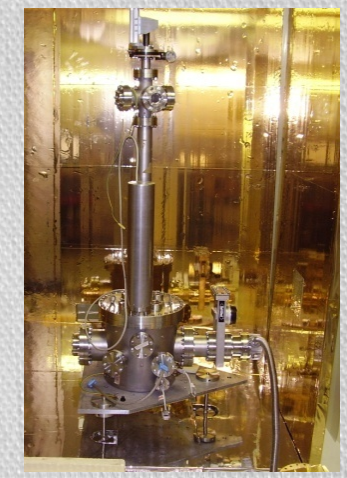
$$\Delta\ddot{x} = \Delta\frac{f_0}{m} + \Delta(\omega^2 x) + \Delta n$$



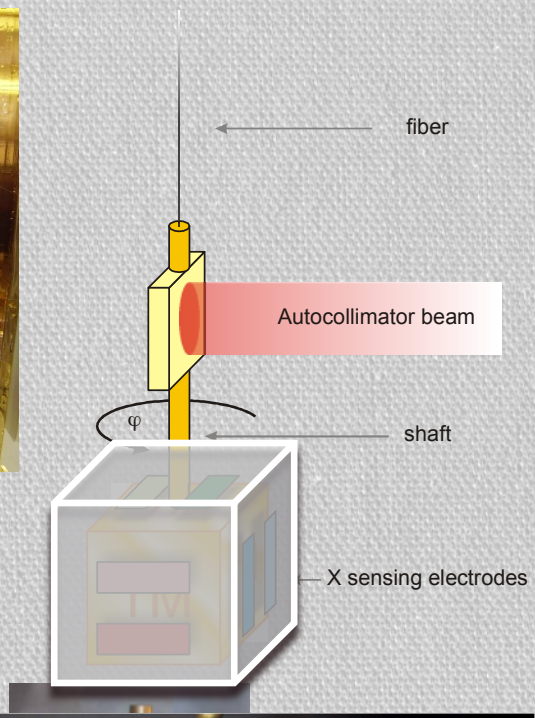
$$f_K = 4mHz,\ \ t_D = 250s,\ \ t_K = 1.5s$$

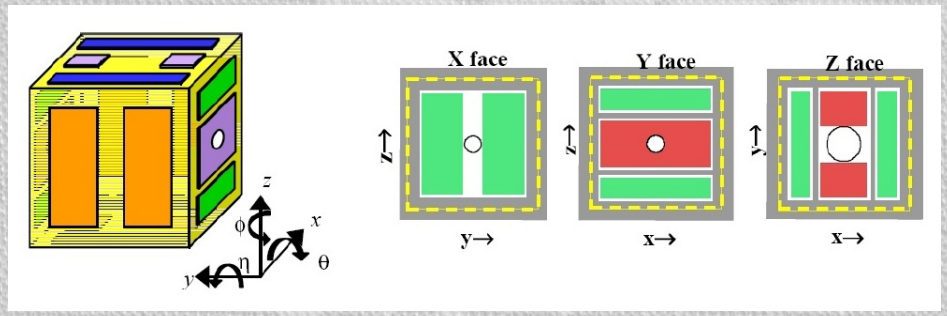
- No matter how noisy the actuation is!
- All others degrees of freedom are under continuous control

Torsion pendulum facility



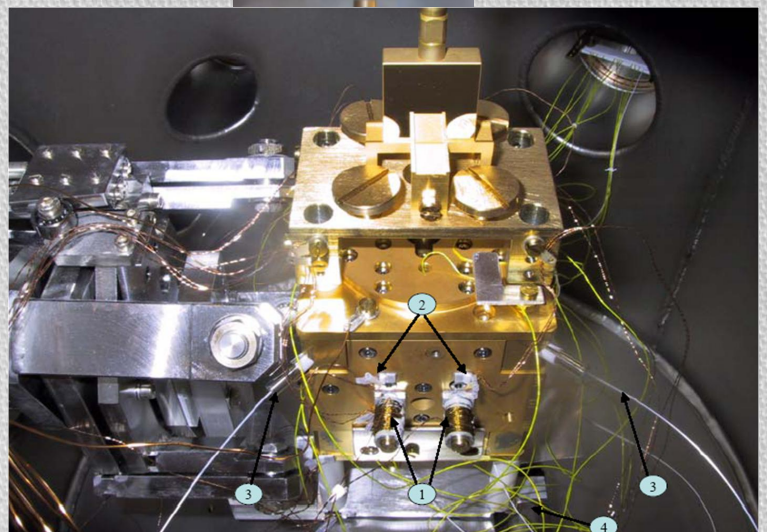
- *1 m* lenght silica fiber
- *50 μm* size





LISA Pathfinder-prototype GRS

- Capacitive gaps of 4 mm on X faces (2.9 mm Y, 3.5 mm Z)
- Audio frequency actuation
  - *x* electrodes, 10 V → 20 nN authority for N_ϕ



1TM pendulum

- sensitive to torques around *Z*-axis (N_ϕ)
- Period T_0 ~ 490s, energy decay time τ~2 year (Q~10^6)
- torque noise < 1 fN m /$Hz^{1/2}$ at mHz frequencies

THE TORSION PENDULUM FREE-FALL MEASUREMENT CONCEPT

1. Measure pendulum torque noise in absence of applied forces

$$I\ddot{\varphi} = -\Gamma\varphi - \frac{I}{\tau}\dot{\varphi} + N(t)$$

$$N_m \equiv I\ddot{\phi} + \Gamma\phi + \frac{I}{\tau}\dot{\phi}$$

Measured torque time series

$$S_{N_m} = S_N$$

Estimated torque noise without actuation

2. Measure force noise while continuously holding TM/pendulum centered with an applied DC torque

$$I\ddot{\varphi} = -\Gamma\left(\varphi - \varphi_{EQ}\right) - \frac{I}{\tau}\dot{\varphi} + N(t) + N_{ACT}(t)$$

$$N_{ACT} = -\Gamma\varphi_{EQ}$$

$$S_{N_m} = S_{N'} + S_{N_{ACT}}$$

Estimated torque noise with actuation

3. Measure force noise while holding the TM centered on average with periodic impulses with duty cycle

$$I\ddot{\varphi} = -\Gamma\left(\varphi - \varphi_{EQ}\right) - \frac{I}{\tau}\dot{\varphi} + N(t)$$

$$N_{ACT} \approx -\frac{\Gamma\varphi_{EQ}}{\chi}$$

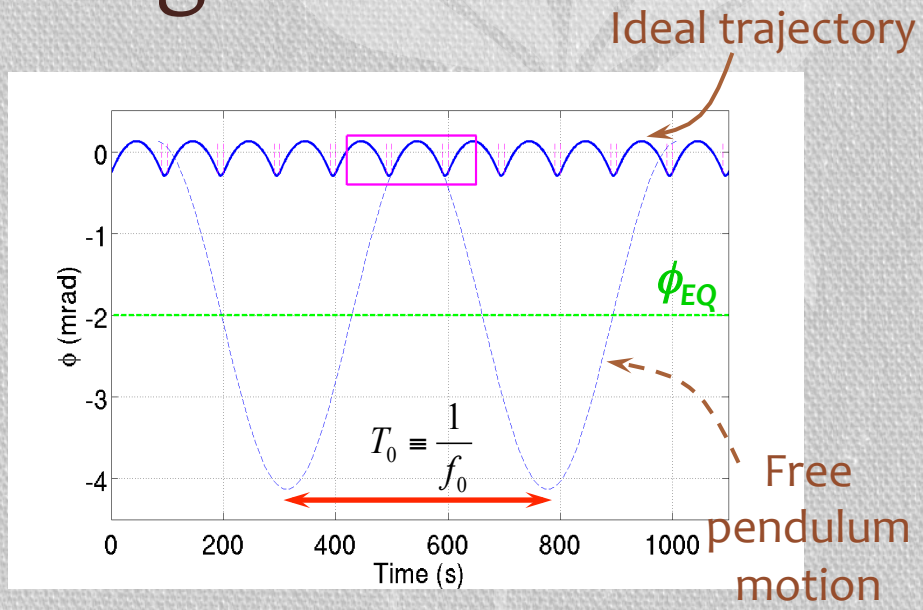
$$S_{N_m} = S_{N'}$$

Recover torque noise without actuation

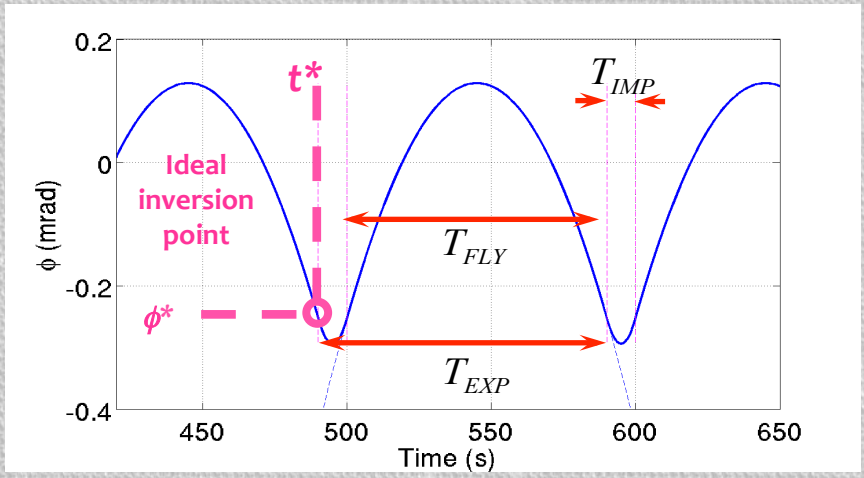
Pendulum Dynamics During Free-Fall

Ideal free-fall trajectory:

$$\varphi_{IDEAL}(t) = \varphi_{EQ}\left(1 - \frac{\pi f_0 T_{FLY}}{\sin \pi f_0 T_{FLY}} \cos 2\pi f_0 t\right)$$

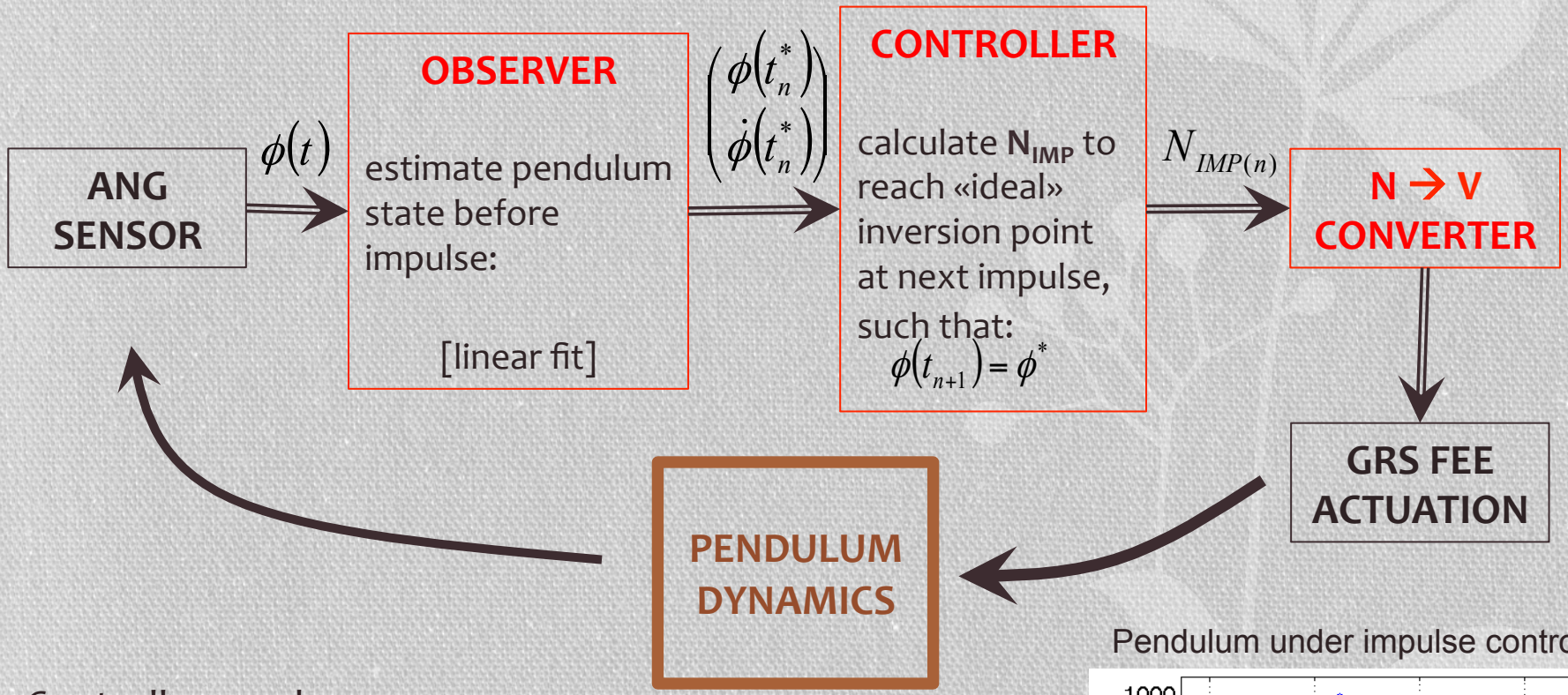


Cycle time:	T_{EXP}
Impulse duration:	$T_{IMP}=\chi\, T_{EXP}$
Flight time:	$T_{FLY}=(1-\chi)\, T_{EXP}$

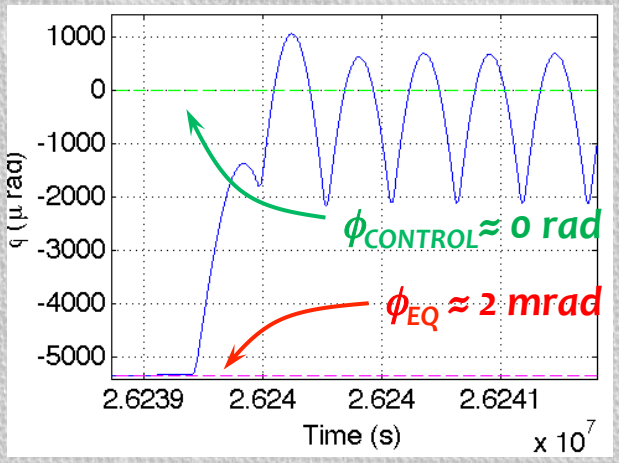


Example of «ideal» pendulum trajectory using:
ϕ_{EQ} = -2 mrad, T_{EXP} = 100 s, χ = 0.1

Control law



Pendulum under impulse control



Controller needs:

- electrostatic actuator calibration
- parameters for pendulum (I, T_o, ϕ_{EQ})
- parameters for experiment (T_{FLY}, χ)

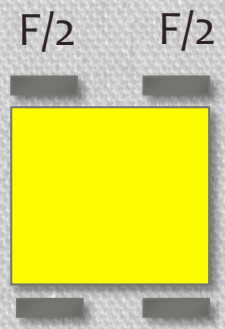
Could choice T_{fly}, T_{imp}, and $\Phi_{control}$
paying attention to allowed dynamical range

LTP vs Torsion Pendulum

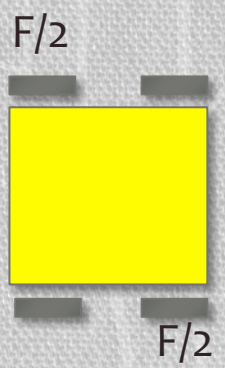
LTP	Torsion Pendulum
$\Delta\ddot{x} = \Delta\frac{f_0}{m} + \Delta(\omega_0^2 x) + \Delta n$	$I\ddot{\phi} = -I\omega_0^2\left(\phi - \phi_{EQ}\right) - \frac{I}{\tau}\dot{\phi} + N(t)$
$\omega_0^2 \approx -10^{-6} s^{-2}$	$\omega_0^2 = \left(2\pi / T_0\right)^2 \approx 1.6 \cdot 10^{-4} s^{-2}$ VARIABLE!
Negative stiffness	To ≈ 830 s (electrostatically softened)
$f_0 = m\Delta a_{DC} \approx nN$	$N_{DC} = \Gamma\phi_{EQ} = I\omega_0^2\phi_{EQ} \approx \begin{matrix} 13\ pN\ m \\ 1.3\ nN \end{matrix}$ VARIABLE!
Differential actuation force to compensate self gravity difference	Applied DC actuation torque, needed to center TM (can choose as desired)

$f_K = 4mHz,$

$t_D = 250s, \quad t_K = 1.5s$



Drift mode actuation performed on different electrodes

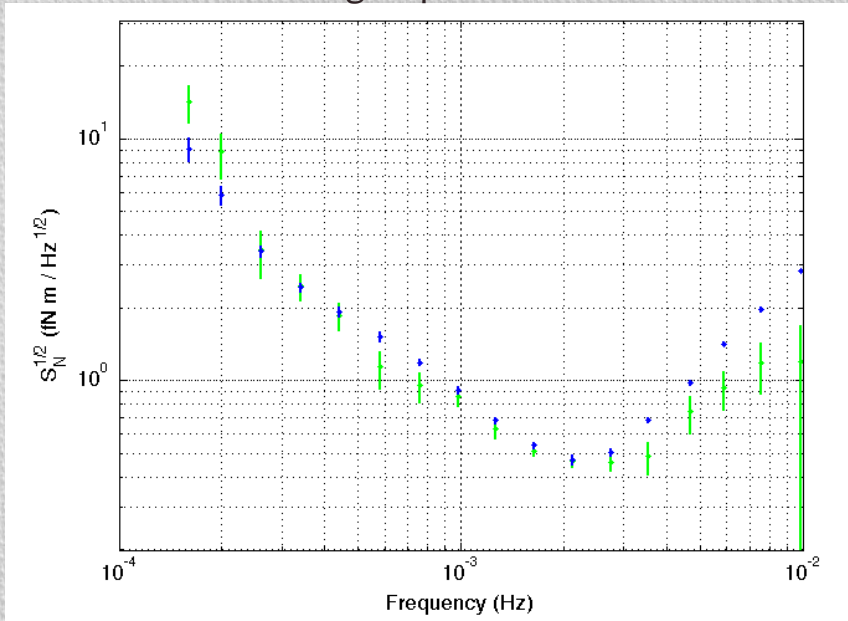


$f_K = 3.6mHz,$

$t_D = 250s, \quad t_K = 25s$

Background torque noise and excess noise resolution

Noise from two groups of three weekends

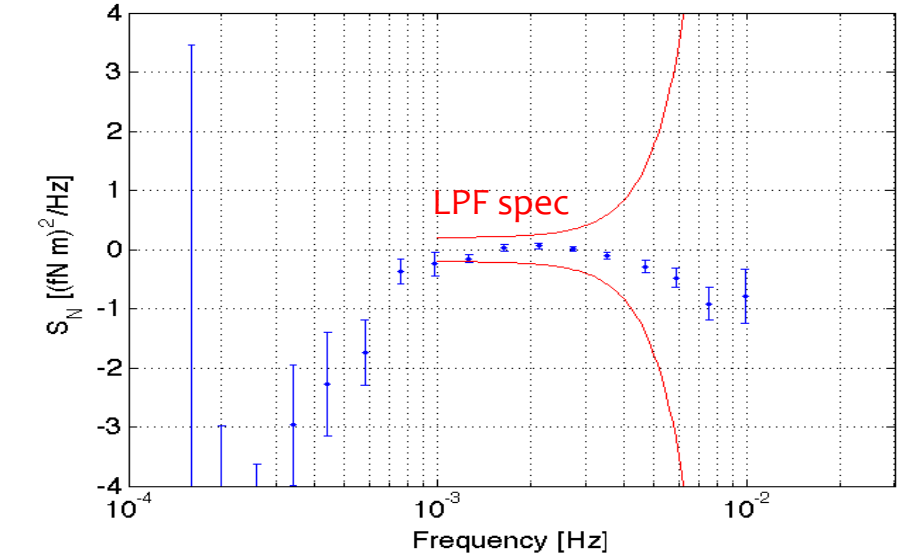


Background noise level < 1 fN m/Hz$^{1/2}$ at 1 mHz frequencies

- equivalent acceleration of 20 fm/s^2/Hz$^{1/2}$ at LPF spec!

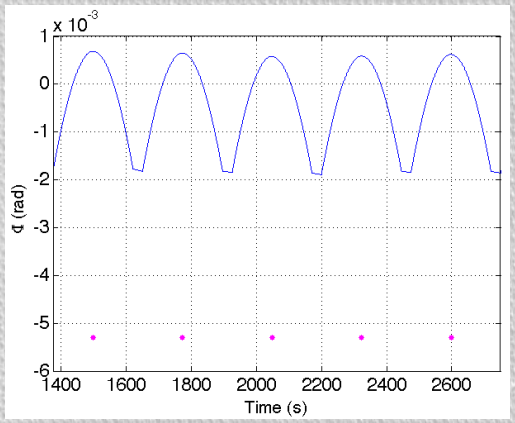
Difference in torque noise from two groups of measurement.

- Reproducibility of noise level over time only in a narrow range
- Allowed detection of extra acceleration noise

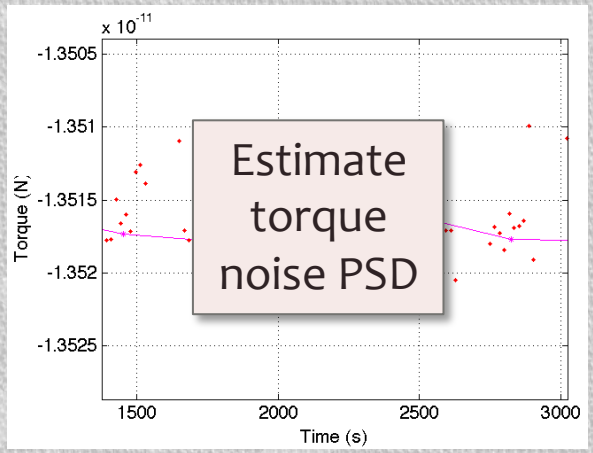


Data analysis techniques examples

- SINUSOIDAL FIT TO EACH FLIGHT



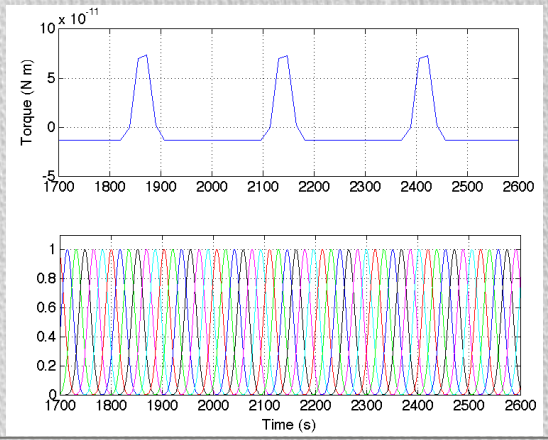
$$N = \Gamma \cdot \phi_{EQ}$$



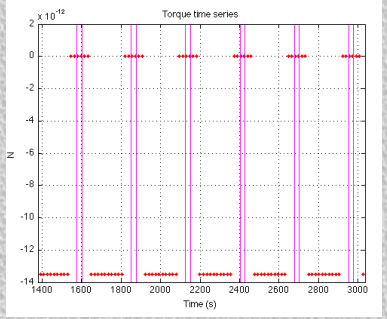
- BLACKMANN-HARRIS FILTERING TECHNIQUE

TORQUE CONVERSION $\phi_{MEAS} \rightarrow N$

BLACKMANN – HARRIS FILTERING AND DECIMATION



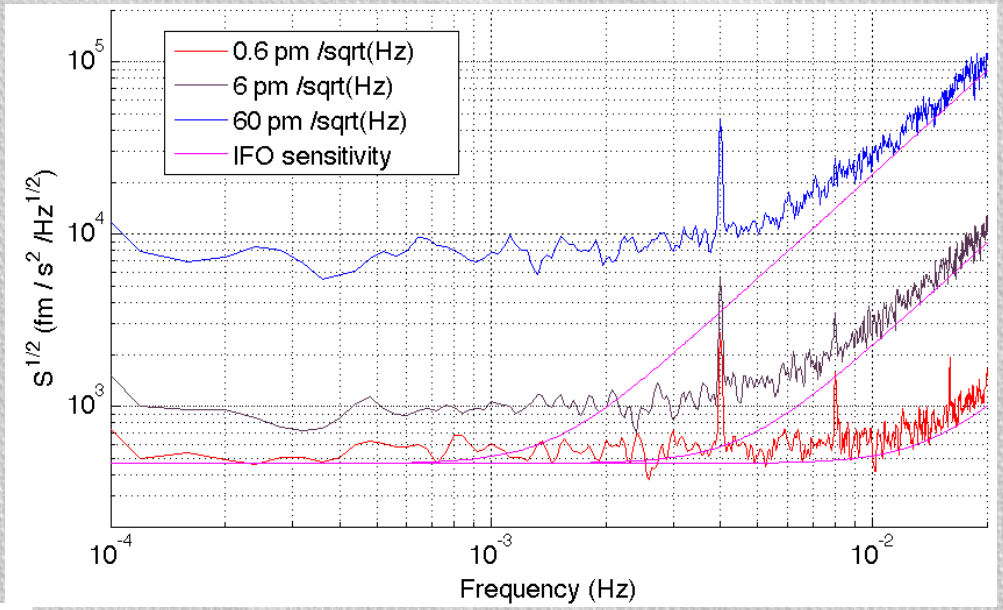
Put to zero data within gaps



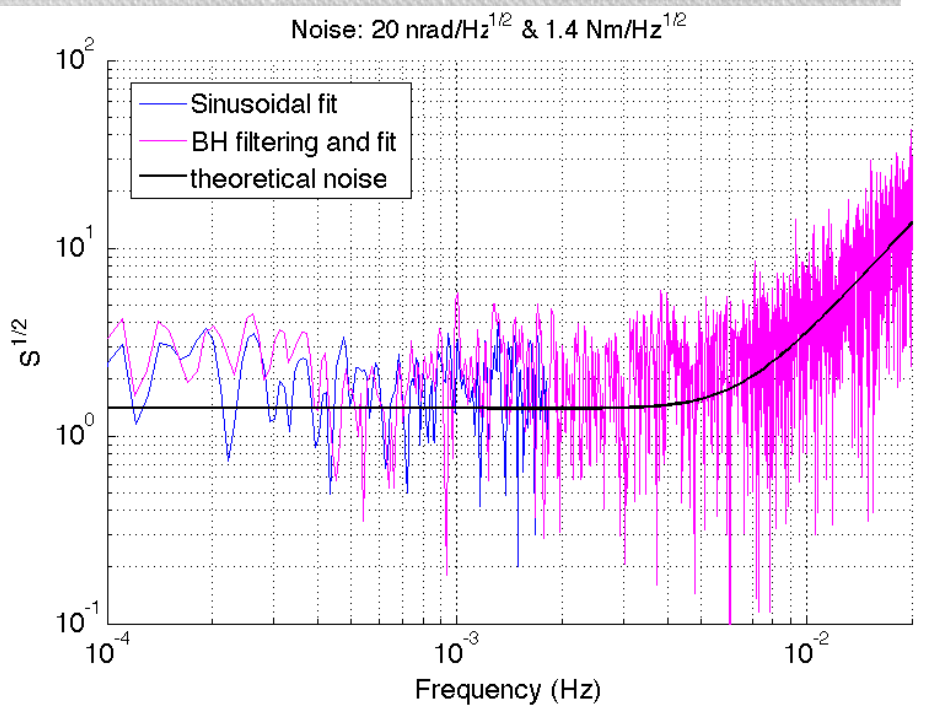
Simplified simulation with white data

The importance of aliasing depends on how much high frequency sensor noise there is.

LTP-like noise level



Simulated torsion pendulum data



Simulated LTP-like free fall white data:

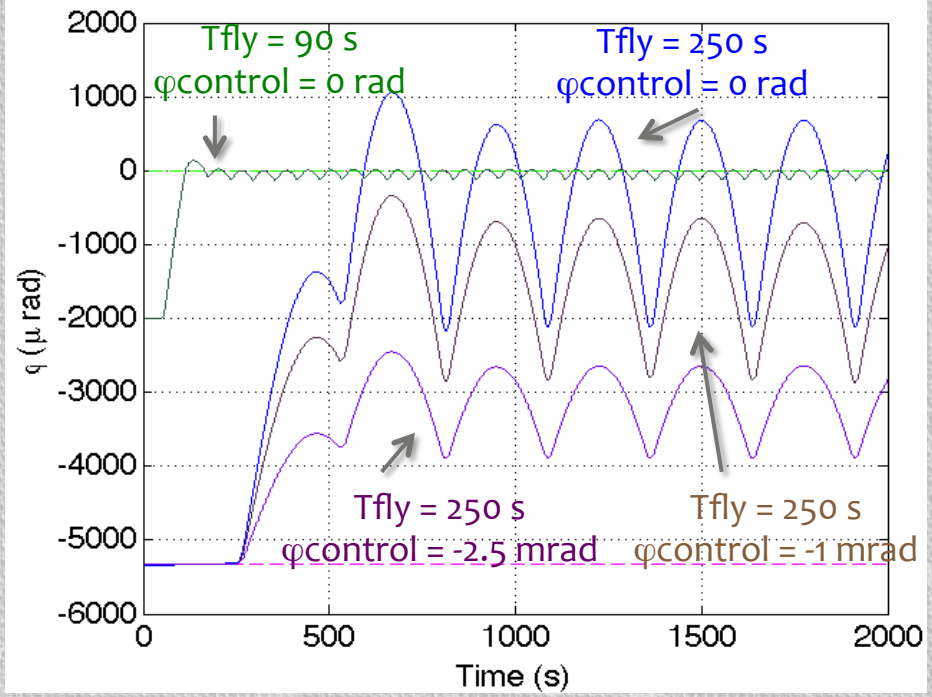
- Very low and positive stiffness
- Period around 4400 s
- Force noise 10 fm / s^2 Hz$^{1/2}$
- Interferometer noise 0.6, 6 and 60 pm / Hz$^{1/2}$

Simulated torsion pendulum free fall data:

- Positive stiffness ≈ 2.9 nN m / rad
- Period around 823 s
- Torque noise 1.4 fN m / s^2 Hz$^{1/2}$
- Sensor angular noise 20 nrad / Hz$^{1/2}$

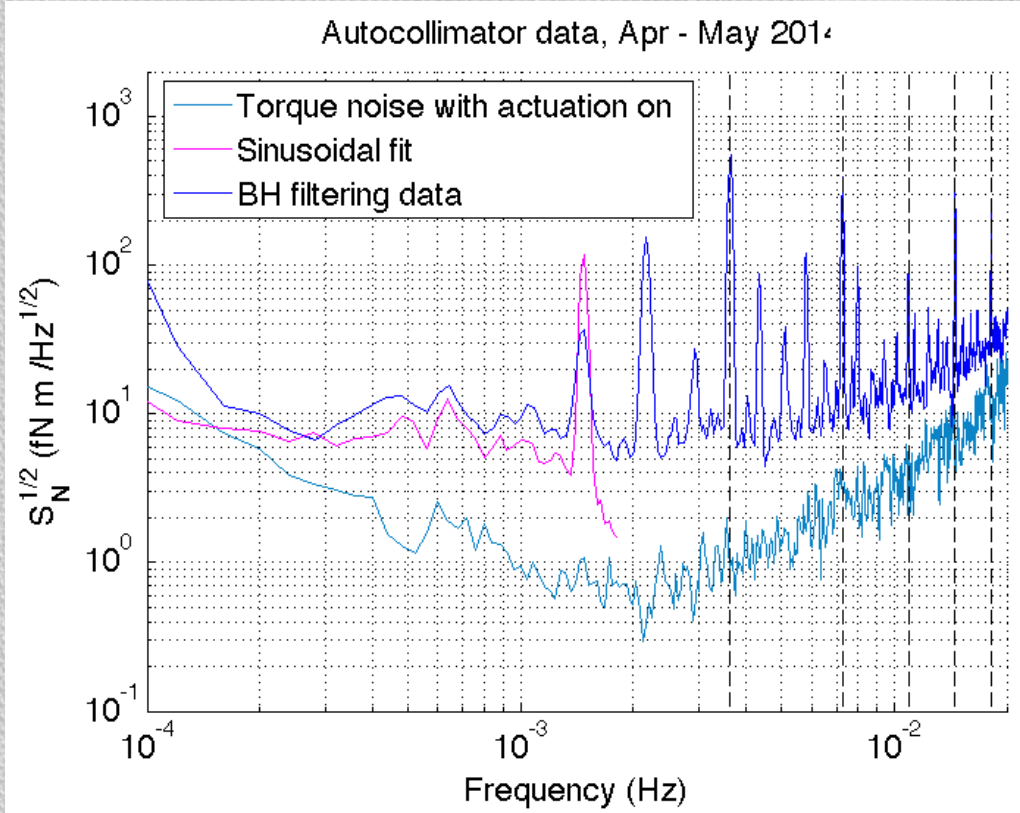
Torsion pendulum preliminary data

- Experimental parameters used:
  - Tf_{ly}: 250 s, 90 s
  - $\Phi_{control}$: 0 rad, -1 mrad, -2.5 mrad
- Controller is stable



Torsion pendulum preliminary data

- Excess noise of 10 fN m / $Hz^{1/2}$
- Spectral leakage from high frequency component
- Still far from noise level with DC actuation on



Torsion pendulum preliminary data

- Difficulties in estimating of dynamic parameters

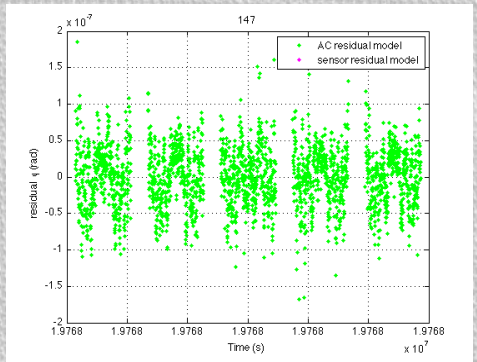
$$N = \Gamma\phi$$

Non linear terms!

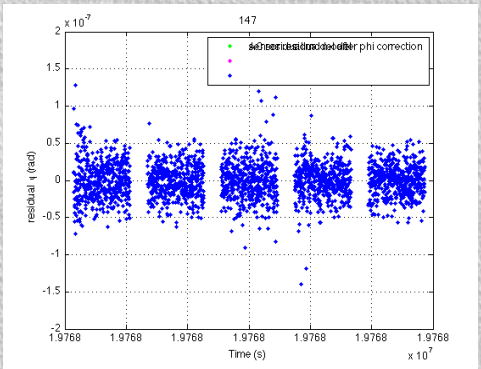
$$\Gamma\phi + a\phi^2 + b\phi^3$$

- Autocollimator non linearity
  → need for correction

φ residual non corrected



φ residual corrected



- Timing problem

Conclusion & future work

- Try to estimate true dynamic pendulum parameters, varying position and length of flights
- Implement different LTP data analysis techniques in collaboration with other groups working on LPF data analysis
- Pendulum noise hunting

Thanks for your attention!!!