Suspended Mirror control: Learning through Virgo Experience

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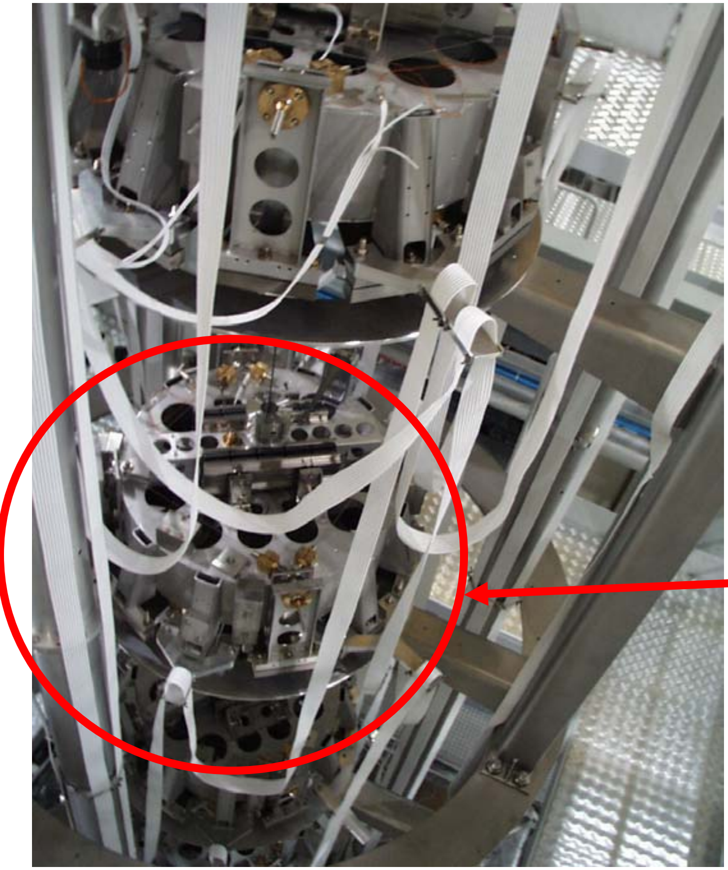
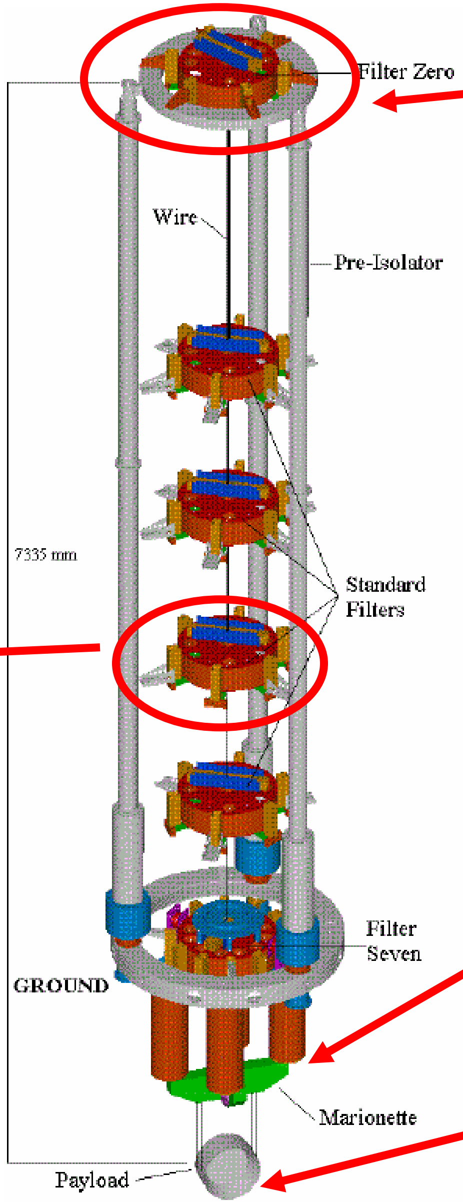
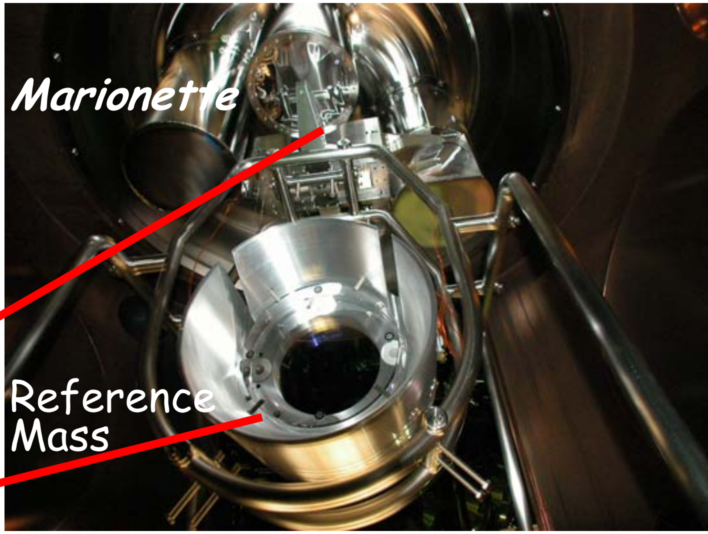
Aspen GWAD February 16, 2004

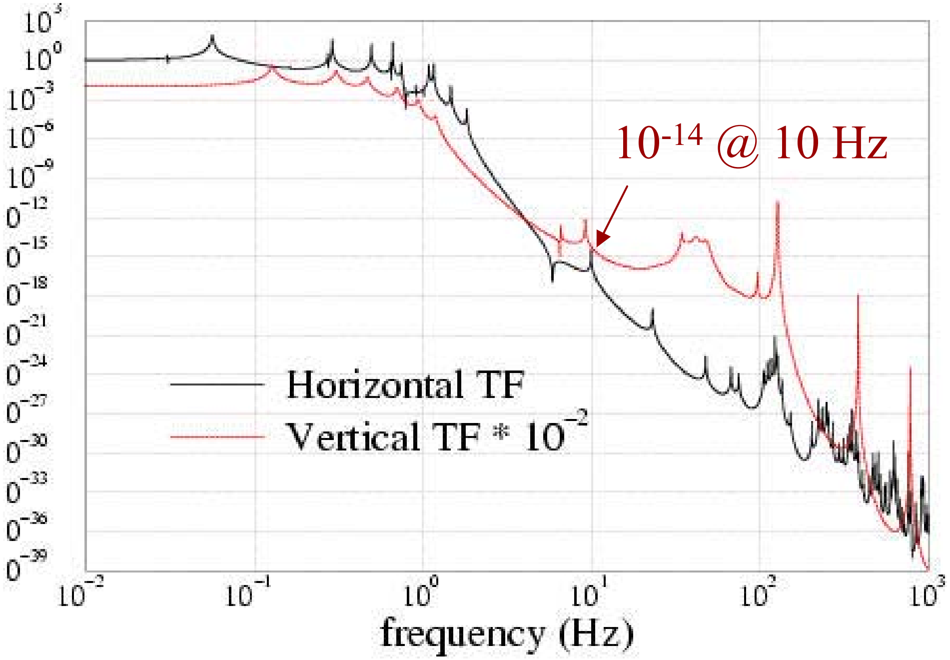
Main elements of mirror suspension







The mechanics of SA suspension is designed to reach 10^{-18} m/Hz$^{1/2}$ at 10 Hz (thermal noise)



10^{-14} @ 10 Hz

- The SA filters off the seismic noise above 4 Hz

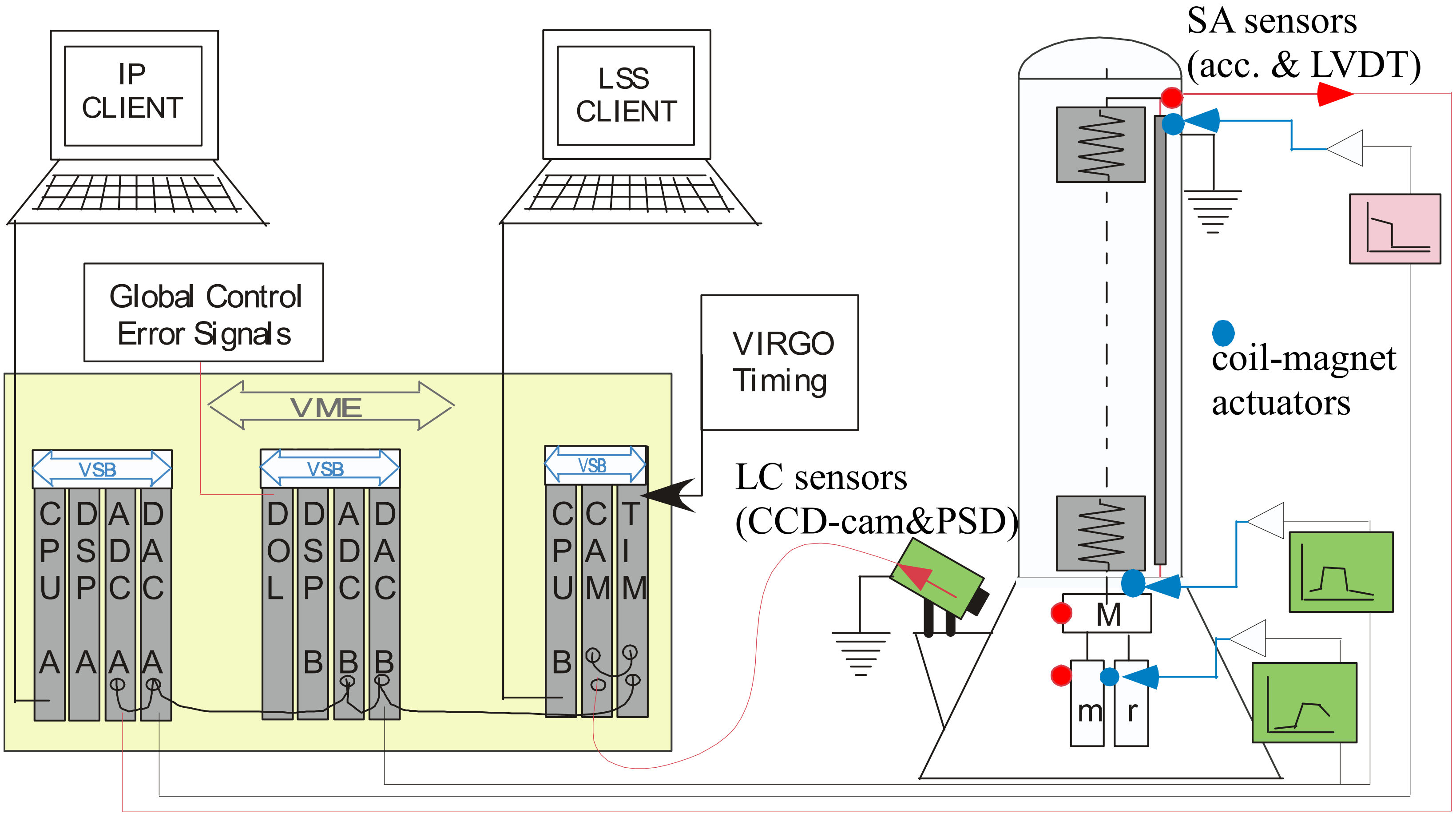
- Below 4 Hz the mirror moves at the SA resonances ≈ tens of μm

- ITF locking requires resonance damping

TOP: Sophisticated control system for the suspension chain

BOTTOM: Efficient mirror local control

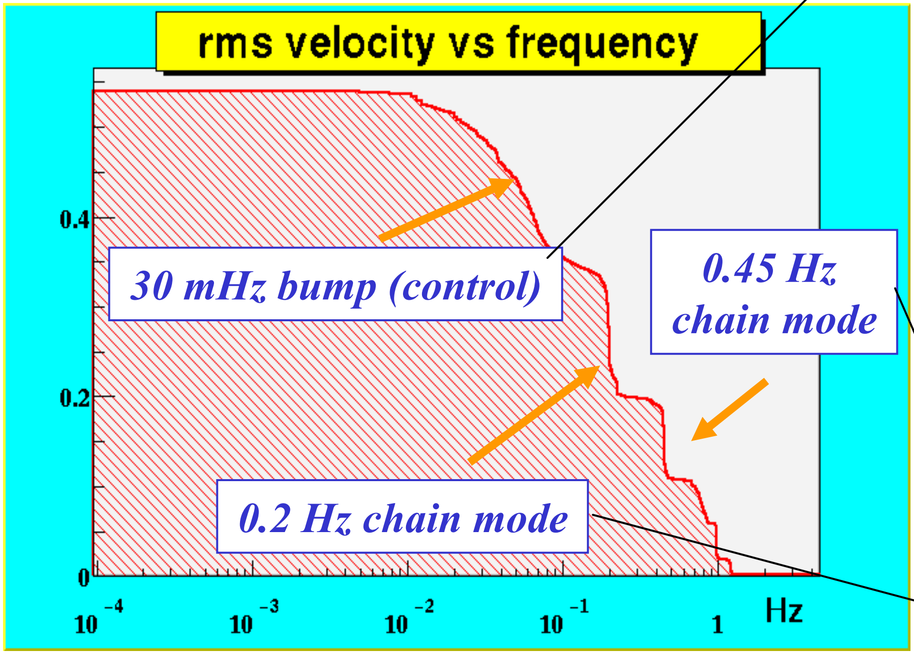
Digital control std chain



CITF: Standard improvements...

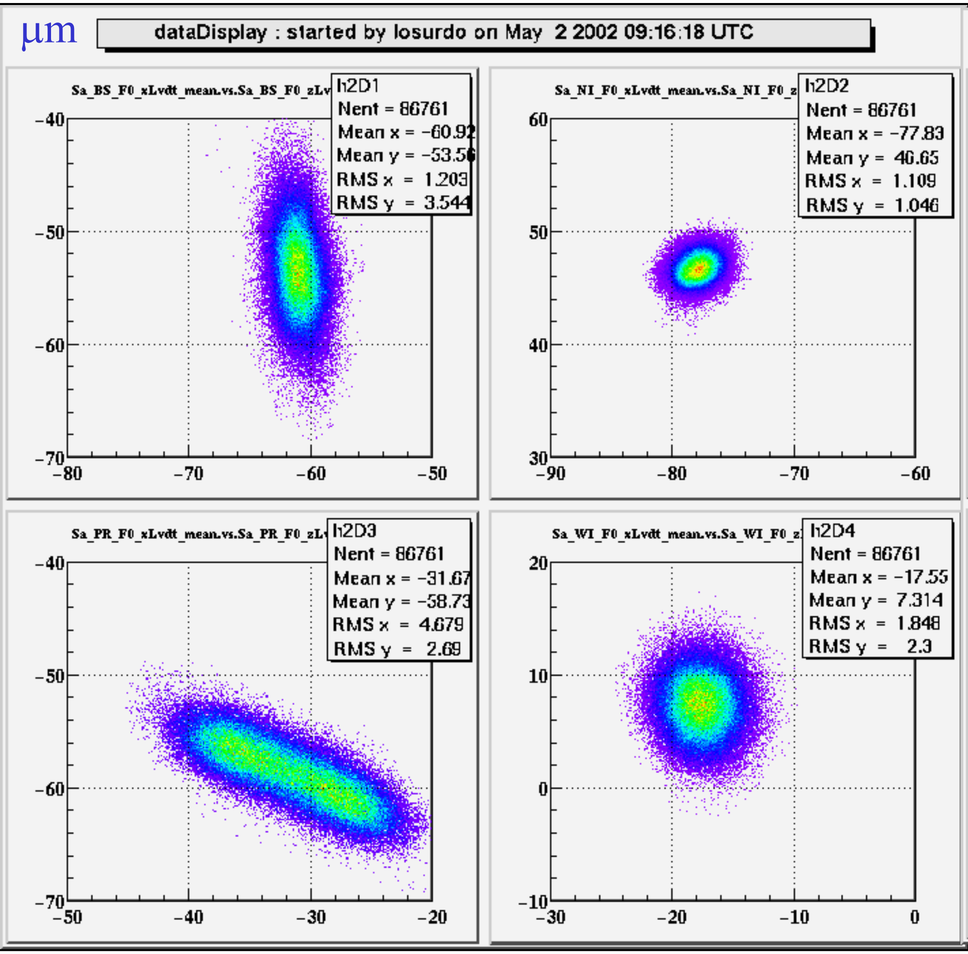
More careful blending of noisy sensor error signals to avoid too small phase margins (Losurdo,Passuello)

Hybrid active control below 4 Hz
LVDT (DC-0.03 Hz) ; Acc. (0.03-4 Hz)



More careful diagonalization of sensors & seismic noise re-injection. Once the energy gets into the chain it is more diffucult to extract it.

e.g.: improvement of 30 mHz bump performed during CITF


µm

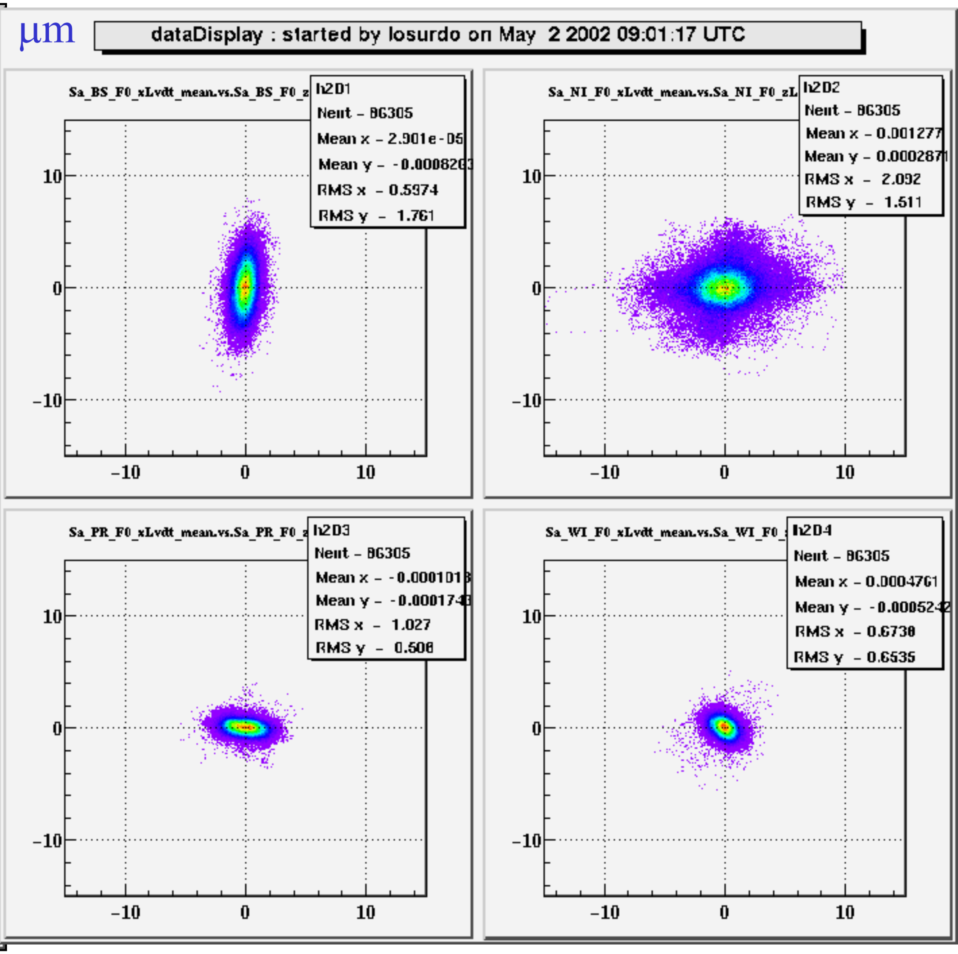
dataDisplay : started by losurdo on May 2 2002 09:16:18 UTC

h2D1
Nent = 86761
Mean x = -60.92
Mean y = -53.56
RMS x = 1.203
RMS y = 3.544

h2D2
Nent = 86761
Mean x = -77.83
Mean y = 46.65
RMS x = 1.109
RMS y = 1.046

h2D3
Nent = 86761
Mean x = -31.67
Mean y = -58.73
RMS x = 4.679
RMS y = 2.69

h2D4
Nent = 86761
Mean x = -17.55
Mean y = 7.314
RMS x = 1.848
RMS y = 2.3


µm

dataDisplay : started by losurdo on May 2 2002 09:01:17 UTC

h2D1
Nent = 86305
Mean x = 2.901e-05
Mean y = -0.000820
RMS x = 0.5974
RMS y = 1.761

h2D2
Nent = 86305
Mean x = 0.001277
Mean y = 0.000287
RMS x = 2.092
RMS y = 1.511

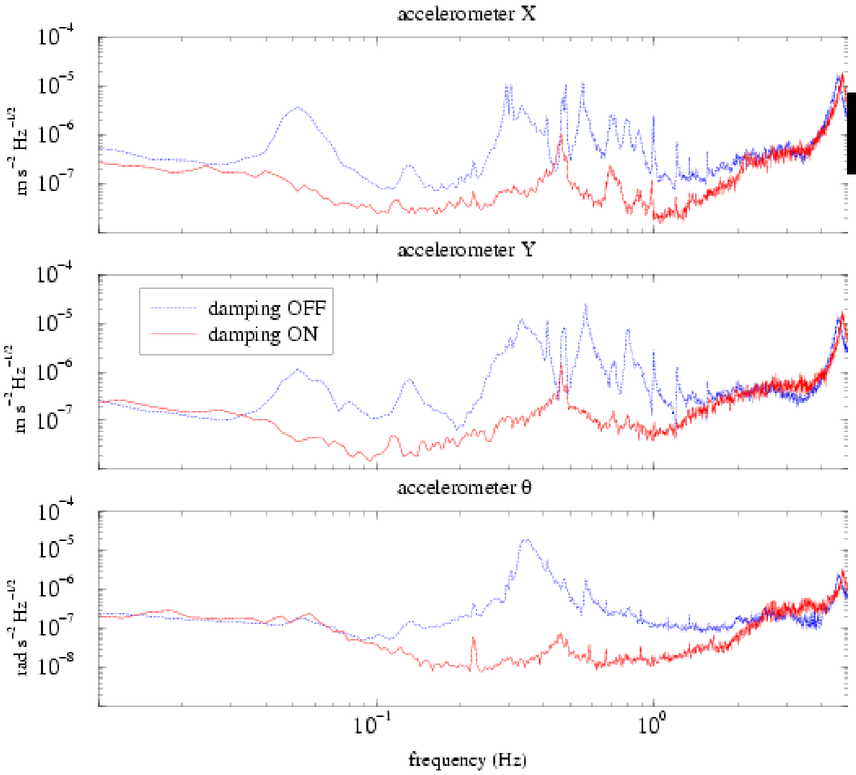
h2D3
Nent = 86305
Mean x = -0.000101
Mean y = -0.000174
RMS x = 1.027
RMS y = 0.506

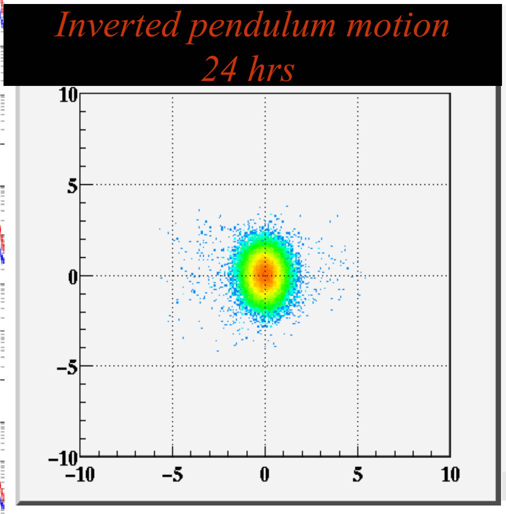
h2D4
Nent = 86305
Mean x = 0.0004761
Mean y = -0.000524
RMS x = 0.6738
RMS y = 0.6535

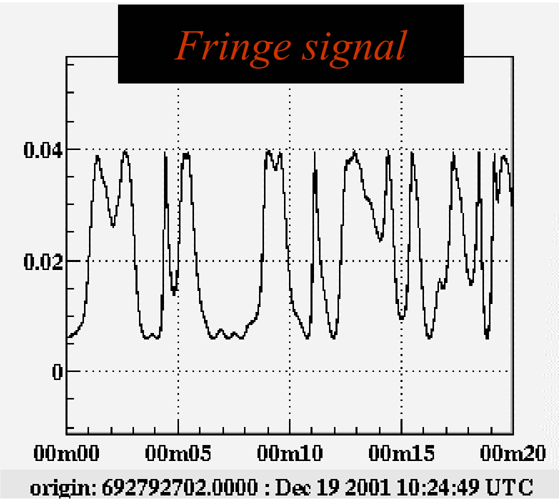
1st overall result: blending position and acceleration signals is delicate matter of digital control design to prevent sensor/seismic noise re-injection

Inertial damping on inverted pendulum (CITF)

- Three d.o.f. damped
- rms translation ~ 1 µm, rms rotation ~ 1 µrad (over long periods)
- Typical relative motion of the mirrors : ~ 10 fringes/20 s
  - ⇒ d/dt(L2- L1) ~ 0.25 mm/s




Inverted pendulum motion 24 hrs


Fringe signal

Features of the mirror suspension control (& CITF→Virgo transition)

- Interferometer operation requires $dL \approx 10^{-12}\ m$

Compensation Tidal strain over 3 km $dL \approx 10^{-3}\ m$

⇓

required control dynamic range $> 10^{9}$: need to split the actuation

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- Longitudinal driving noise

⇓

operation locking force from the marionette (reference solution)

- Low frequency mirror control for fast re-alignment

⇓

larger local control bandwidth: marionette readout implemented

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- Last stage pendulum oscillation during locking

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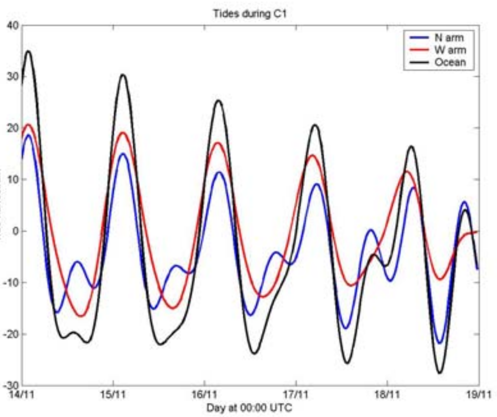
few μm/s: optical lever with image plane readout implemented

PART A:

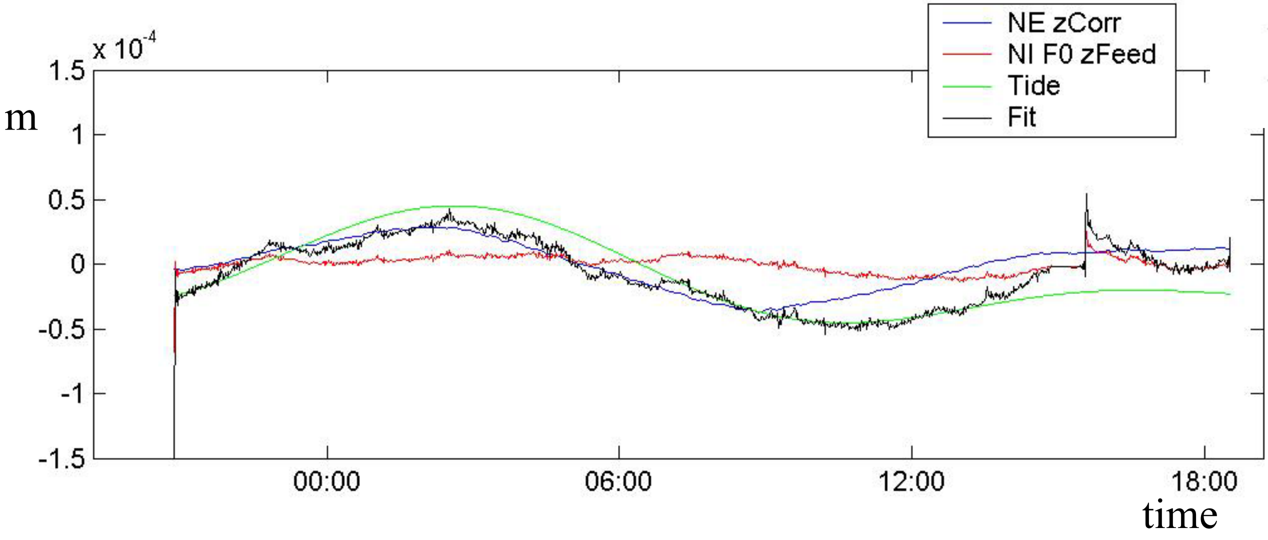
The suspension

PART B:

Alignment Local Control

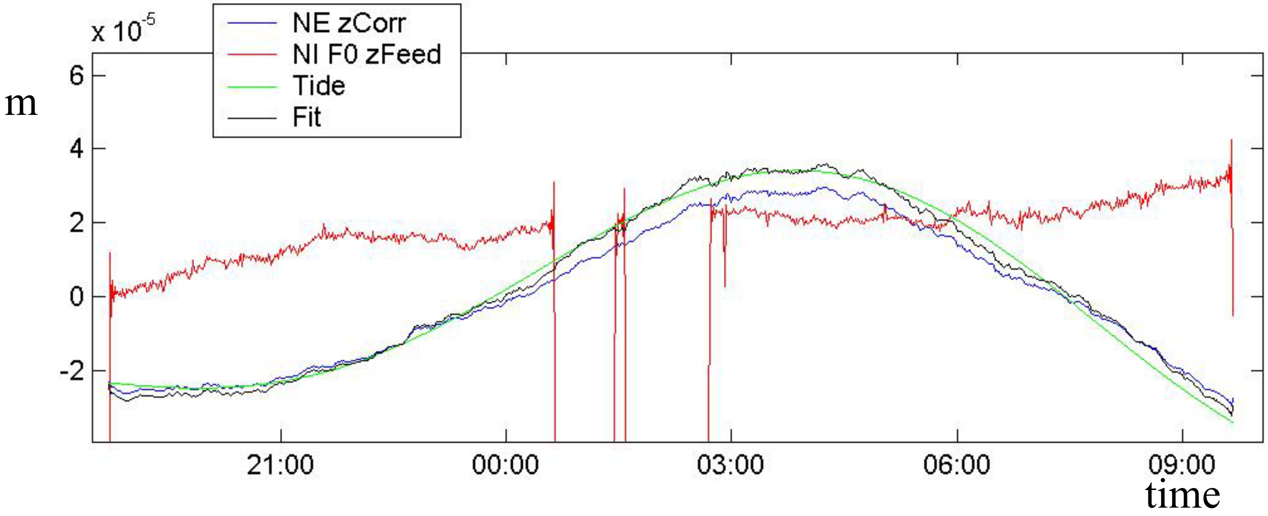


N-arm Effect of tides on the driving dc-component (16-17 Nov 2004 F.Fidecaro – no tidal control)



0.96 NEzCorr+

2.06 NIzFeed



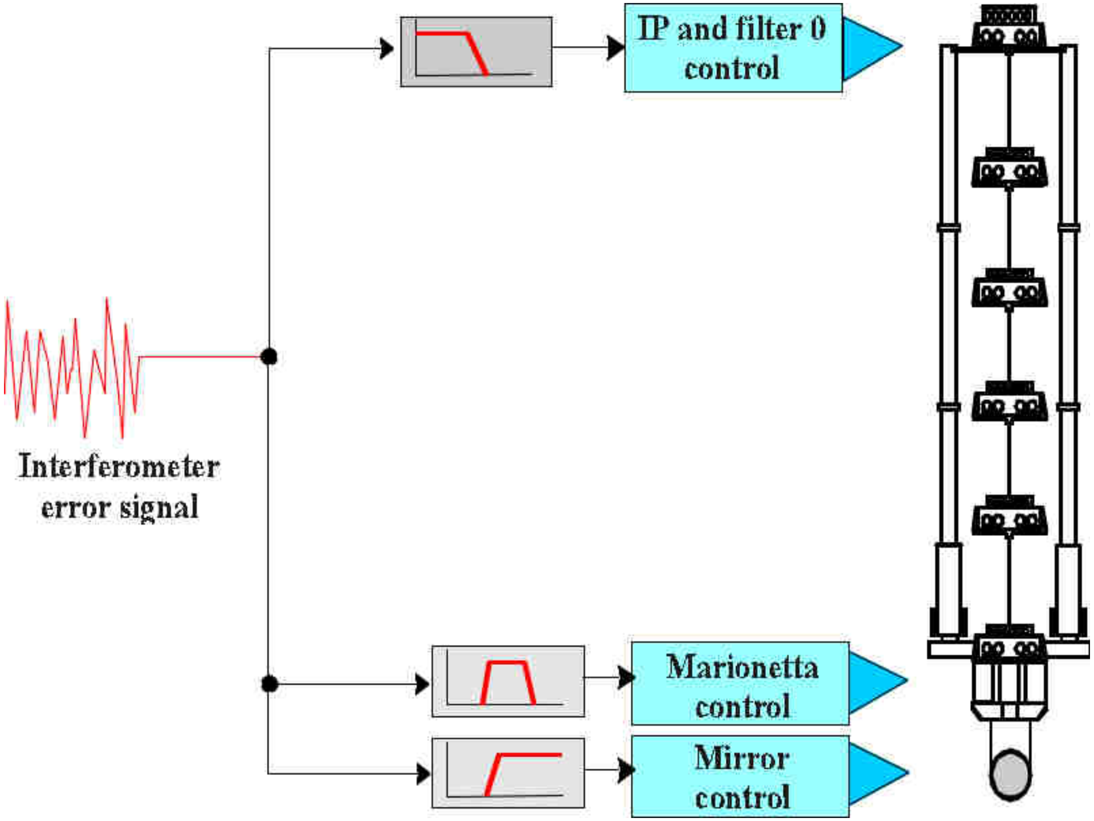
zCorr @10 µm / V
zFeed @ 1 cm/V

1.15 NEzCorr+

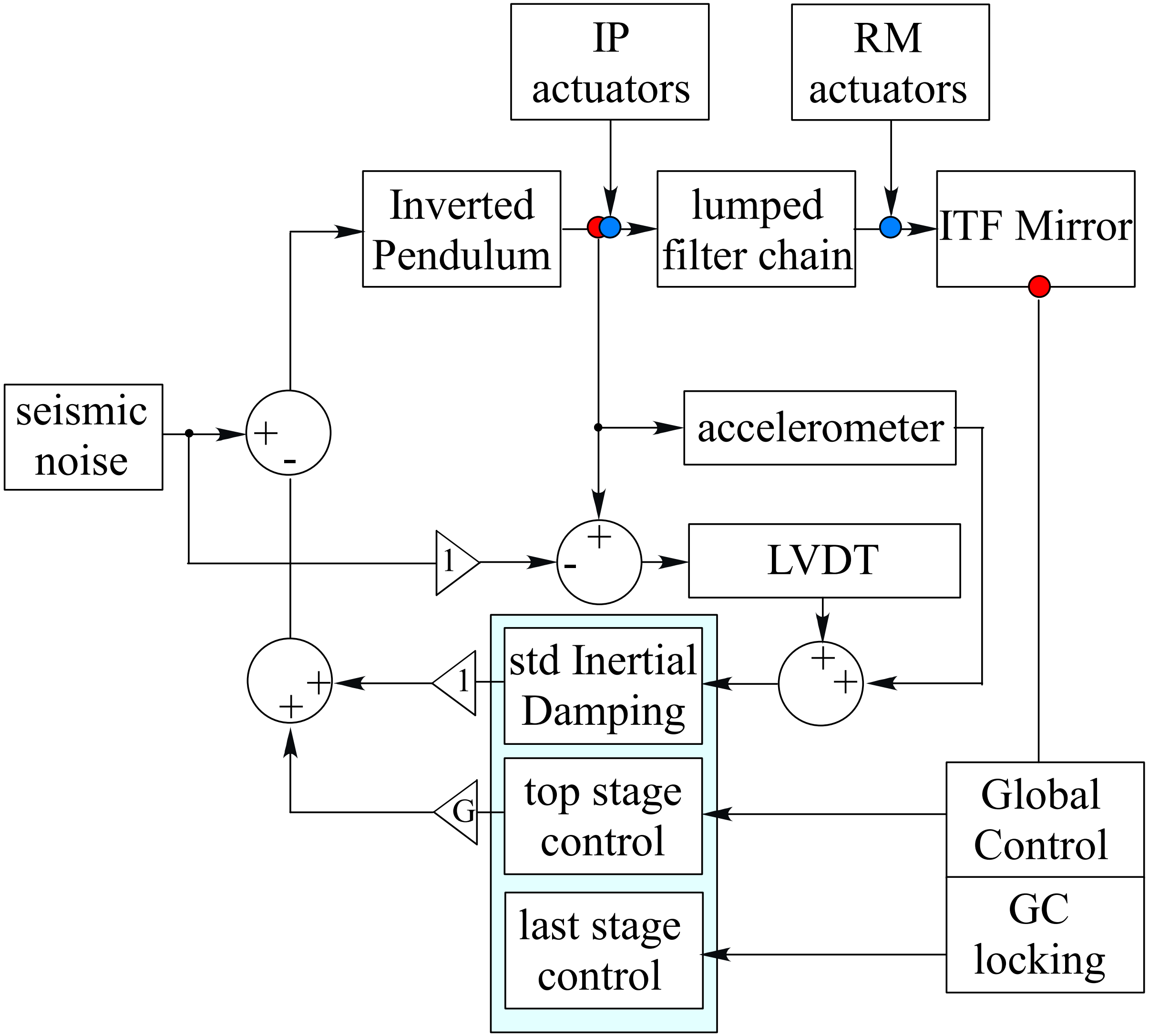
0.01 NIzFeed

Concept (exploiting the three stages of actuation):

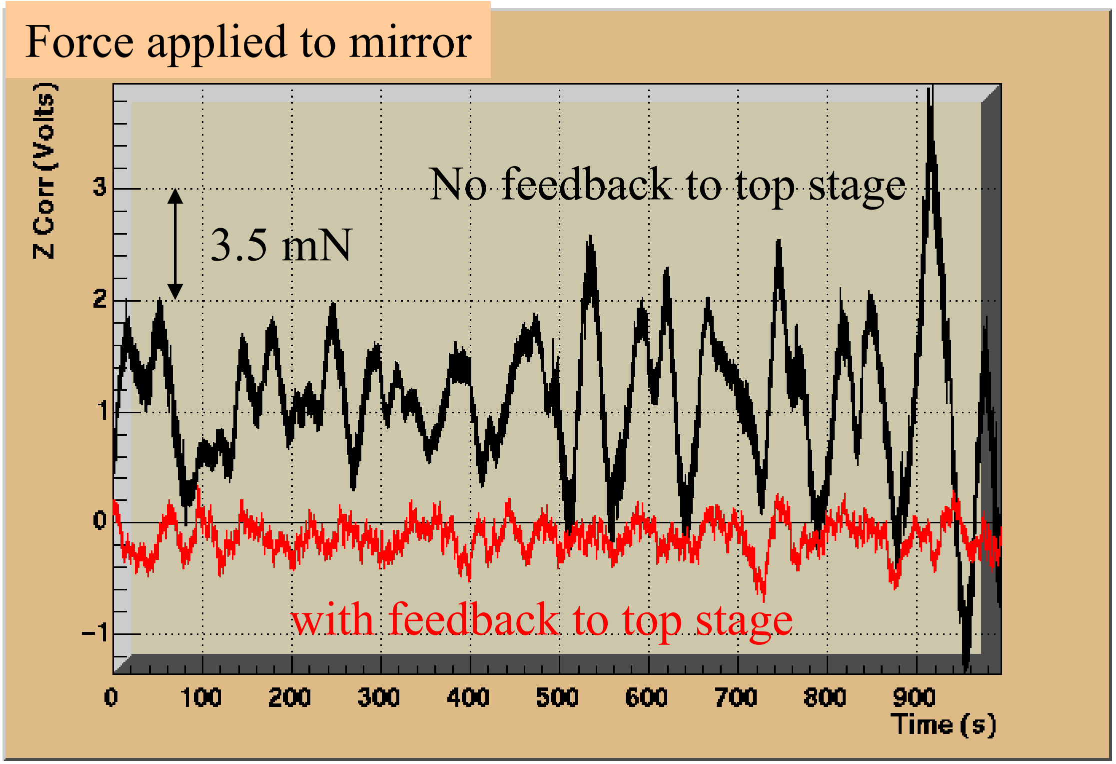
force actuation at different levels along the suspension allows to reduce the direct control action on the mirror (Holloway,Losurdo et Al.)



Block diagram hierarchical control to reduce the dc force on the mirror



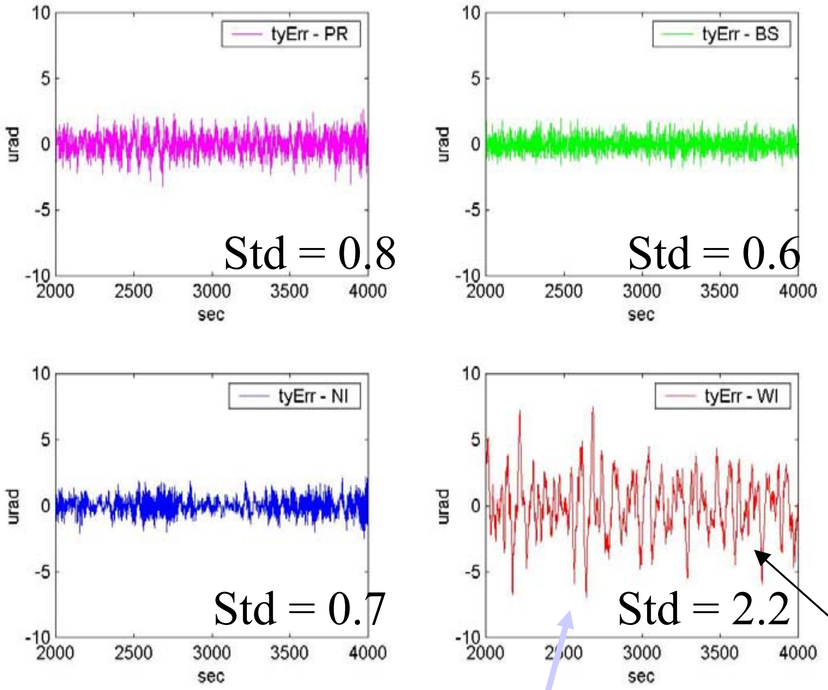
Re-allocation of the mirror low frequency correction (<70 mHz) to the IP



Main result (CITF): - reduction of the locking force on the mirror by a factor ~10
- max force during the test reduced from 23 mN to 1.6 mN

Long term drifts are compensated through the Inverted Pendulum top stage FB

This is not the only advantage (CITF) !



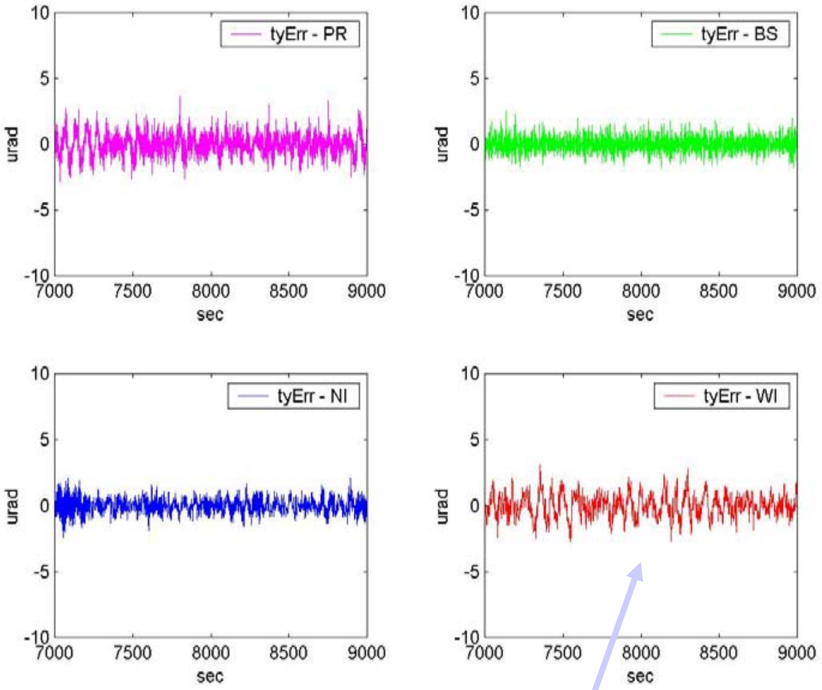
Std = 0.8

Std = 0.6

Std = 0.7

Std = 2.2

Hierarchical control OFF

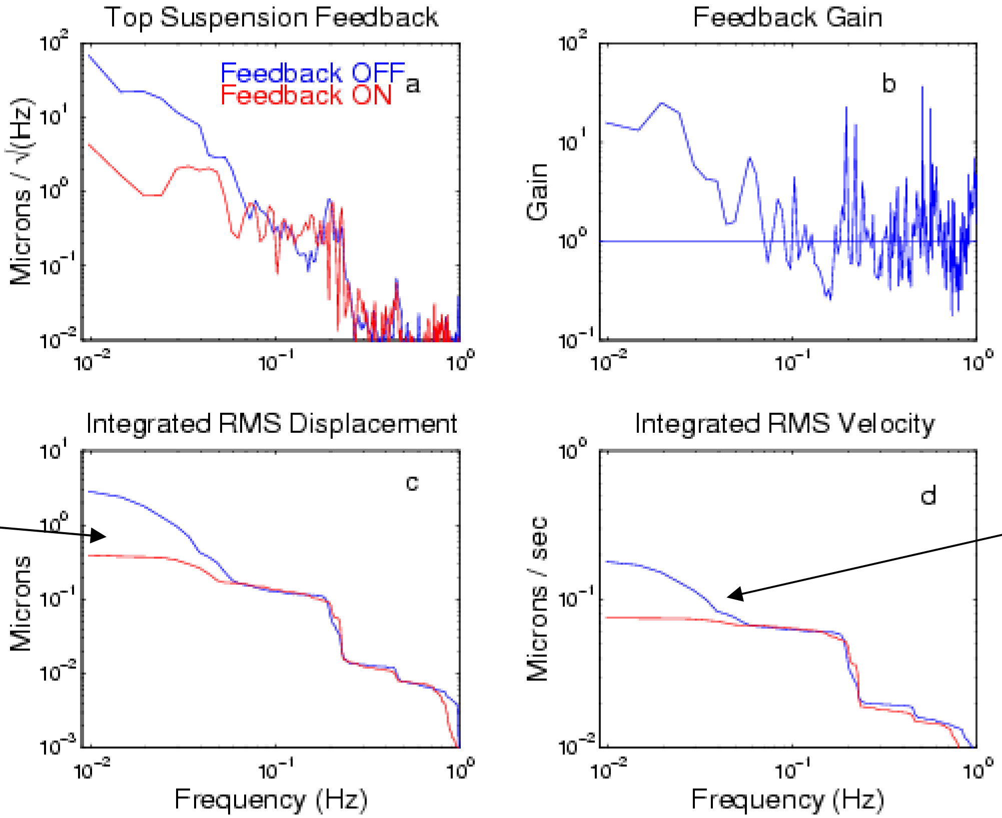


LF resonance of the suspension chain
excited by unperferct driving matrix
for the direct action on the mirror

Hierarchical control ON

Big forces on the mirror excite low frequency internal modes of the suspension

A "quieter" action on the mirror



3 ➔ 0.4 µm

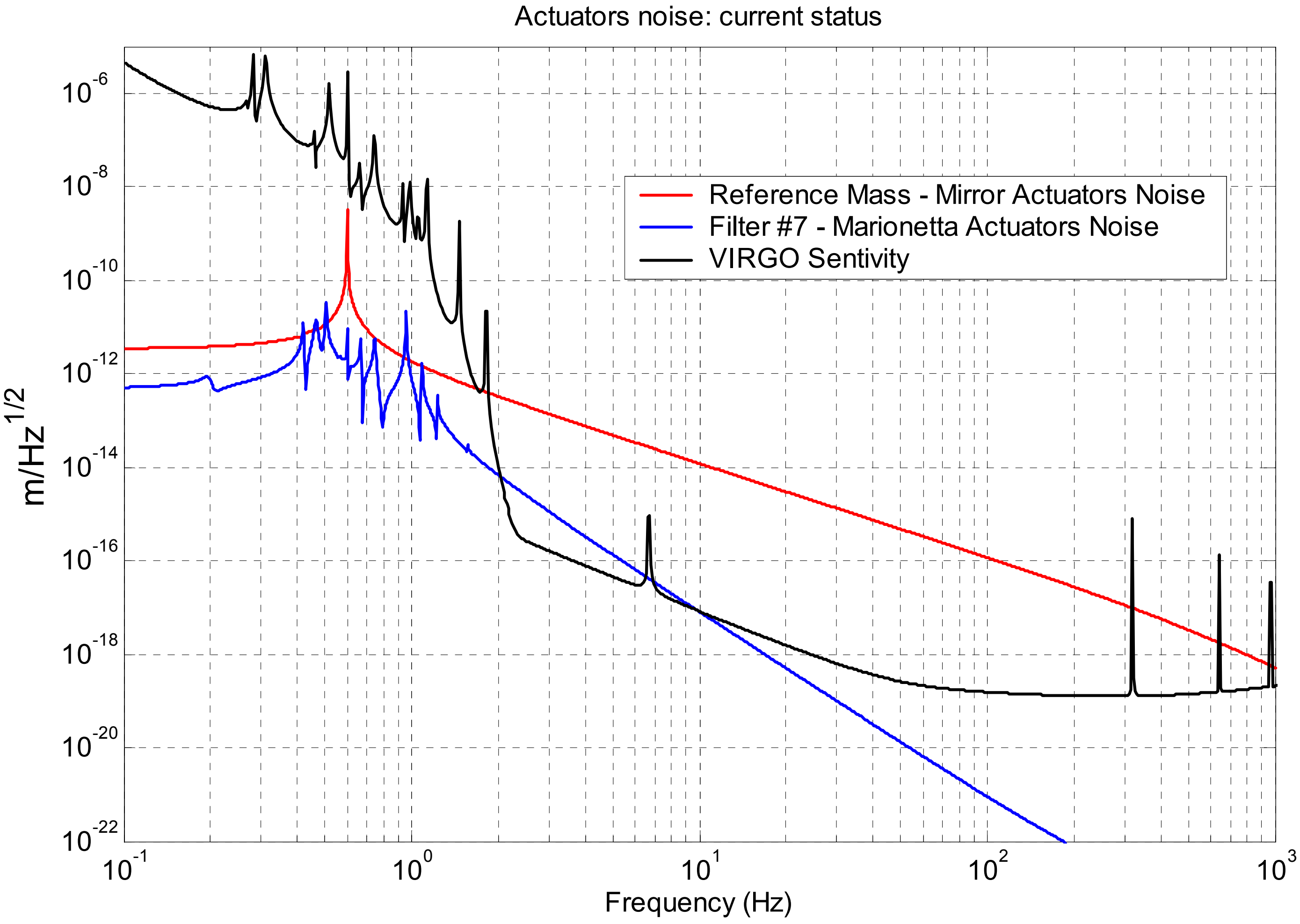
0.2 ➔ 0.075 µm/s

100 s chunk

2nd overall result: The locking correction force has to operate around zero

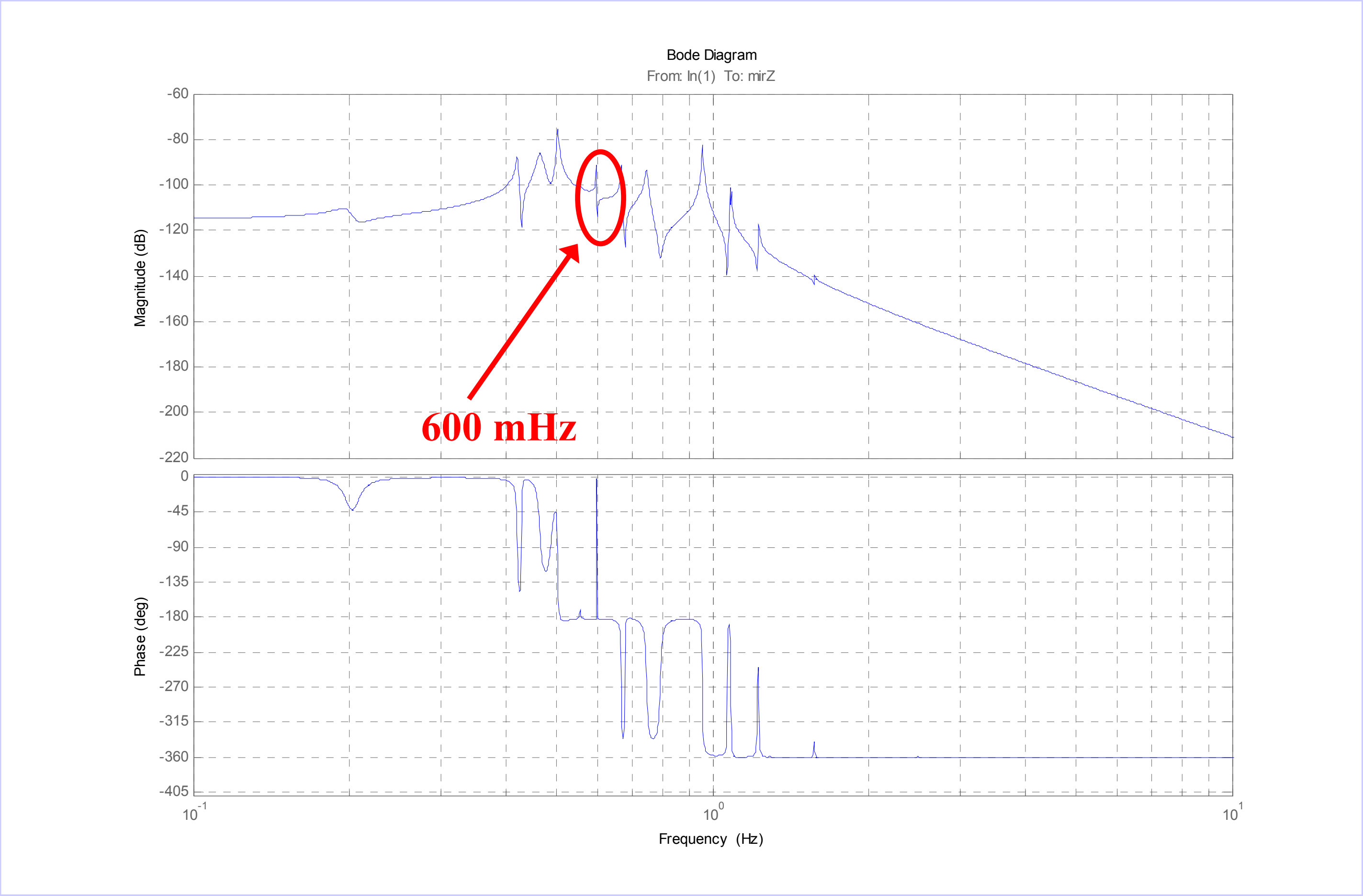
Driving noise/std solution:

use the F7-marionette actuators after lock acquisition



BUT …. :

the switch of the control reaction mass ➔ F7 actuators IS NOT EASY !



Driving noise/Work in progress (a great help from simulation):

- Simulation of lock keeping from the marionette OK
- Simulation of lock keeping during reaction-mass ➔ F7 control switch in progress

Driving noise/Backup solutions:

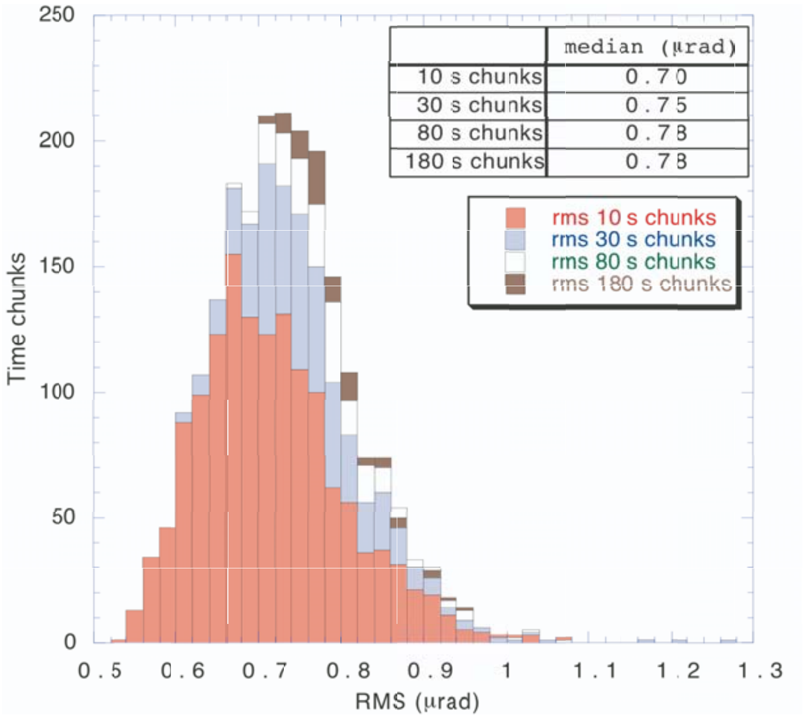
- Low noise electronics & related strategies under study
- Simulation of lock acquisition from F7 control switch to be done

3rd overall result: exploit the actual ITF simulation to design locking schemes

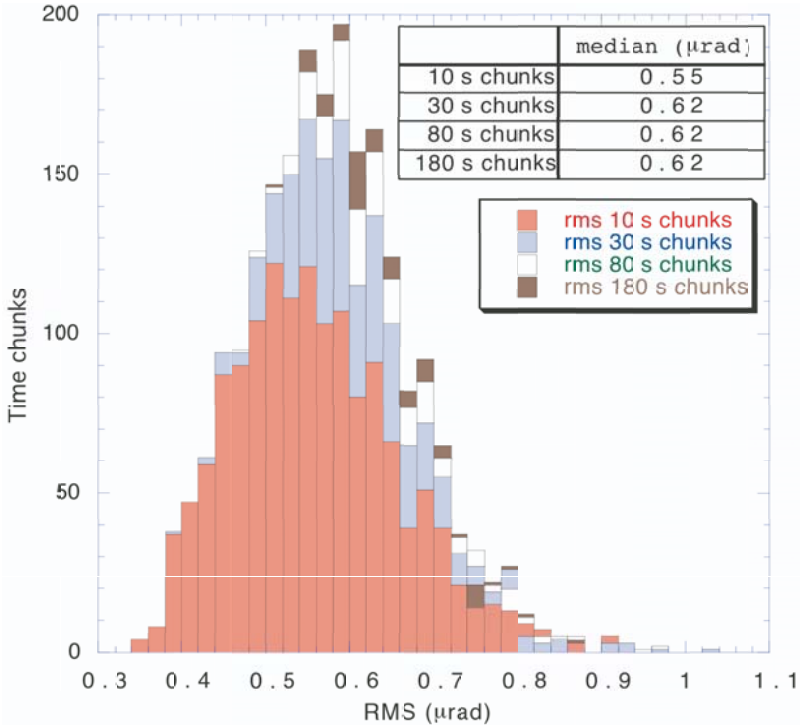
CITF Angular local control of last suspension stage:

Mirror angle read-out (CCDcamera+Optical Lever), F7-marionette torque actuation

Main duty : prealign and allow to switch-on the ITF automatic alignment



	median (µrad)
10 s chunks	0.70
30 s chunks	0.75
80 s chunks	0.78
180 s chunks	0.78



	median (µrad)
10 s chunks	0.55
30 s chunks	0.62
80 s chunks	0.62
180 s chunks	0.62

Specs OK

- Good performance & accuracy (0.6-0.7 µrad RMS)
- Good dynamic range 5 10^4

BUT:

Compensation of all the low frequency torsional modes due to the suspension chain (e.g. 16 mHz) is needed

↓

In CITF we exploited the noisy-readout control technique enhance the gain at low frequency without DAC saturation f > 1 Hz (APP **20**,6 p.617)

↓

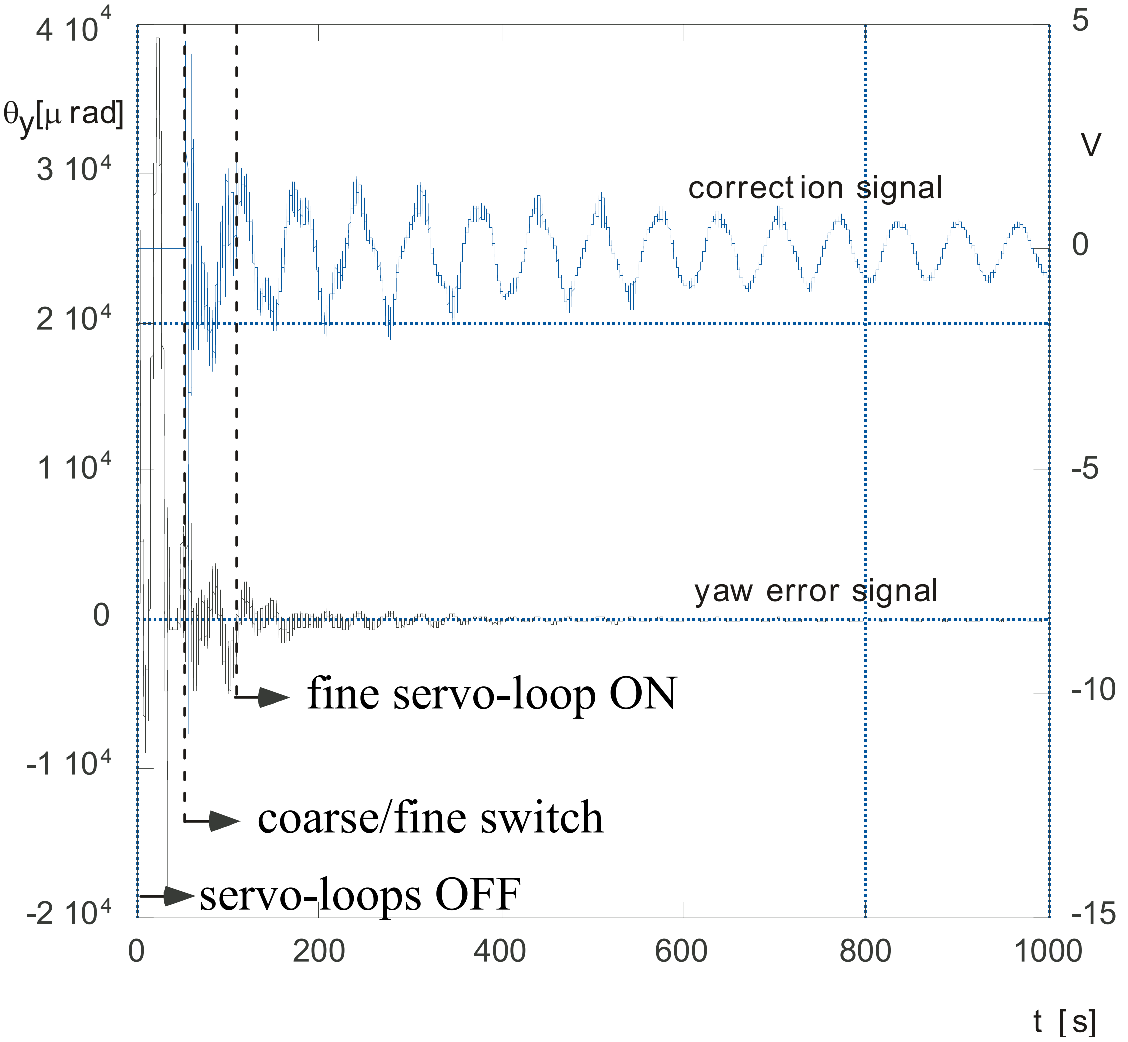
small Alignment Local Control BW (100 mHz)

↓

mirror fast realignments not possible !!

4th overall result: larger angular control bandwidth required (3-5 Hz)

(CITF) Mirror read-out ➔ F7-Marionette action



CITF longitudinal local control of last suspension stage:

No dedicated optics (only large field view CCD-camera) → 60 µm RMS

⇓

600 mHz residual motion excited

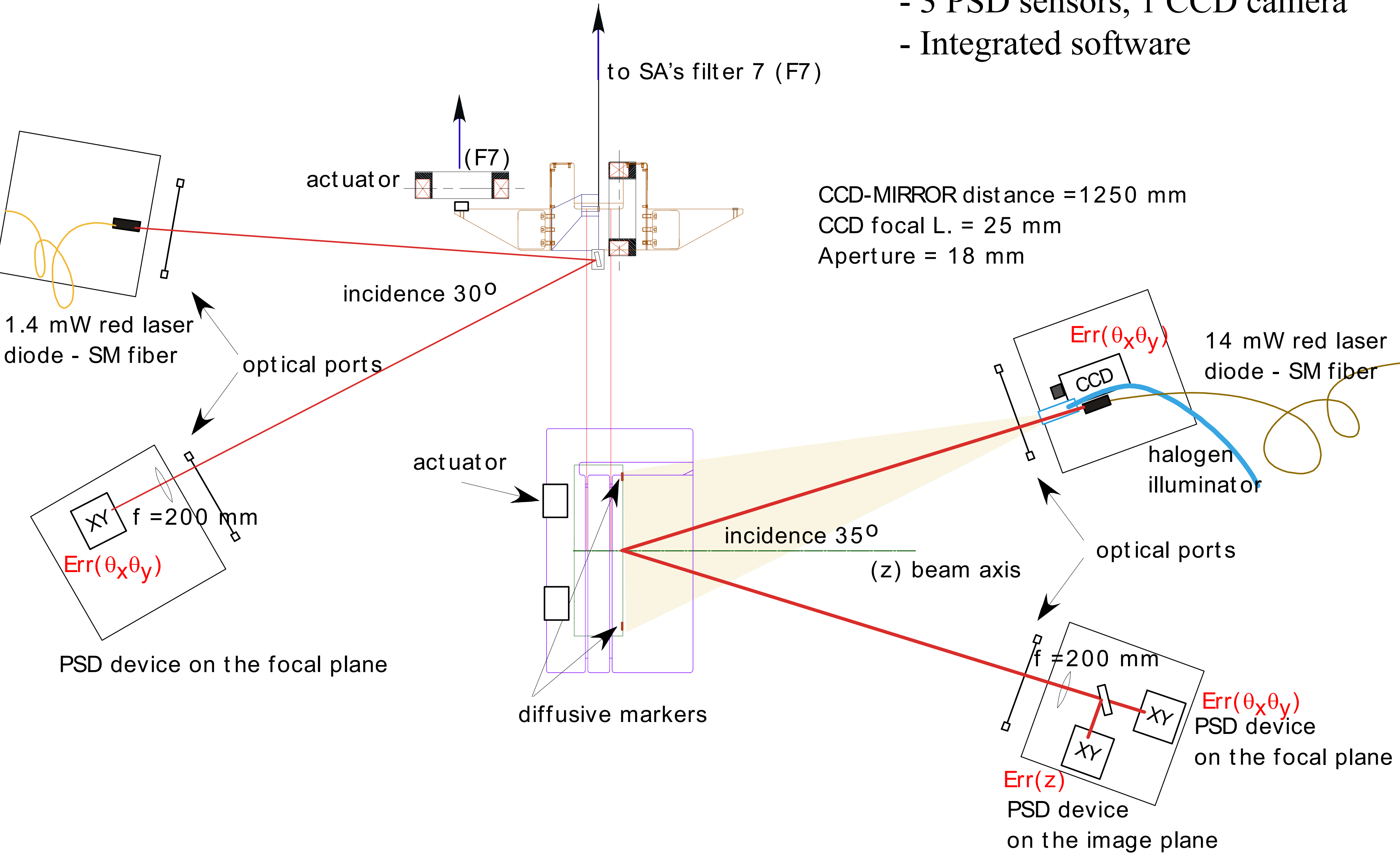
⇓

Recycled Michelson Locking possible only thanks to tuned simulation studies and sophisticated triggers

5th overall result: mirror longitudinal damping seismic noise limited needed

Last stage control upgrade implemented

- 2 optical levers
- 3 PSD sensors, 1 CCD camera
- Integrated software



Last stage control upgrade designed

in the image plane → $\Delta x_2 = -2(D/L)\,\Delta z = -\,0.36\,\Delta z$

in the focal plane → $\Delta x_2 = 2\cdot f\cdot\Delta\alpha = 0.4\,\Delta\alpha$

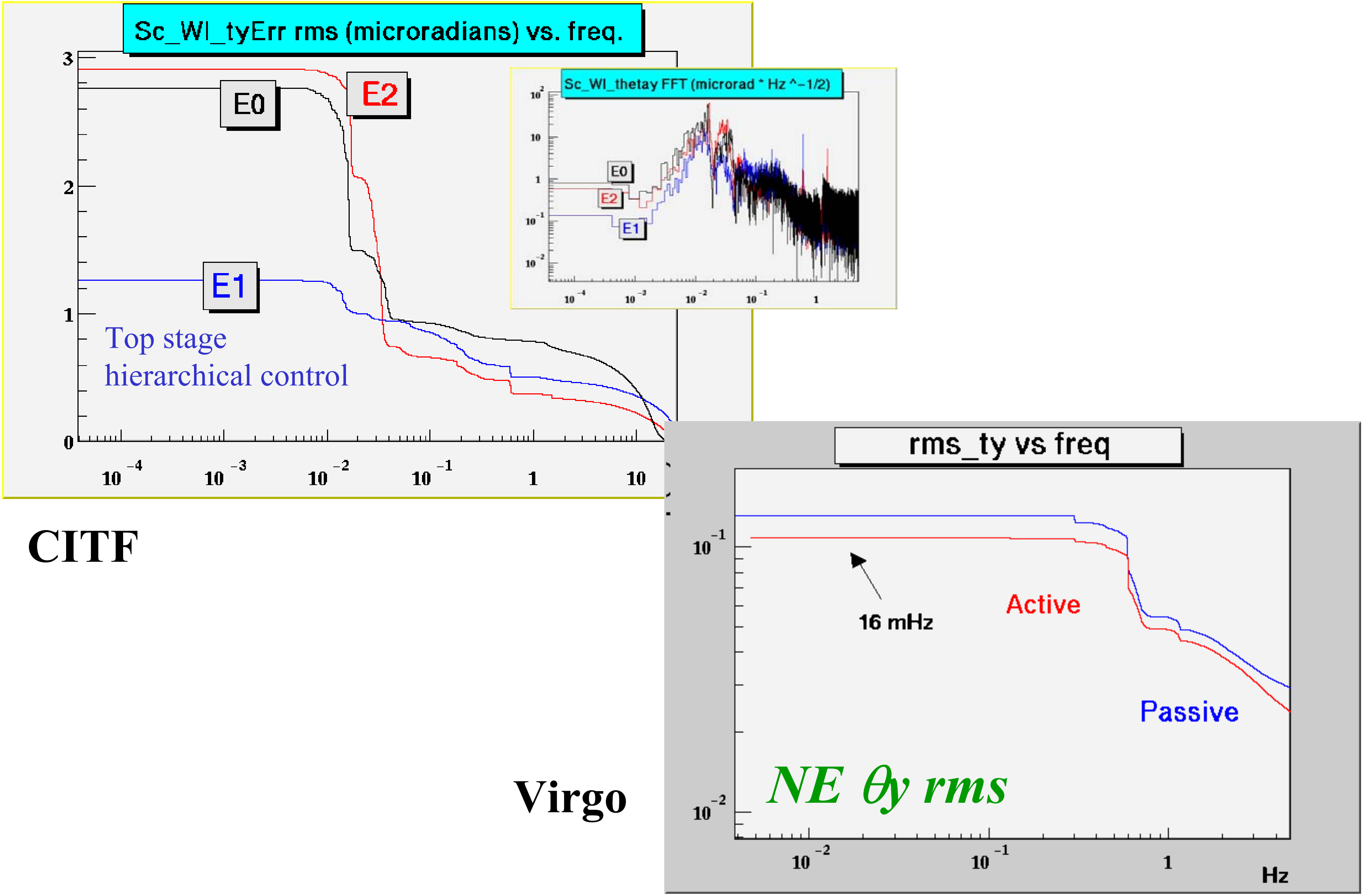
$$\tilde{X}_2 = \begin{cases} (f = 0.6\ \mathrm{Hz}) \approx 10^{-7}\ \mathrm{m}/\sqrt{\mathrm{Hz}} \\ (f = 10\ \mathrm{Hz}) \approx 10^{-8}\ \mathrm{m}/\sqrt{\mathrm{Hz}} \end{cases}$$

Then,

$$\tilde{Z}\,(0.6\ \mathrm{Hz}) = \frac{\tilde{X}_2}{0.36} \approx 3\cdot 10^{-7}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$$

$$\tilde{\alpha}\,(10\ \mathrm{Hz}) = \frac{\tilde{X}_2}{0.4} \approx 2.5\cdot 10^{-8}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$$

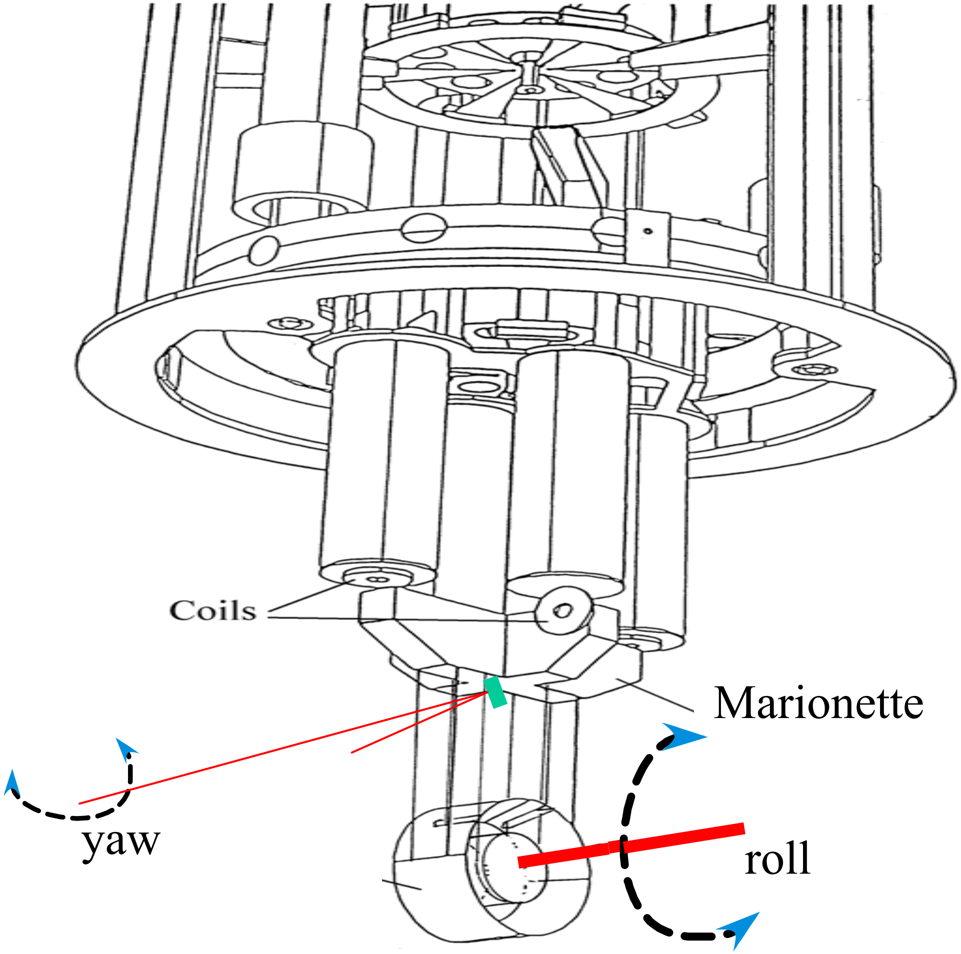
Angular rms budget due to locking



CITF

Virgo

Readout upgrade & microseism



New local controls read the marionette angle through a tilted mirror (10 deg) couples a θz (roll) resonance at 300 mHz to θy (yaw).

Roll is not controlled !!

A storm during run C1 caused an increase of the roll @300 mHz of about 100 times

⇓

Loss of lock !!

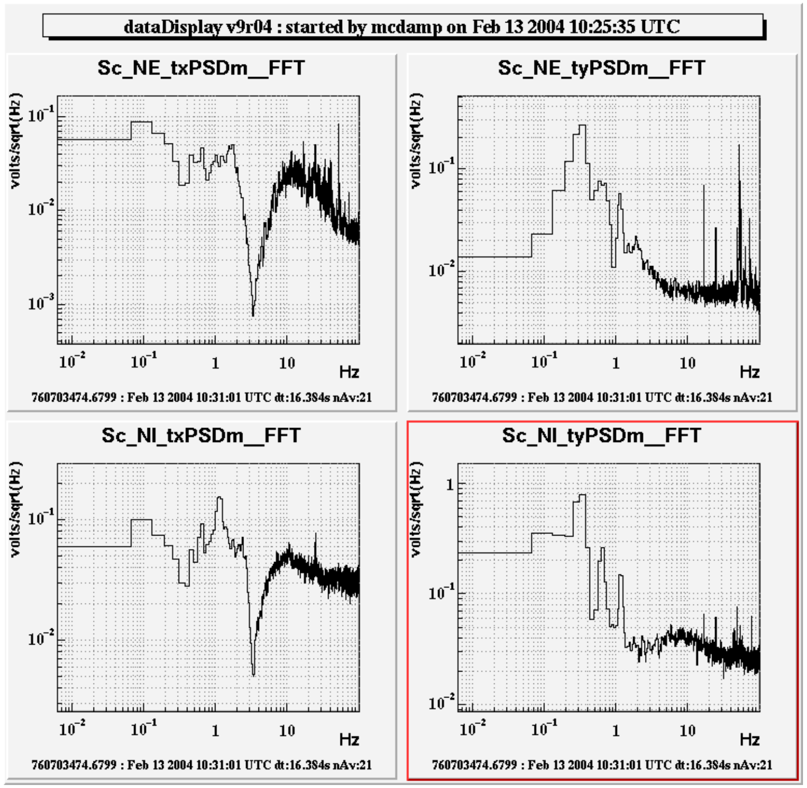
An optimistic comment:

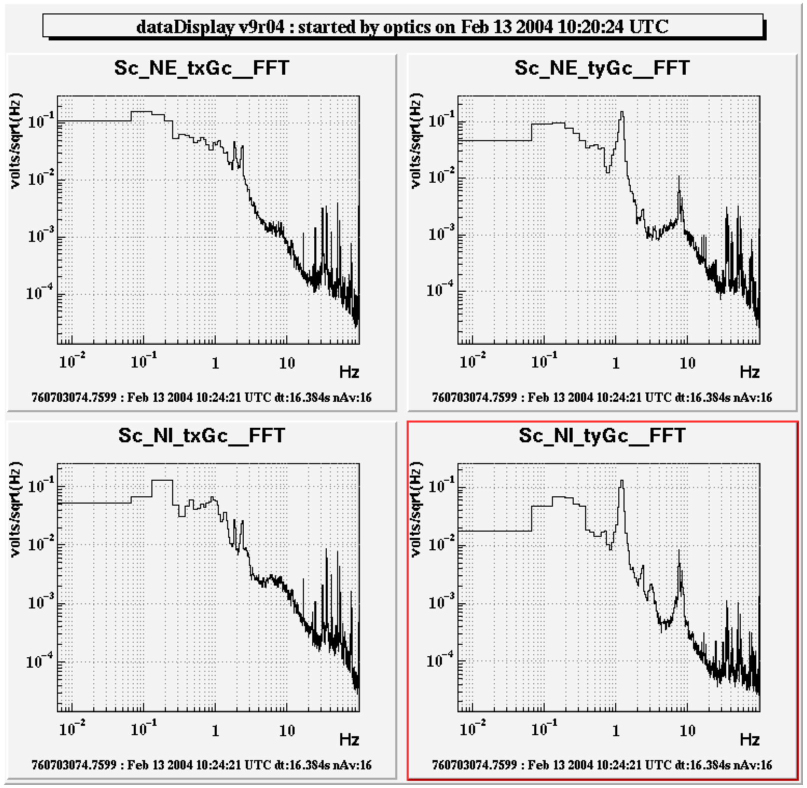
We realized that the mirror was actually moving along a d.o.f. (always neglected). We had to patch the inertial damping & LC filters.

6th overall result: mirror suspension last stage control should provide 6 d.o.f. actuation

N arm (I)

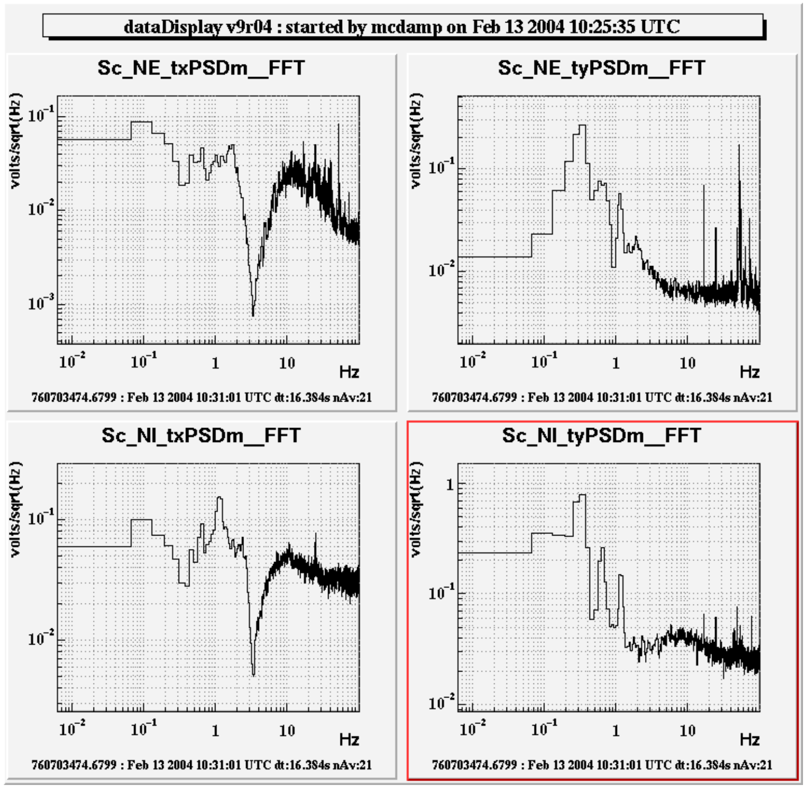
- **LC only drives the mirror through the mationette**
- **AA signals monitored** (freise,loupias,majorana)



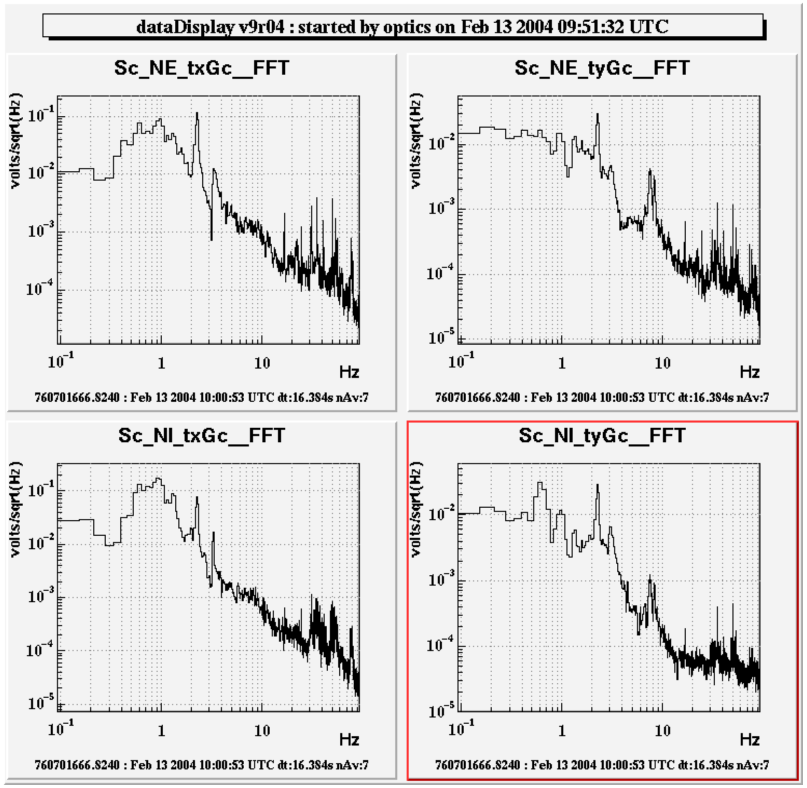


N arm (II)

- AA drives the mirror through QPHD signals
- LC marionette signals monitored

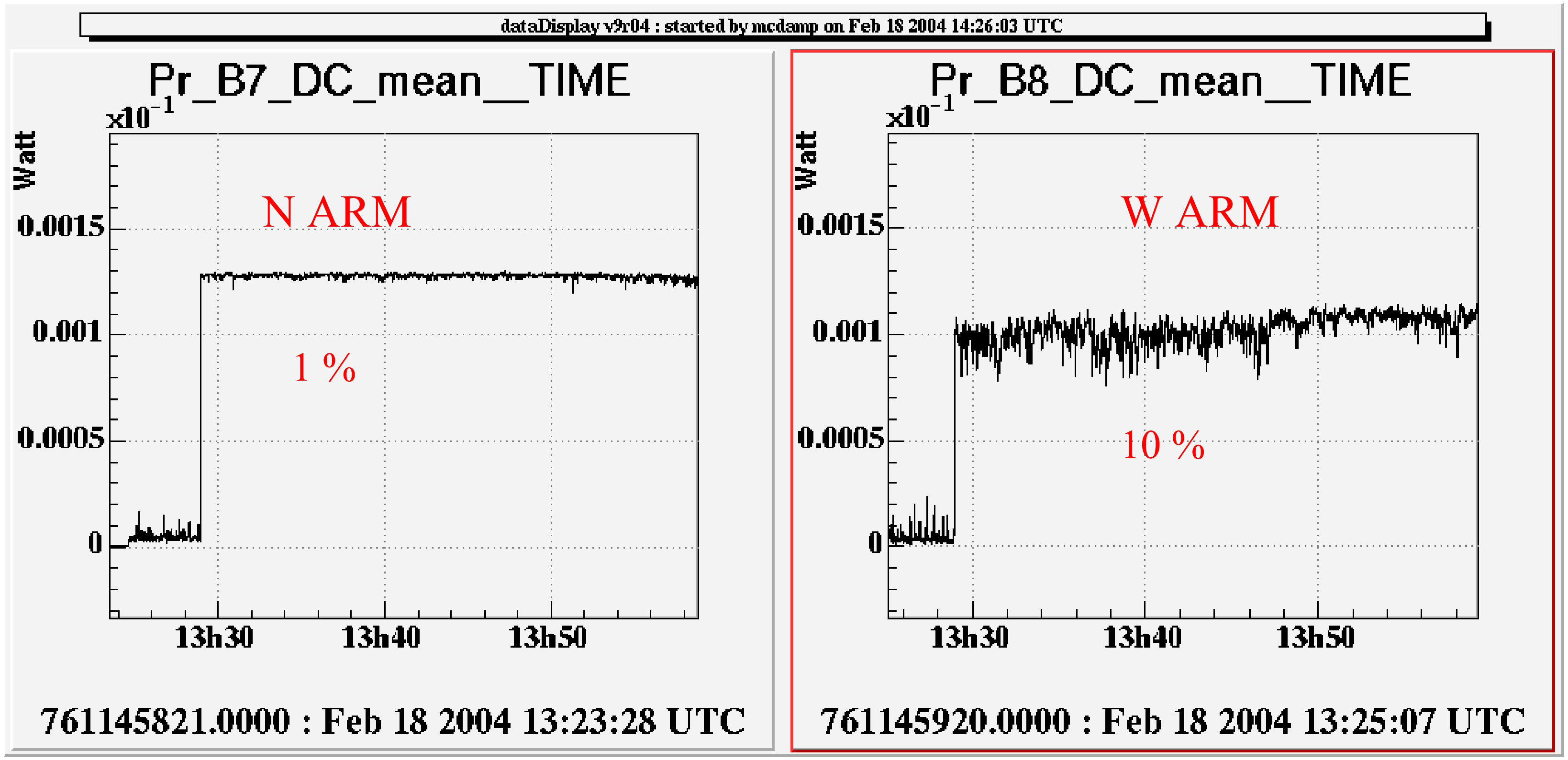


dataDisplay v9r04 : started by mcdamp on Feb 13 2004 10:25:35 UTC



dataDisplay v9r04 : started by optics on Feb 13 2004 09:51:32 UTC

Automatic vs Local Alignment Control (before run C2): stored power fluctuations with the two FP cavities simultaneously locked



AA ON - LOCAL control OFF

AA OFF - LOCAL control OFF

Conclusions (not too bad.....)

- blending position and acceleration signals is delicate matter of digital control design to prevent sensor/seismic noise re-injection
  (the suspension control “less inetrial”, but with smaller residual RMS
  for Virgo crossing frequency 30 mHz ➔ 70 mHz)
- the locking correction force has to operate around zero
- exploit the actual ITF simulation to design locking schemes
- 3-5 Hz angular control bandwidth required
- mirror longitudinal damping seismic noise limited needed
- mirror suspension last stage control should provide 6 d.o.f. Actuation (!!)