

Seismic isolation and local controls in Virgo



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INFN Roma

Workshop on Geophysics and Gravitational-
Wave Detectors

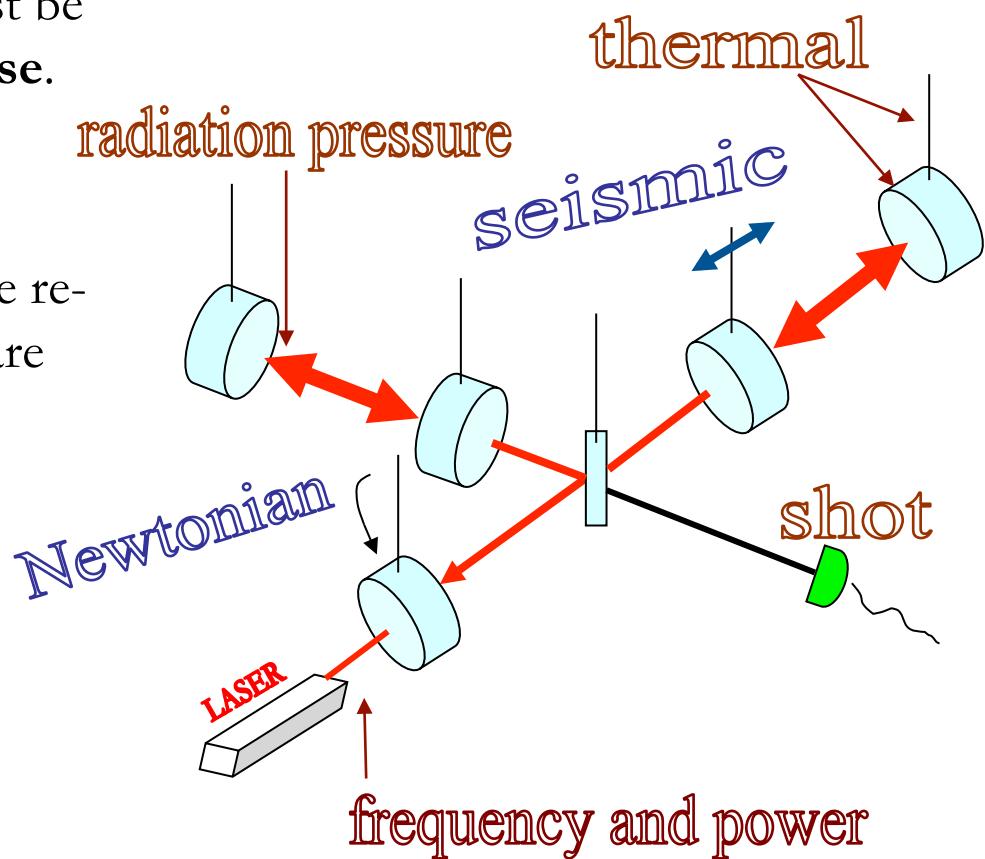
IPGC Paris, mardi 17 avril 2012

Standard approach in high sensitivity detectors

- Core intrinsic noise (test-mass and optical probe) must be reduced enough.

- Noise due to external disturbance must be reduced to the level of core intrinsic noise.

- Technical noise sources, i.e. disturbance re-injected in order to operate the machine, are designed to be negligible in the detection bandwidth.



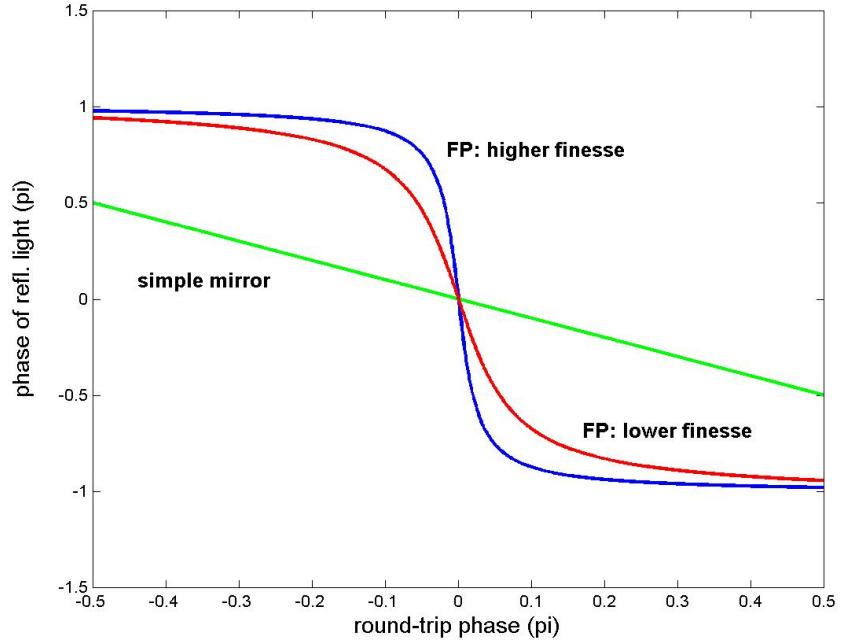
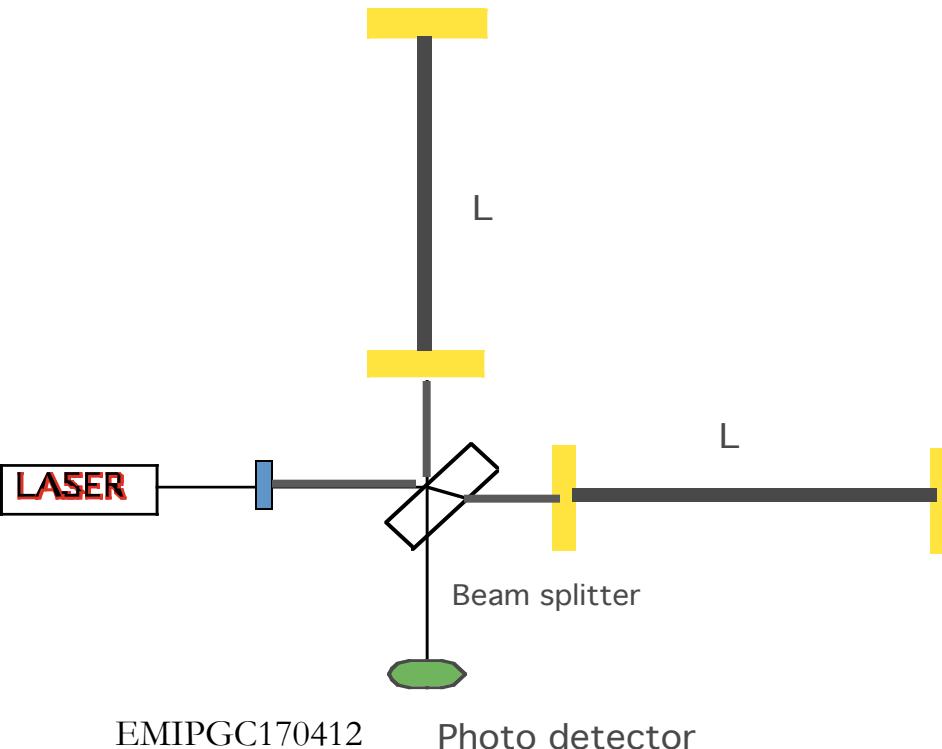
Standard layout used in ground-based detectors

I) The optical path where the GW-induced phase shift is accumulated can be enhanced by means of Fabry-Perot resonant cavities.

II) Dark fringe detection to reduce read-out noise.

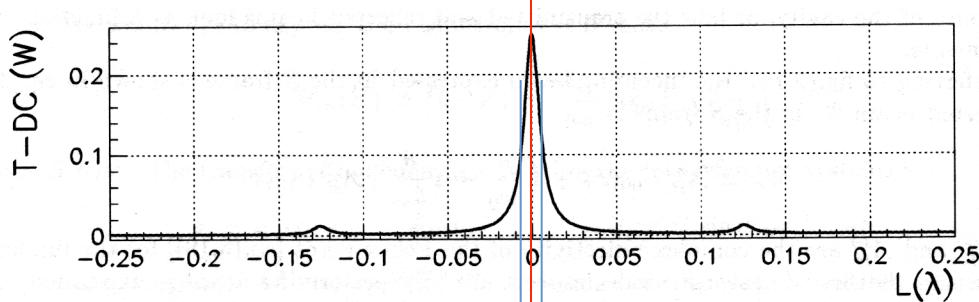
III) Recycling of ITF reflection.

Effective path for Virgo ~ 120 km

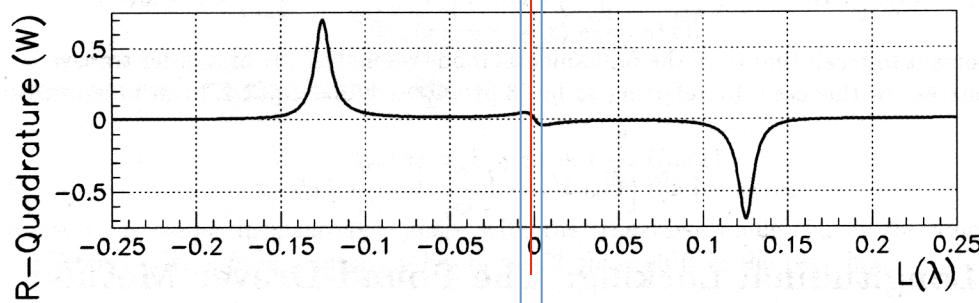
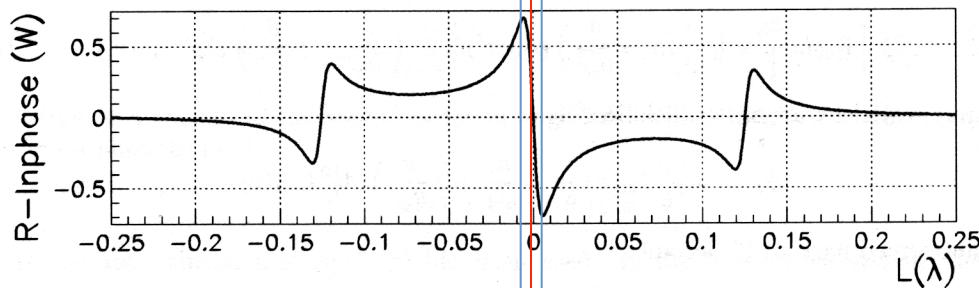


The response of the ITF is much steeper => control system needed

DC reflected light



Demodulated
Pound-Drever
signals

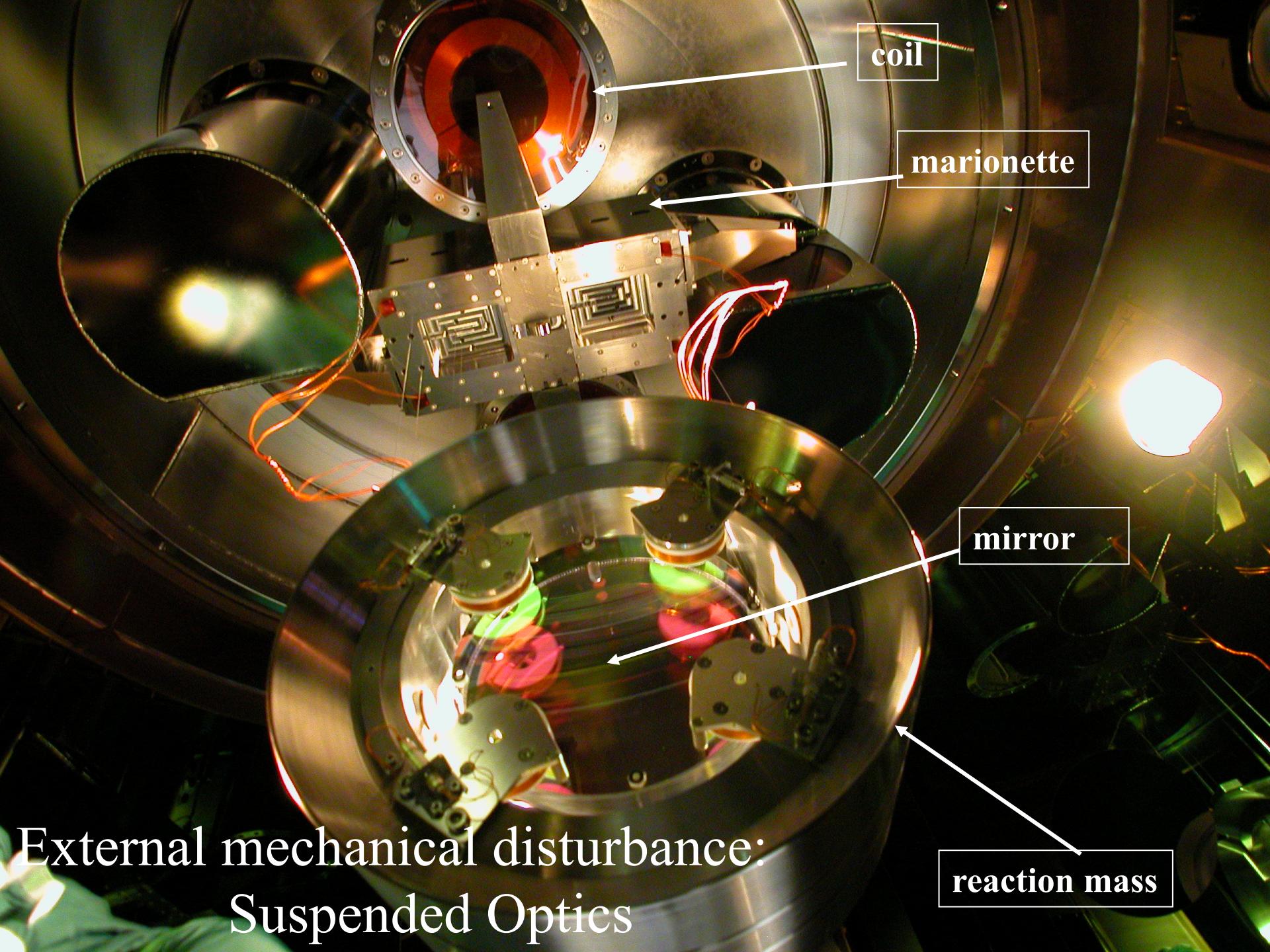


Linear range

$$FWHM = \frac{\lambda}{2F}$$

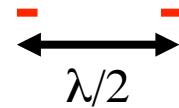
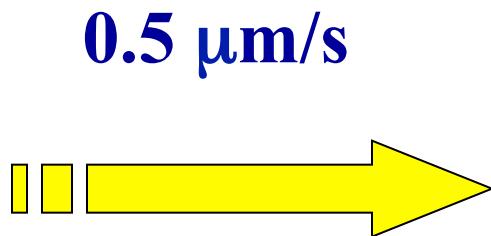
Control $\delta l = \frac{1}{10} \frac{FWHM}{2} = \frac{\lambda/2}{10 \cdot 2 \cdot F}$

safety factor

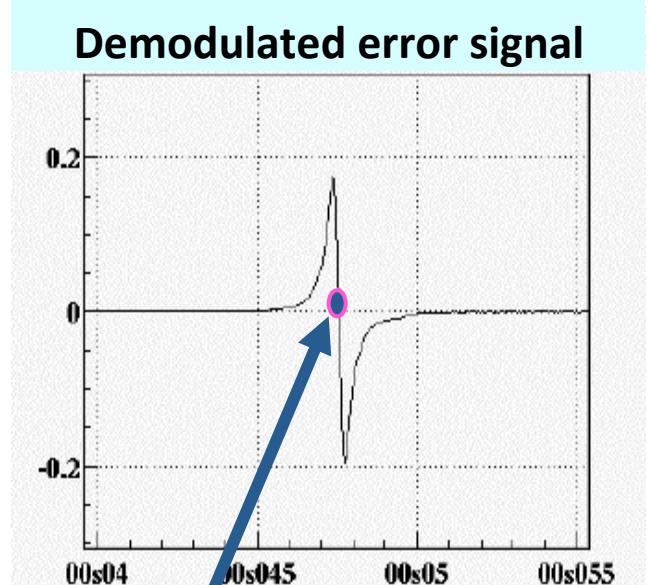


External mechanical disturbance:
Suspended Optics

Suspension digital control



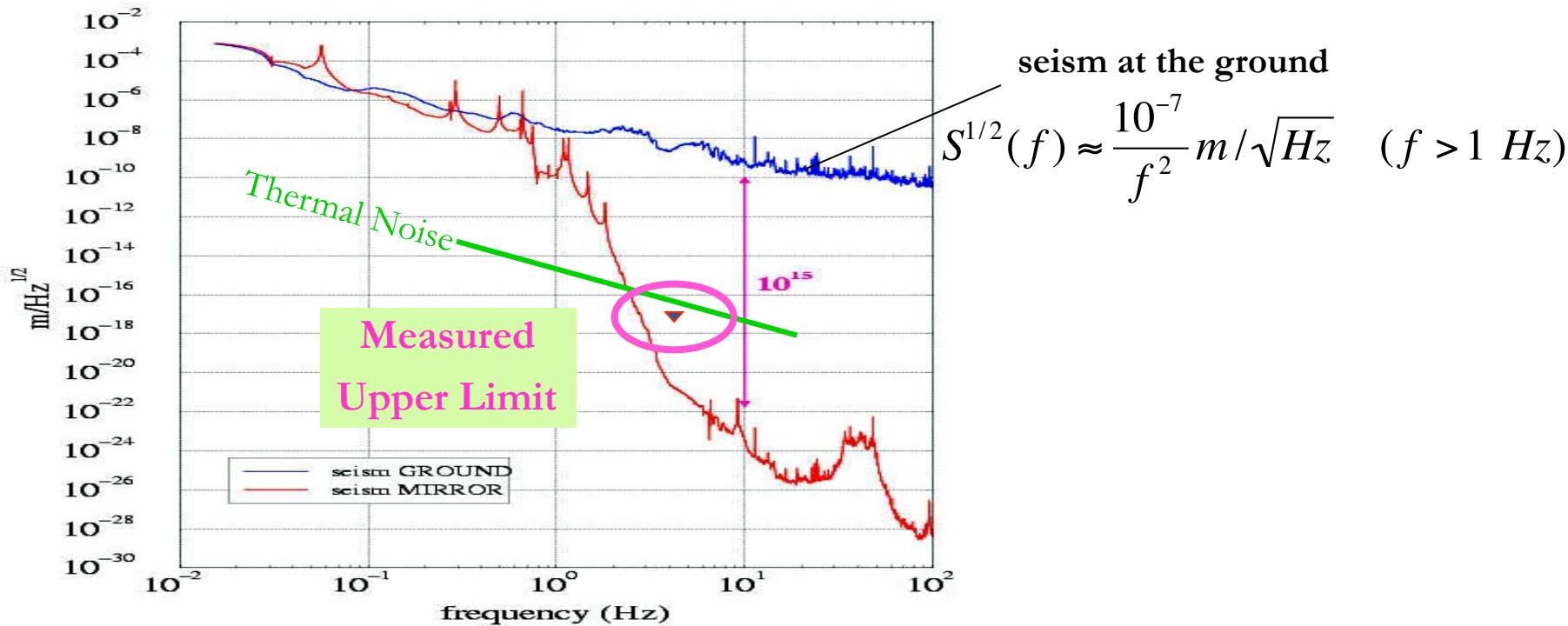
Resonance Crossing
 $\lambda /100$



Longitudinal working point (to be locked)

Ground-based detection: control system is needed

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

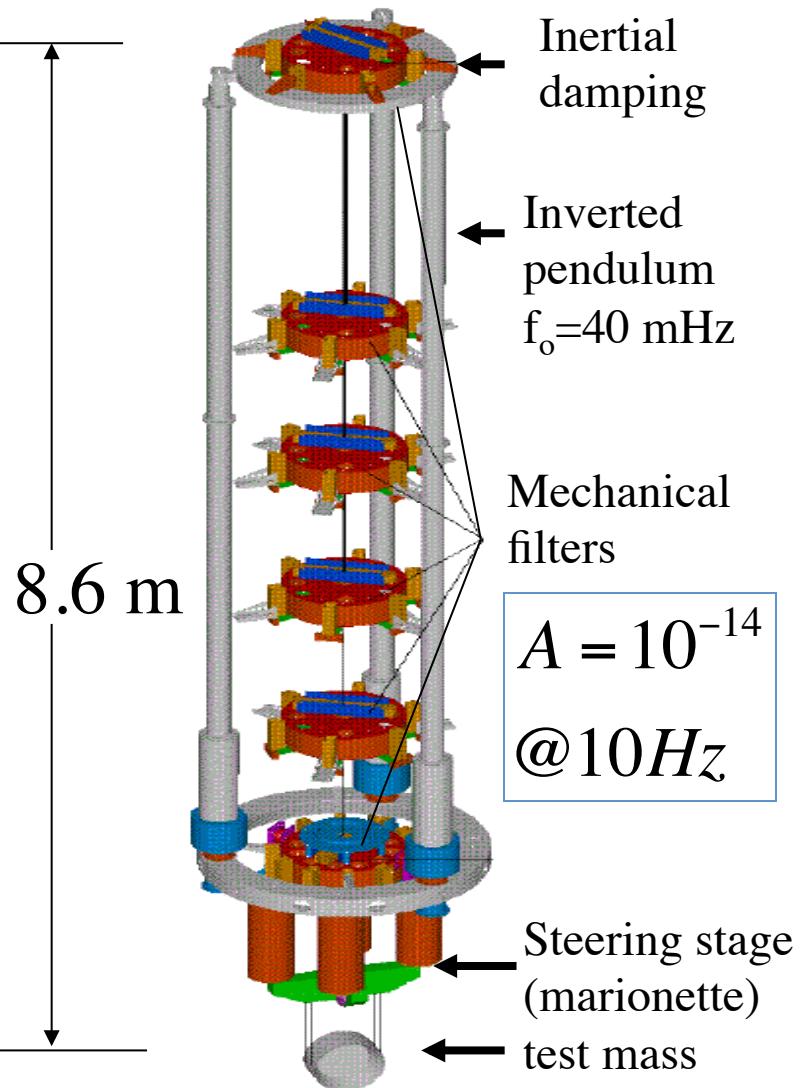


- The SA filters off the seismic noise above 4 Hz
- Below 4 Hz the mirror moves at the SA resonances few tens of mm
- ITF locking requires resonance damping

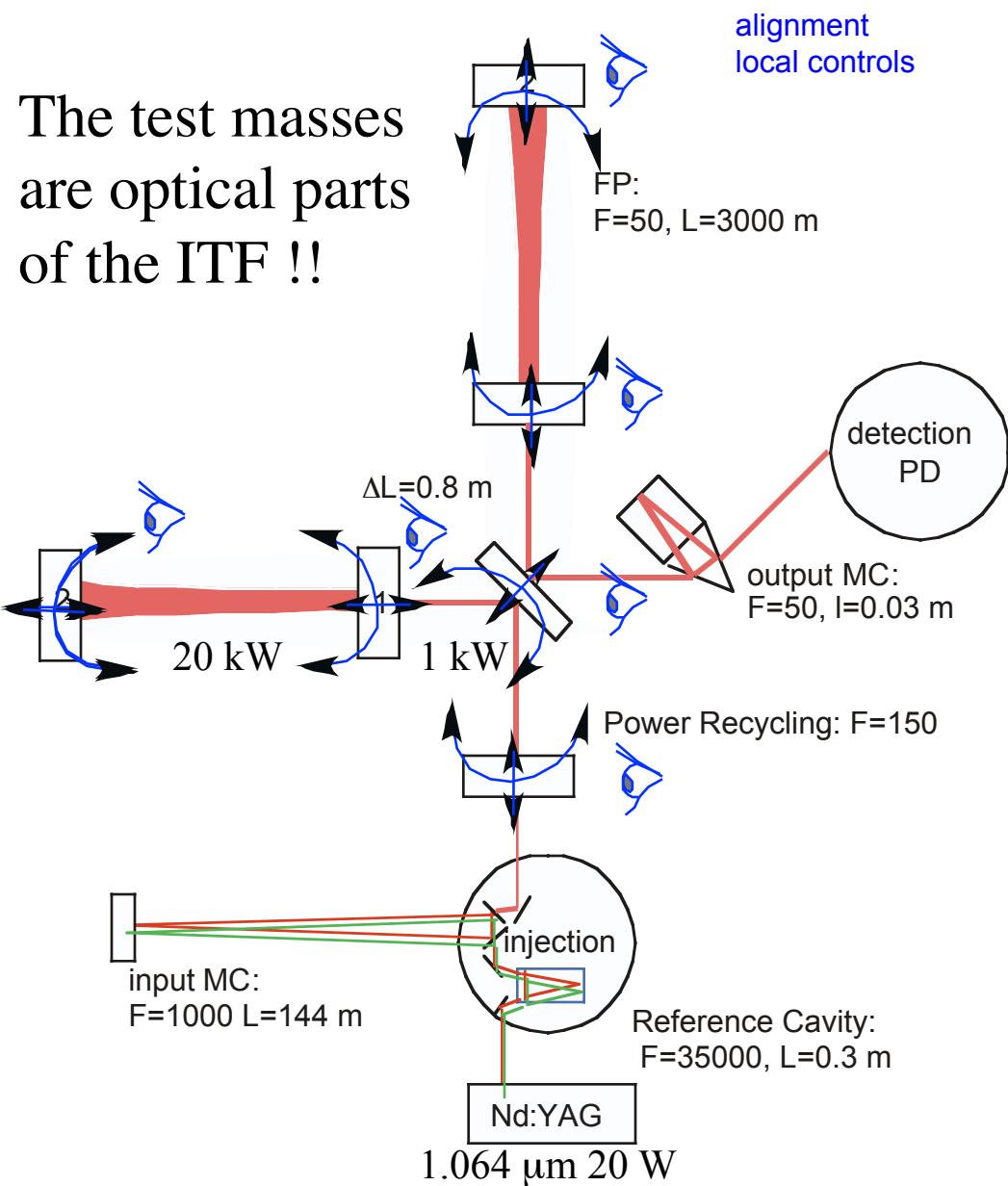
TOP: Sophisticated control system for the suspension chain

BOTTOM: Efficient and noiseless payload control

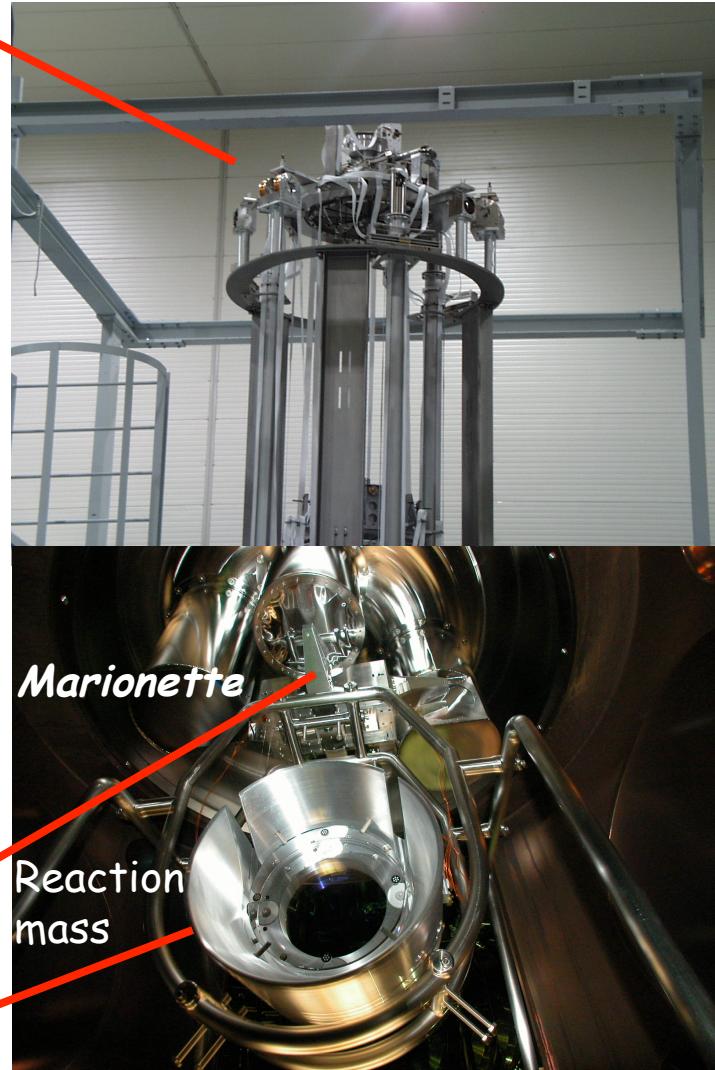
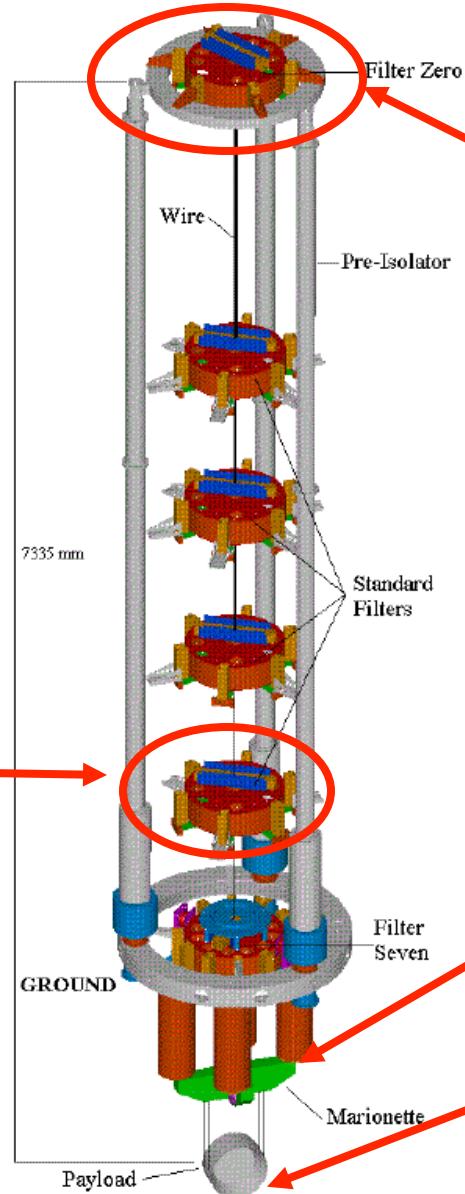
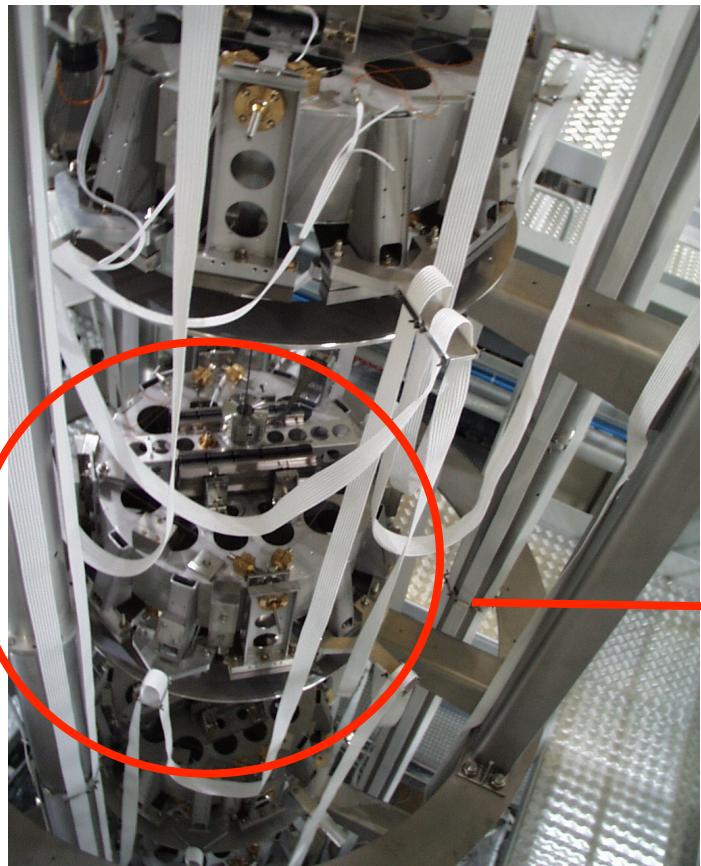
SA



meter

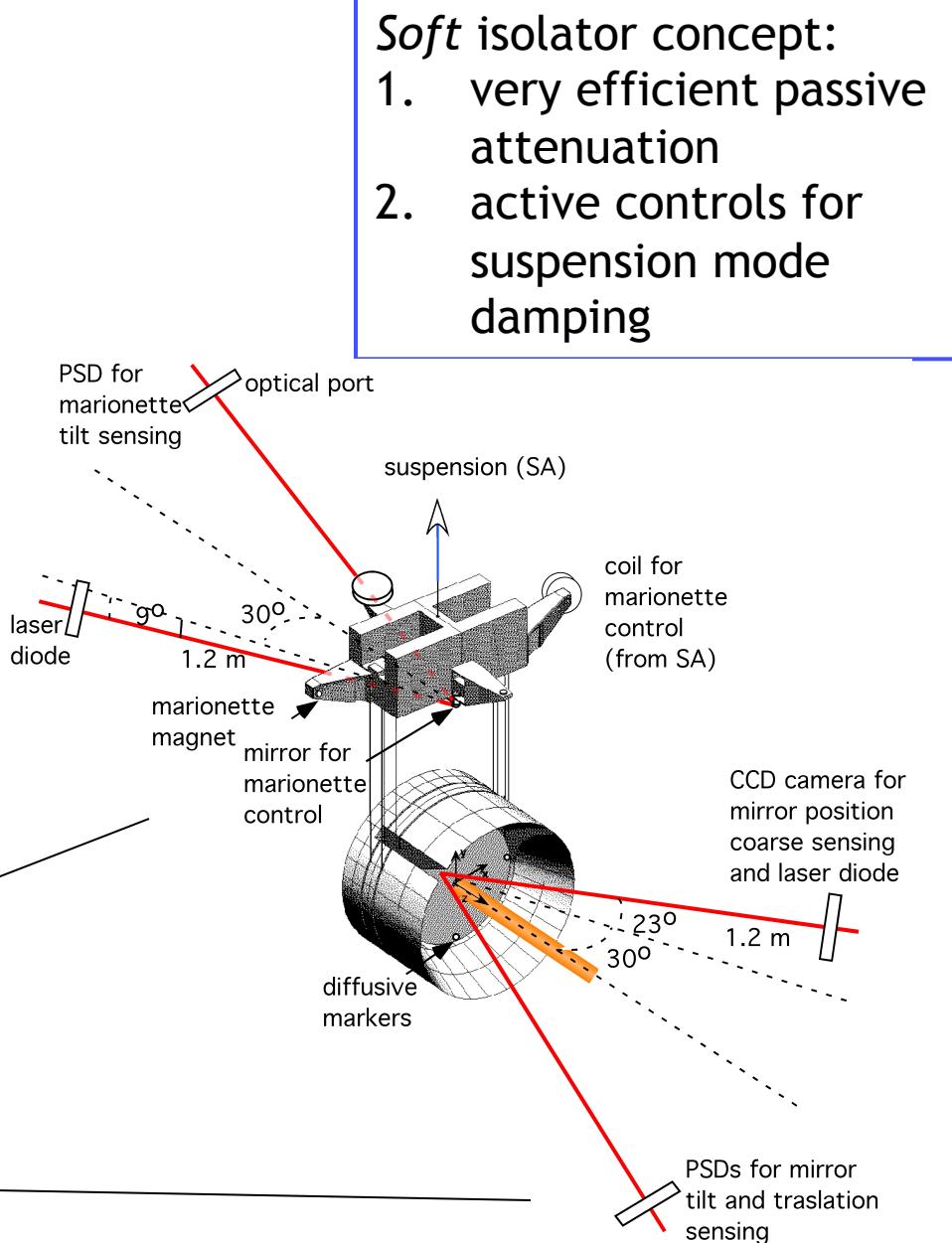
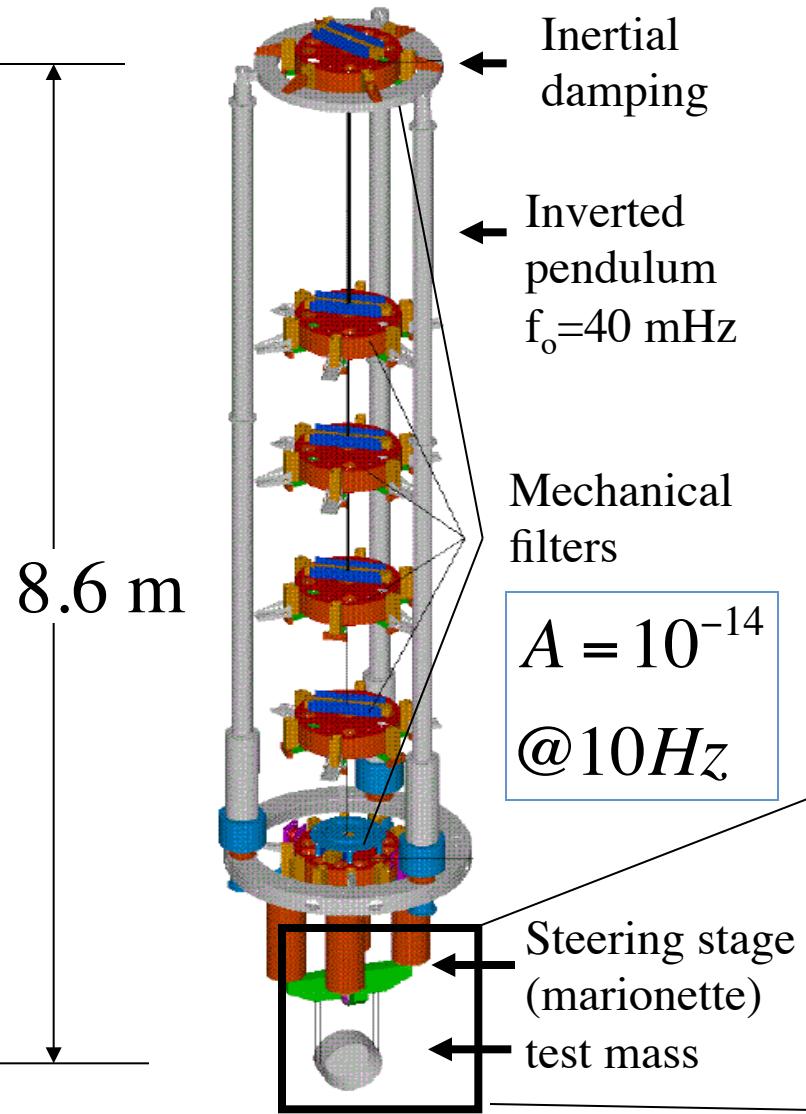


Susp-gallery



At 10 Hz seismic displacement is 10^{12} times larger than expected GW

Virgo “standard-super-attenuator” to allow LF sensitivity



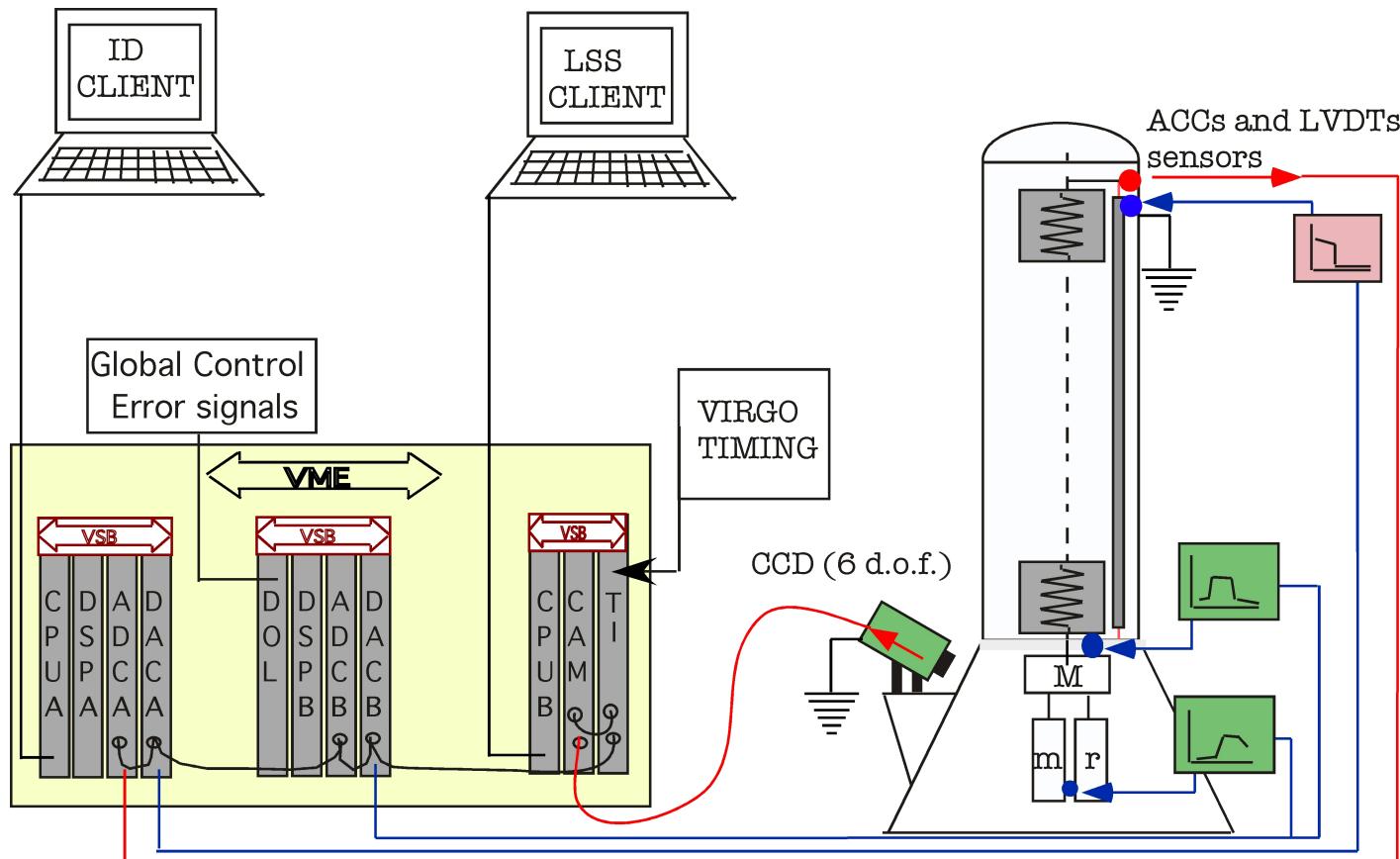
THE CENTRAL AREA



Suspension digital control (9 stations):
~all controls are operated using suspended actuators

I) Local controls apply corrections to mirror position using local sensors: **swinging interference**

II) Local controls receive error signals from global sensors.
ITF Locked, resonant light

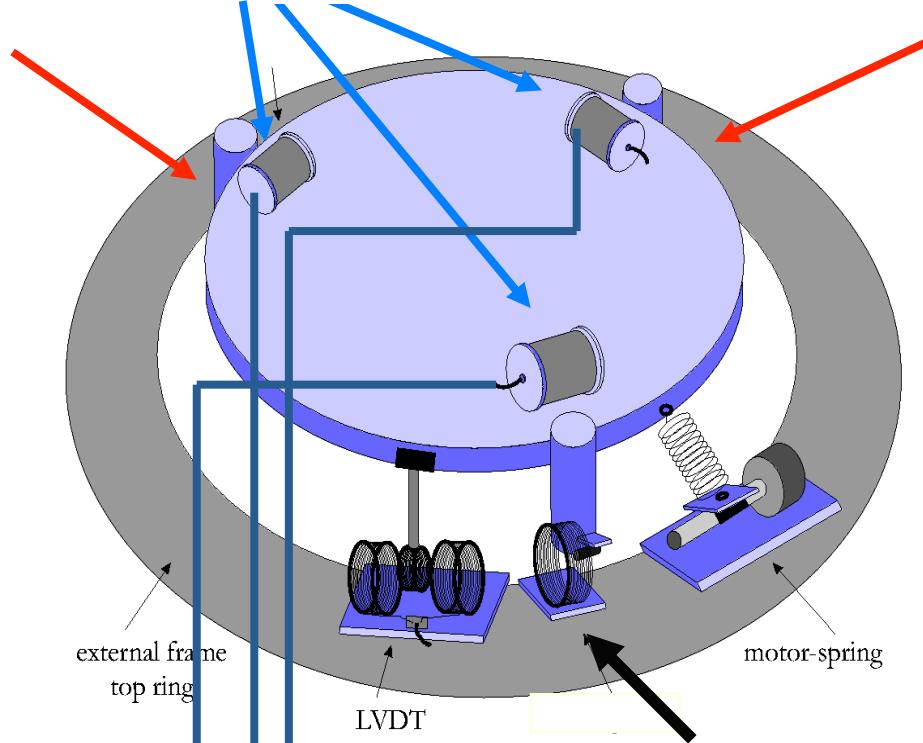


Local Controls: Inertial Damping

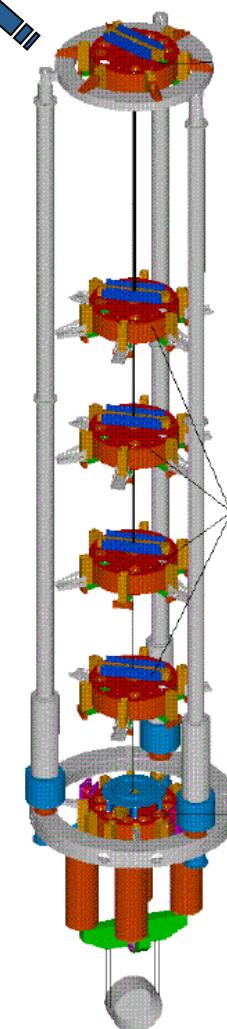
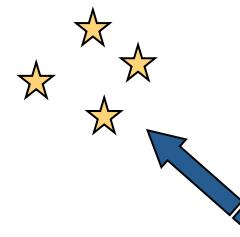
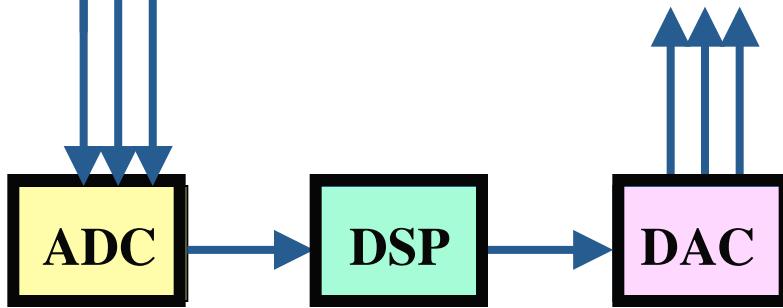
- Inertial sensors (accelerometers):
 - DC-100 Hz bandwidth
 - Equivalent displacement sensitivity: $10^{-11} \text{ m/sqrt(Hz)}$
- Displacement sensors LVDT-like:
 - Used for DC-0.1 Hz control
 - Sensitivity: $10^{-8} \text{ m/sqrt(Hz)}$
 - Linear range: $\pm 2 \text{ cm}$
- Coil magnet actuators:
 - Linear range: $\pm 2 \text{ cm}$
 - 0.5 N for 1 cm displacement
- Loop unity gain frequency:
 - 5 Hz
- Sampling rate:
 - 10 kHz

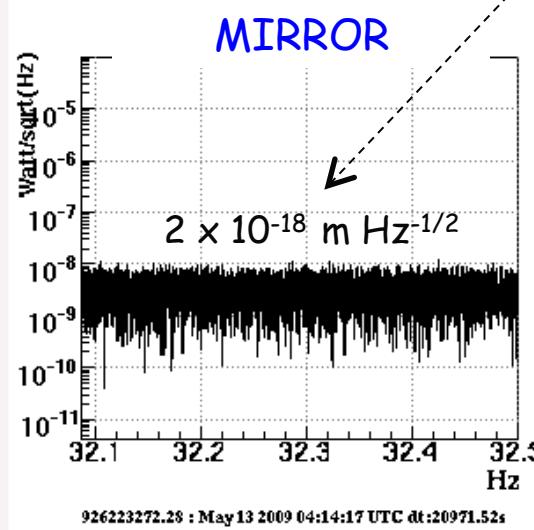
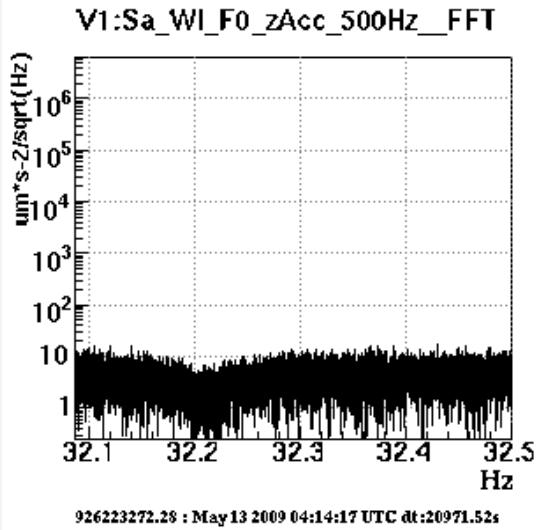
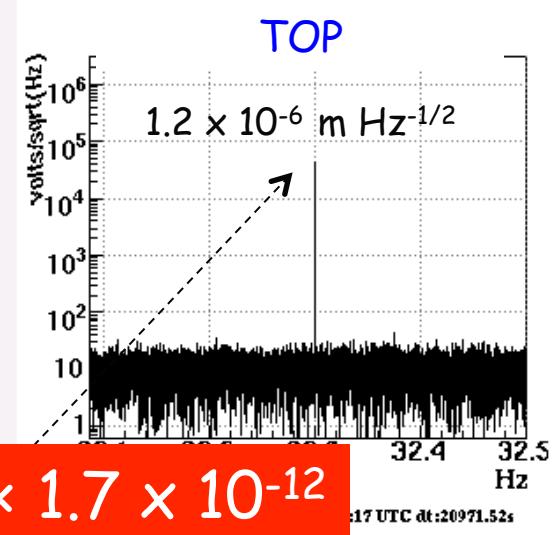
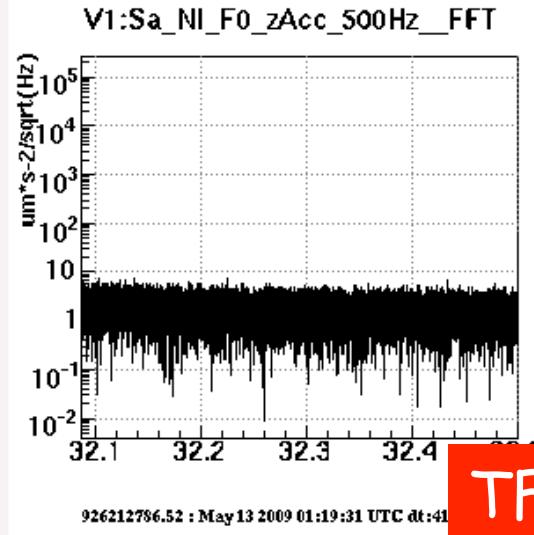
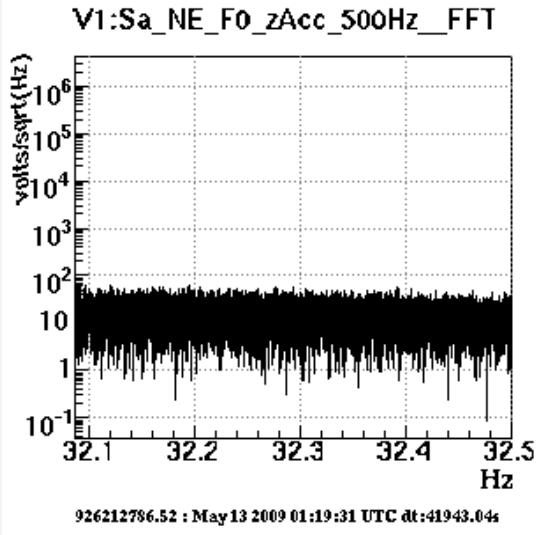


Accelerometers

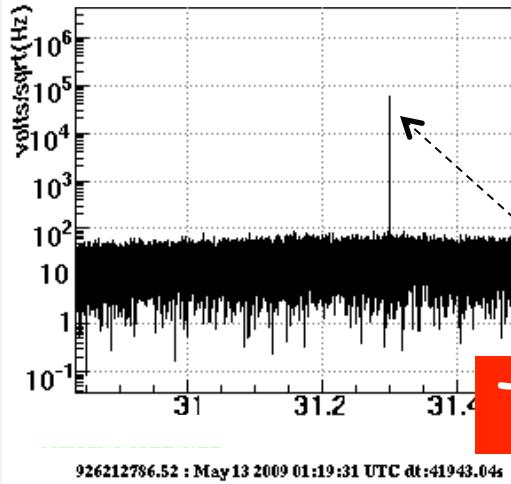


Actuators

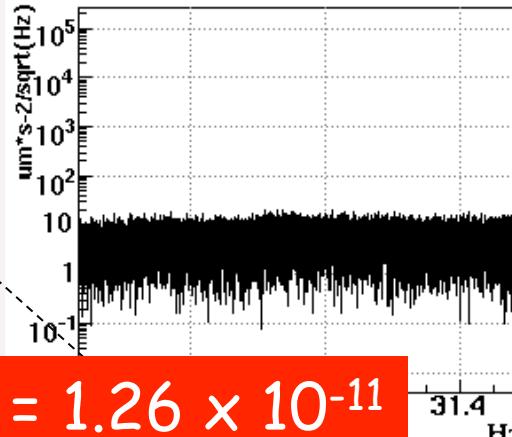




TOP



V1:Sa_NI_F0_zAcc_500Hz_FFT

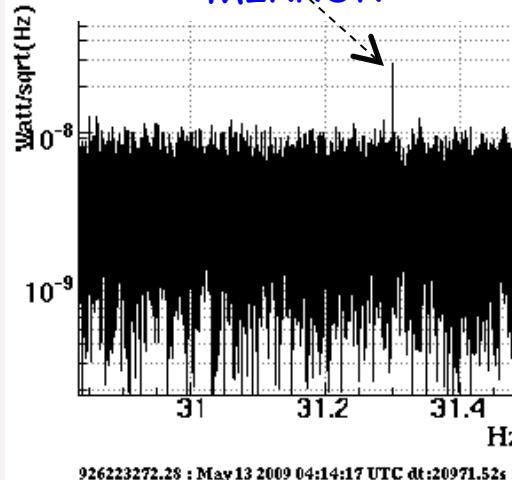
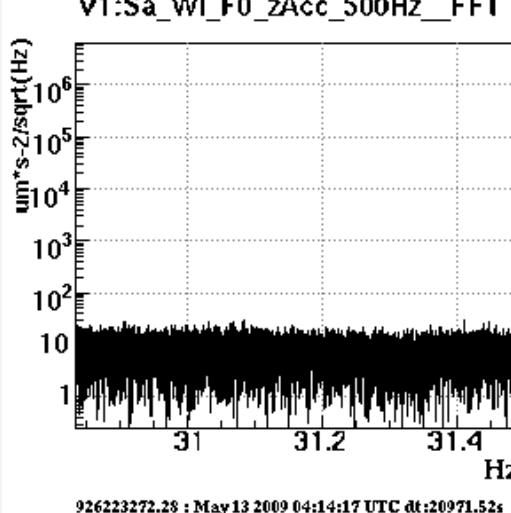


V1:Sa_WE_F0_zAcc_500Hz_FFT

926223272.28 : May 13 2009 04:14:17 UTC dt:20971.52s

$$TF = 1.26 \times 10^{-11}$$

MIRROR



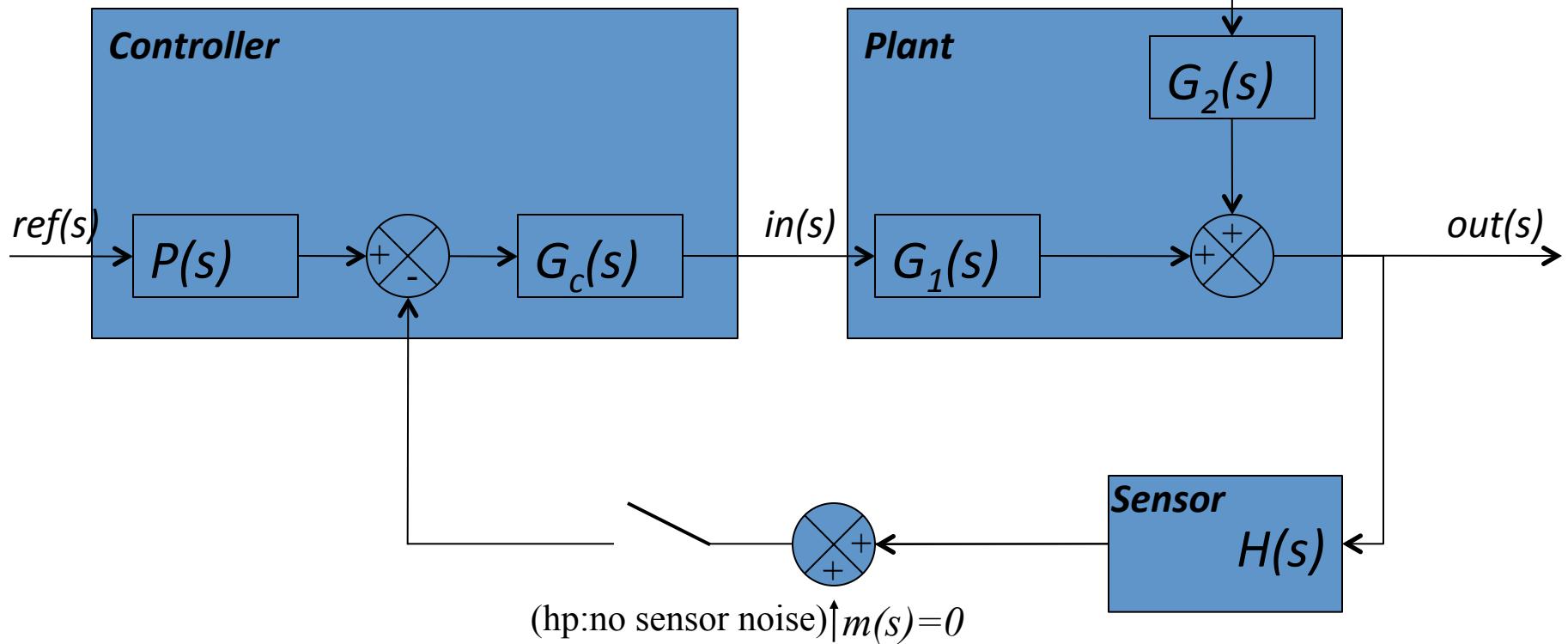
Role of suspension stages and control configuration:

“Divide et impera” means: 1) single point suspension, 2) separation of mechanical DOF, 3) inertial damping, 4) hierarchical control → i.e. only small forces close to test masses.

| | stage | variable | actuator ref |
|--|-------------|--------------------------|-----------------|
| SA: meant to prevent external disturbance | SA TOP | Pos/Accel 3D+yaw | Ground(~)/stars |
| | SA BOTTOM | Position 2D+yaw | Ground |
| Payload: meant to use test masses as optical elements | MARIONETTE | Position 2D+pitch/yaw | SA BOTTOM |
| | REACT. MASS | Position 1D+pitch/yaw | REACT. MASS |

Basic requirements: **sensing and actuation diagonalization**
+
hierarchical control

negative feedback basics (I)



In open-loop we have:

$$out(s) = in(s)G_1(s) + dist(s)G_2(s)$$

In order to deduce the effect of the feedback switch block schematization can be used.

$$out(s) = ref(s) \frac{P(s)}{H(s)} \frac{T(s)}{1+T(s)} + dist(s) G_2(s) \frac{1}{1+T(s)}$$

$$T(s) = G_c(s) G_1(s) H(s) \quad \text{Loop gain}$$

$$\left. \frac{out(s)}{dist(s)} \right|_{in(s)=0} = \frac{G_2(s)}{1+T(s)}$$

In absence of input driving the disturbance transfer function is reduced by increasing the loop gain $T(s)$

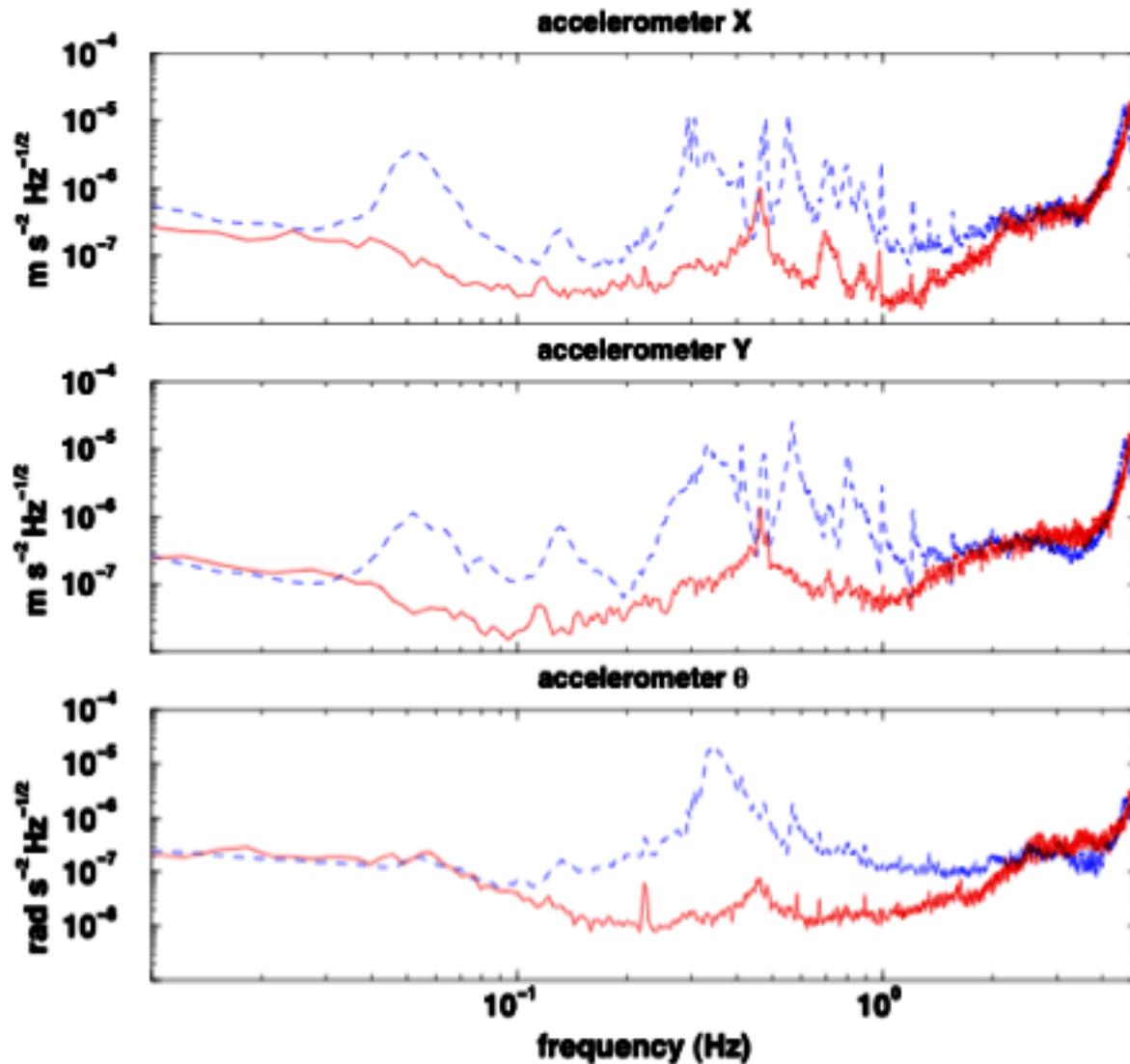
$$\left. \frac{out(s)}{ref(s)} \right|_{dist(s)=0} = \frac{P(s)}{H(s)} \frac{T(s)}{1+T(s)} \approx \frac{P(s)}{H(s)} \quad \left| T(s) \gg 1 \right.$$

The capability to follow the reference with high-gain loops makes the system stuck by $H(s)$

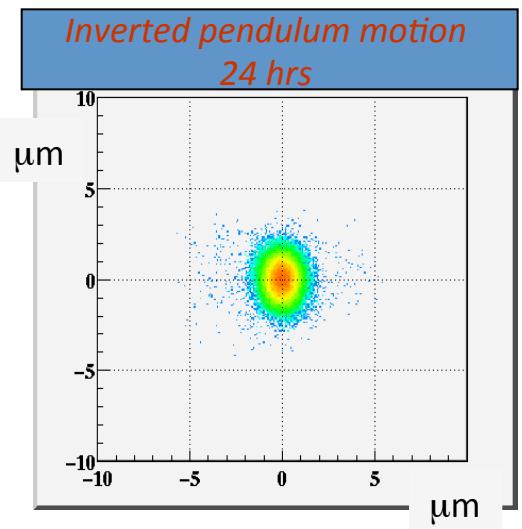
Considering a noise on $H(s)$

$$out(s) = \frac{ref(s)P(s) - m(s)}{H(s)} \frac{T(s)}{1+T(s)} + dist(s) G_2(s) \frac{1}{1+T(s)}$$

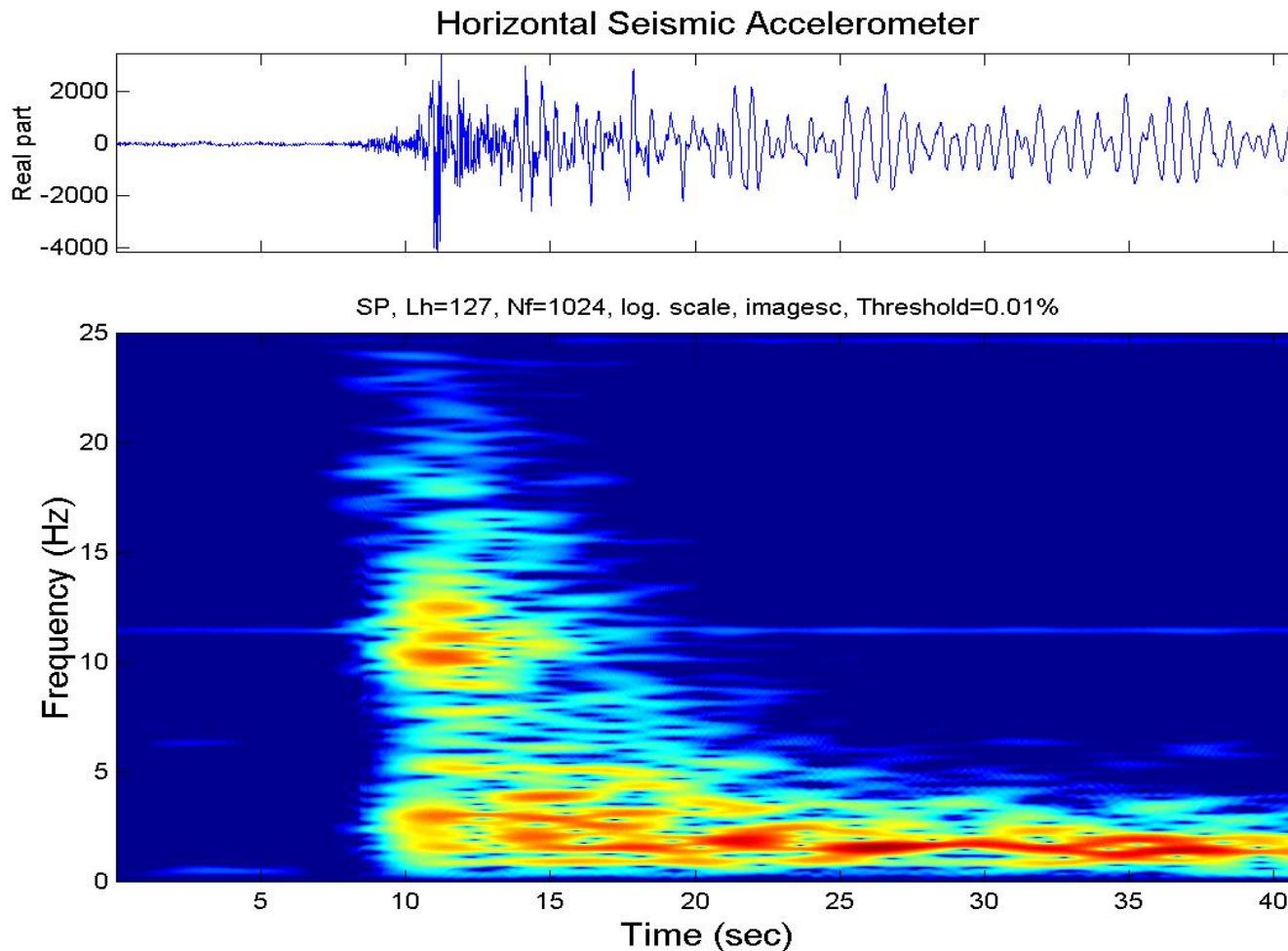
The example of inverted pendulum control



- 1 μm relative displacement
- 0.25 $\mu\text{m/sec}$ relative speed



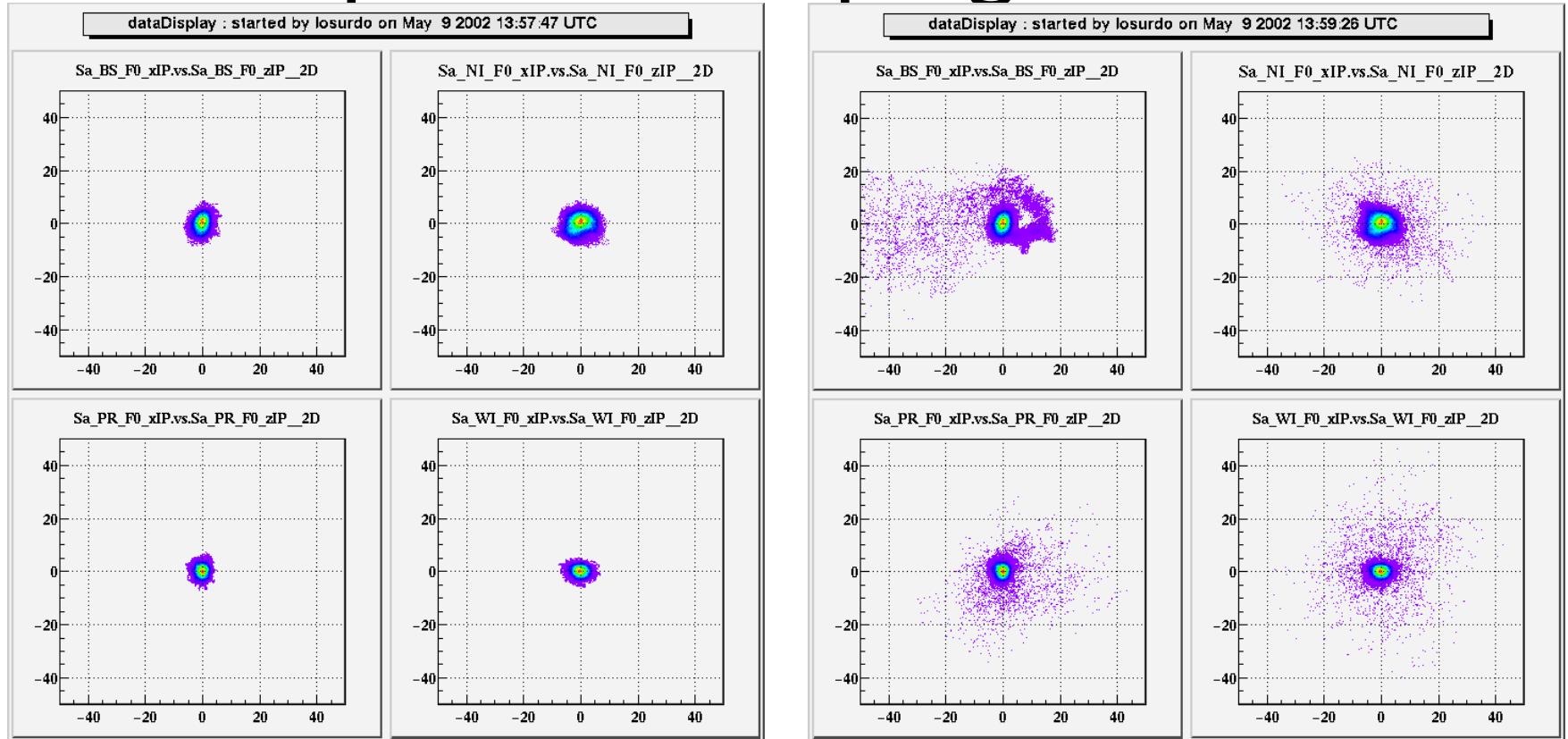
Earthquake detection tests since the beginning
5 May 2002 magnitudo 3.3
Epicenter: Orciano Pisano (~20 Km from VIRGO)



Data elaborated by Lee Holloway at Urbana (II)

EMIPGC170412

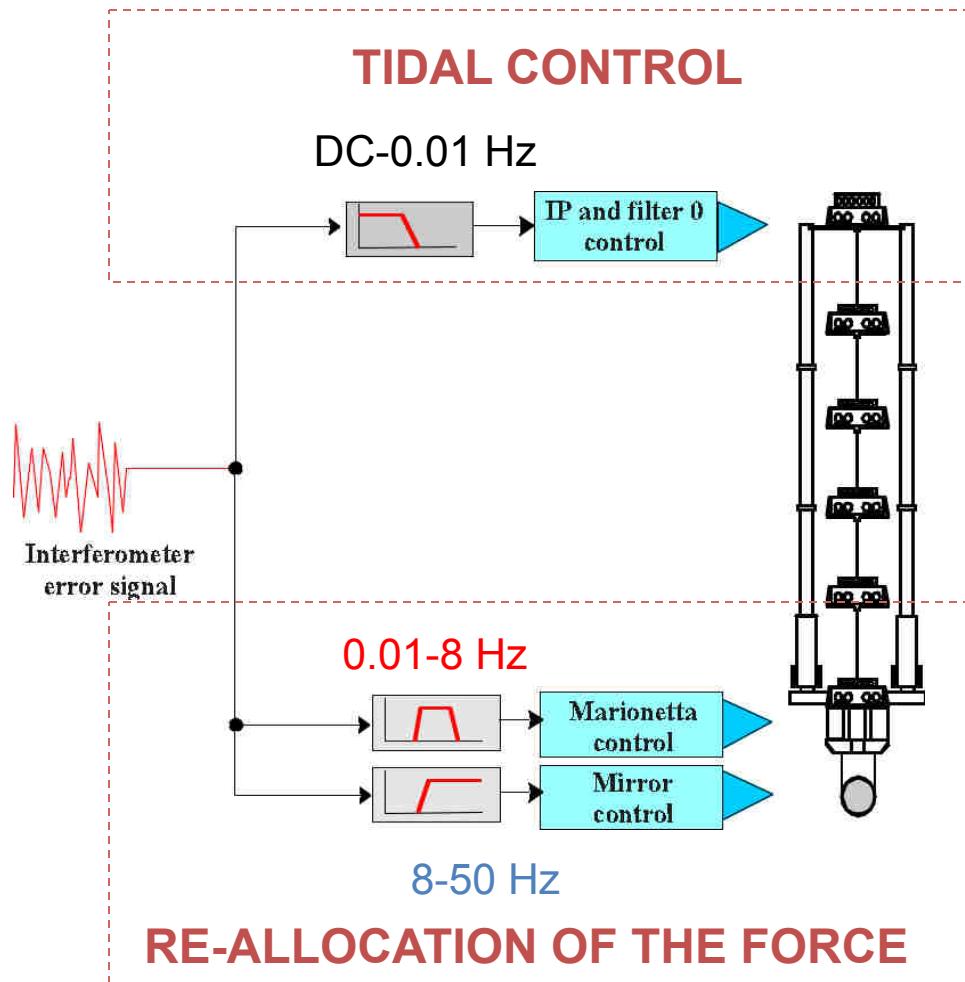
Earthquake: damping robustness



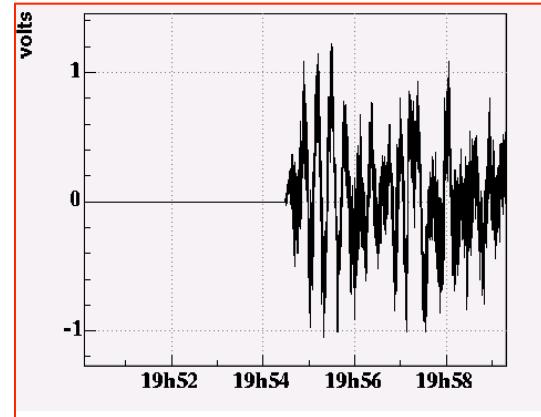
IP displacements relative to the
external frame just before the earthquake

IP displacements relative to the
external frame during the earthquake

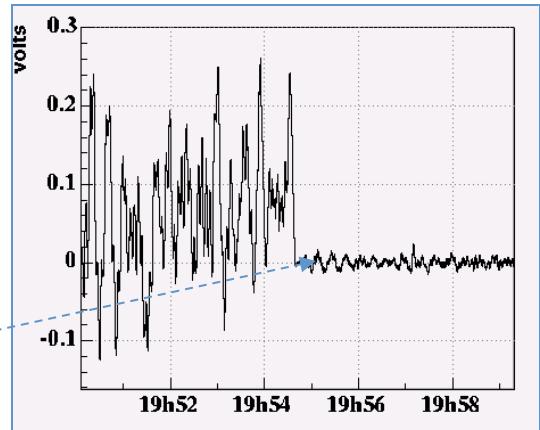
Actuation on the test masses: Local hierarchical control



Corrections sent to the Marionette coil/magnets



Corrections sent to the mirror coil/magnets



Magnetic actuation force on the mirror reduced
Switch to low noise coil drivers

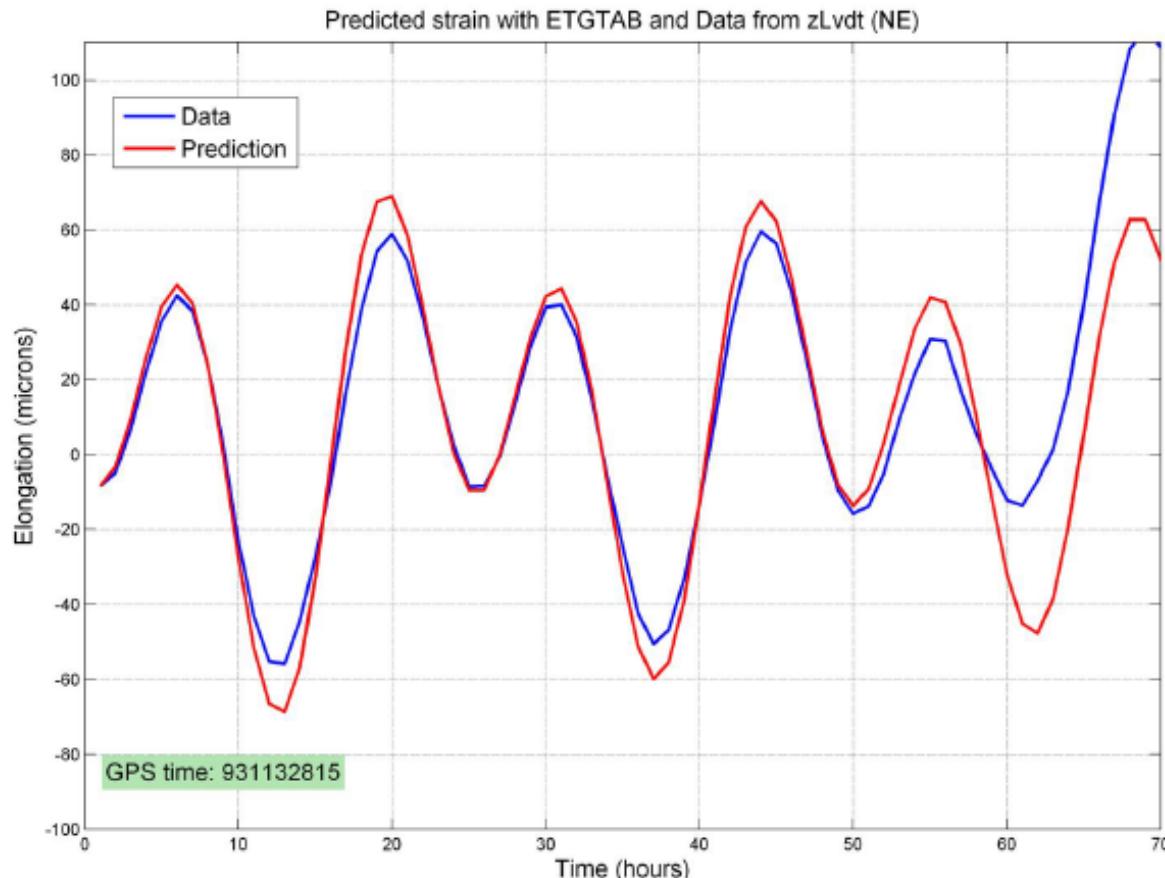
The position seen by the LVDTs of a suspension top stage driven by the lock monitor (V. N. Rudenko's talk).

Simulation results using ETGTAB prediction (1)

- Prediction and Lvdt Data from North arm

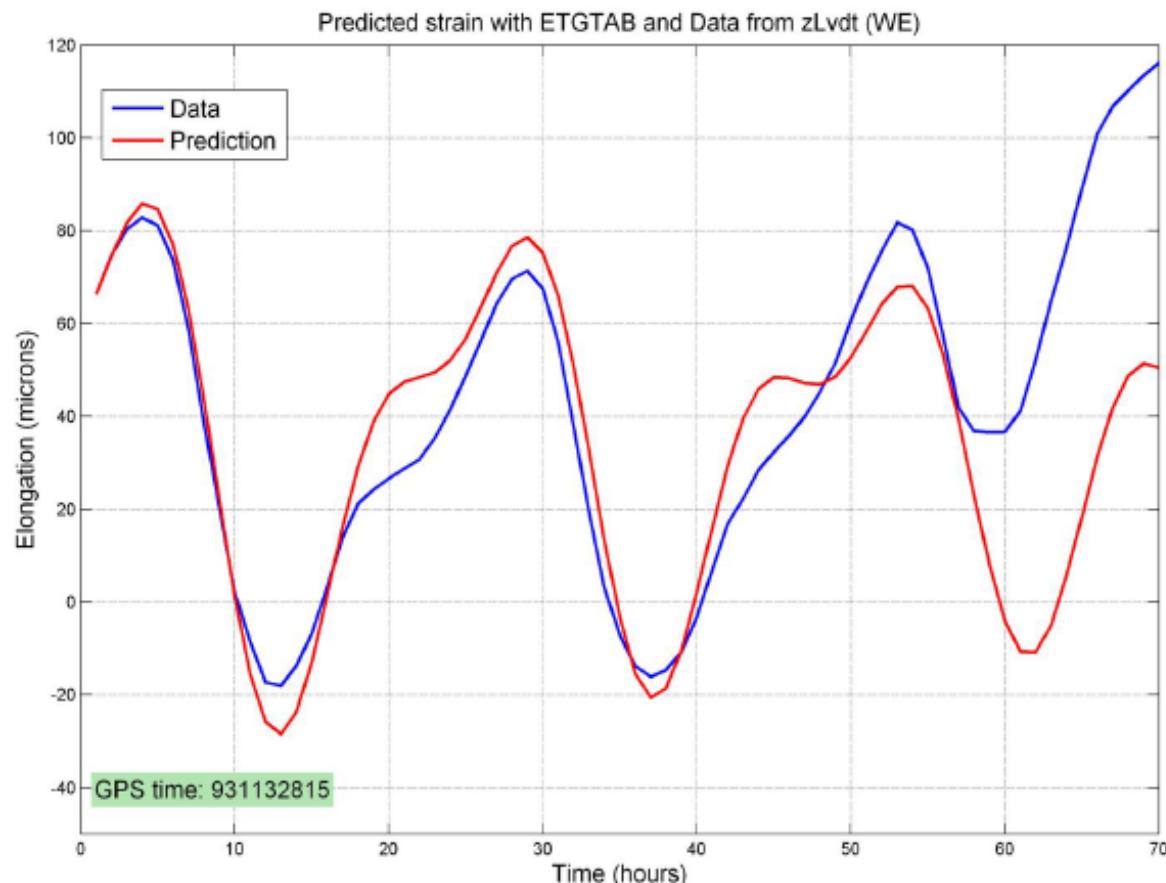
I)
Long
operation is
needed to do
tide FFT

II)
Deformation
drifts are
caused by
many
overlapped
effects



Simulation results (2)

- Prediction and Lvdt Data from West arm



Use of the strain prediction

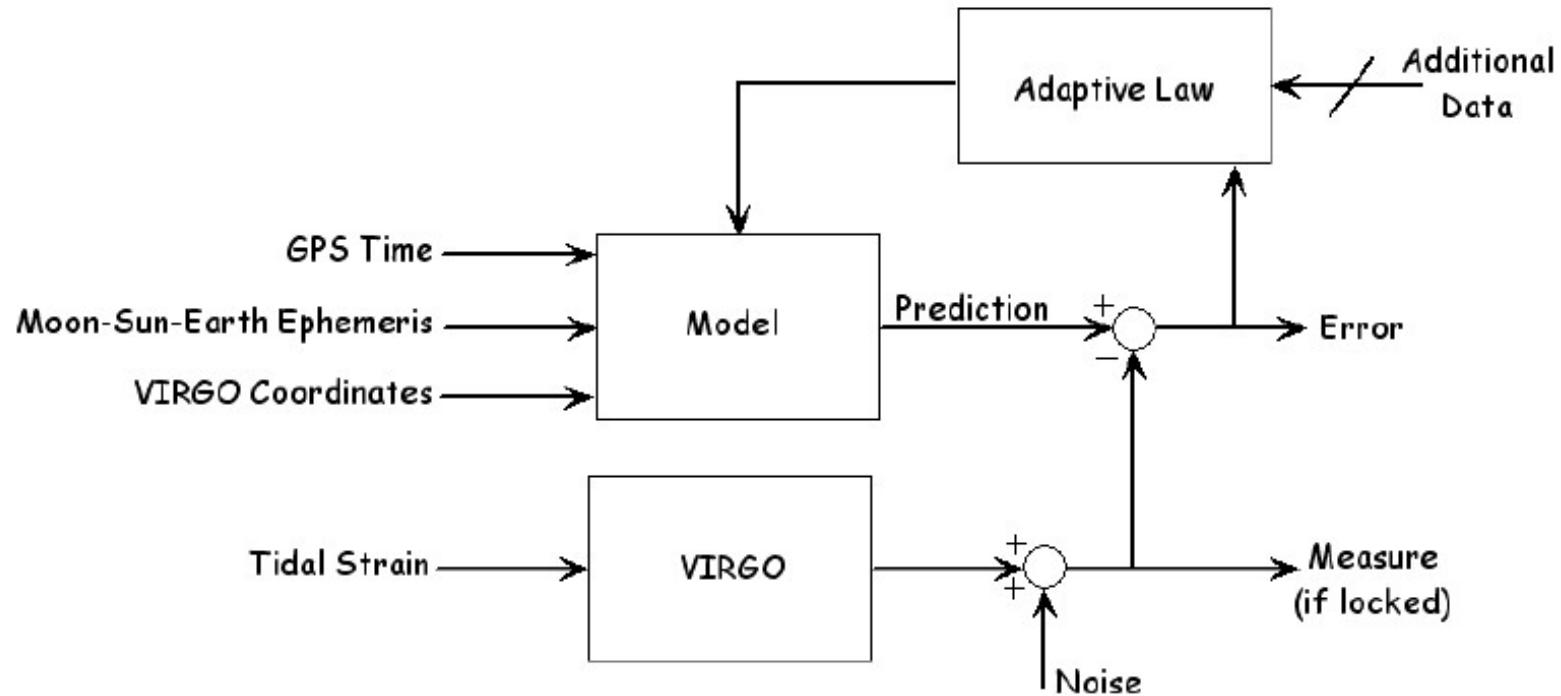
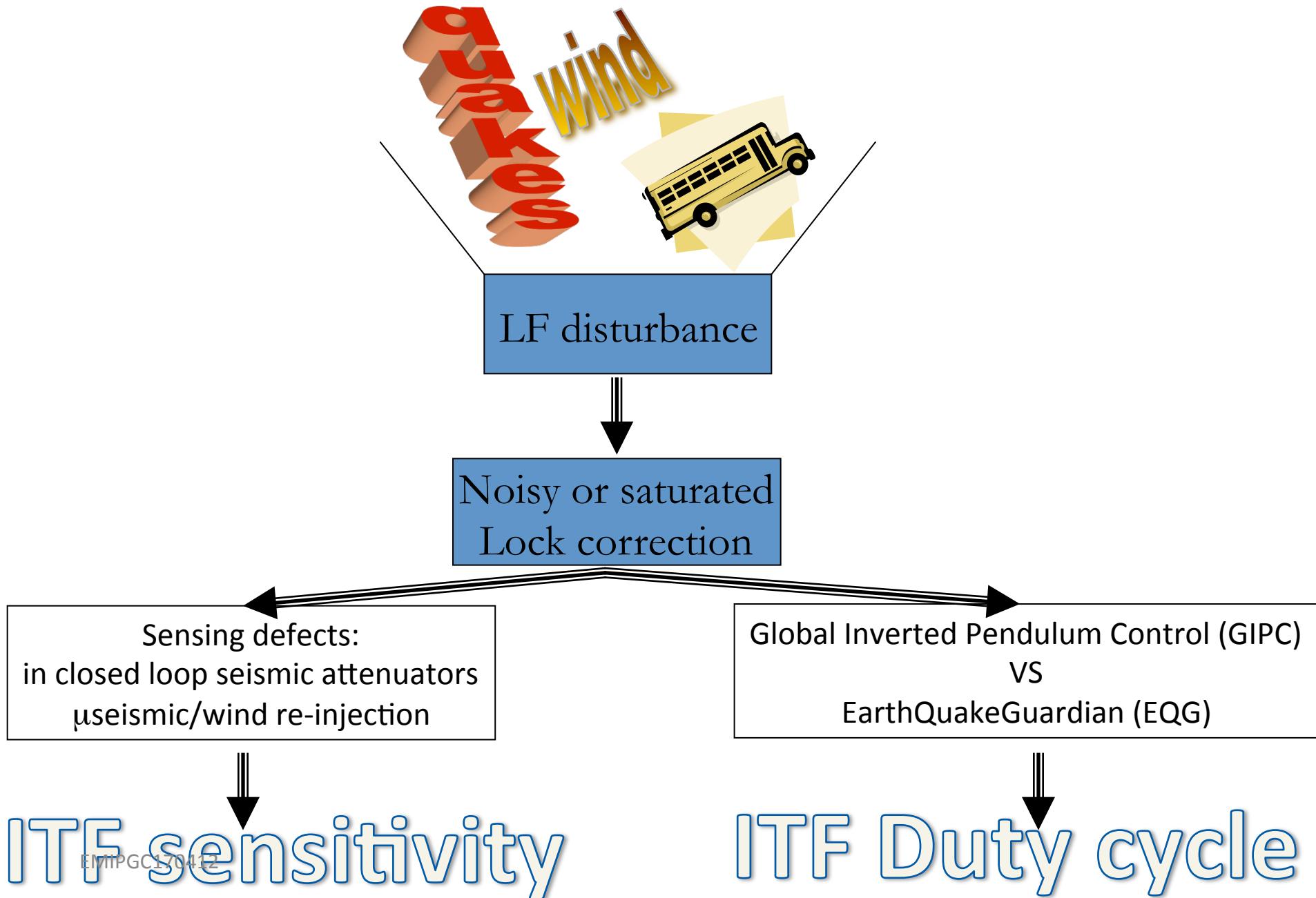


Figure: Strain prediction system scheme

Suspension dedicated work :
further “cost”
of LF sensitivity demand

Mirror-Suspension Control (MSC): enjoying the practice of digital control





Sensing defects:
in closed loop seismic attenuators

useismic/wind re-injection

Position/Acceleration pre-filtering and blending for top-stage control

$$LP(s) \cdot (x - x_s) + s^{-2} \cdot HP(s) \cdot a_x = x_{qi}$$

x, a_x = position and acceleration Laplace's Tr.
 x_s = seism driven sensor reference
 qi = "quasi-inertial"

$$LP(s) + HP(s) = 1$$

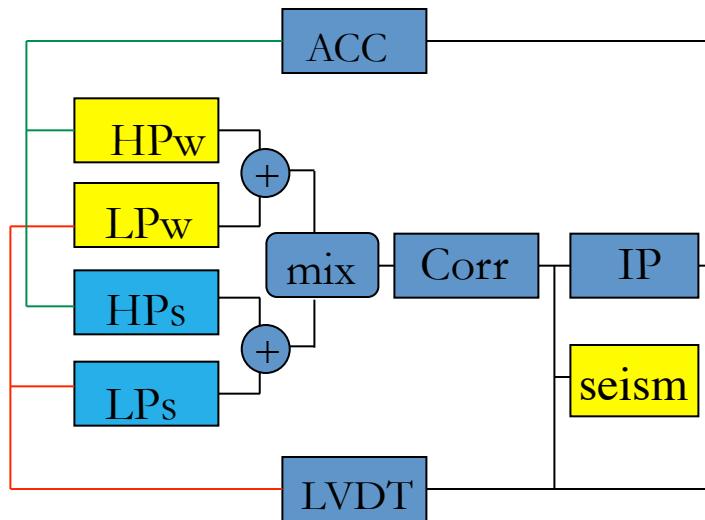
$$x_{qi} = x - LP(s) \cdot x_s$$

Increase LP(s) slope

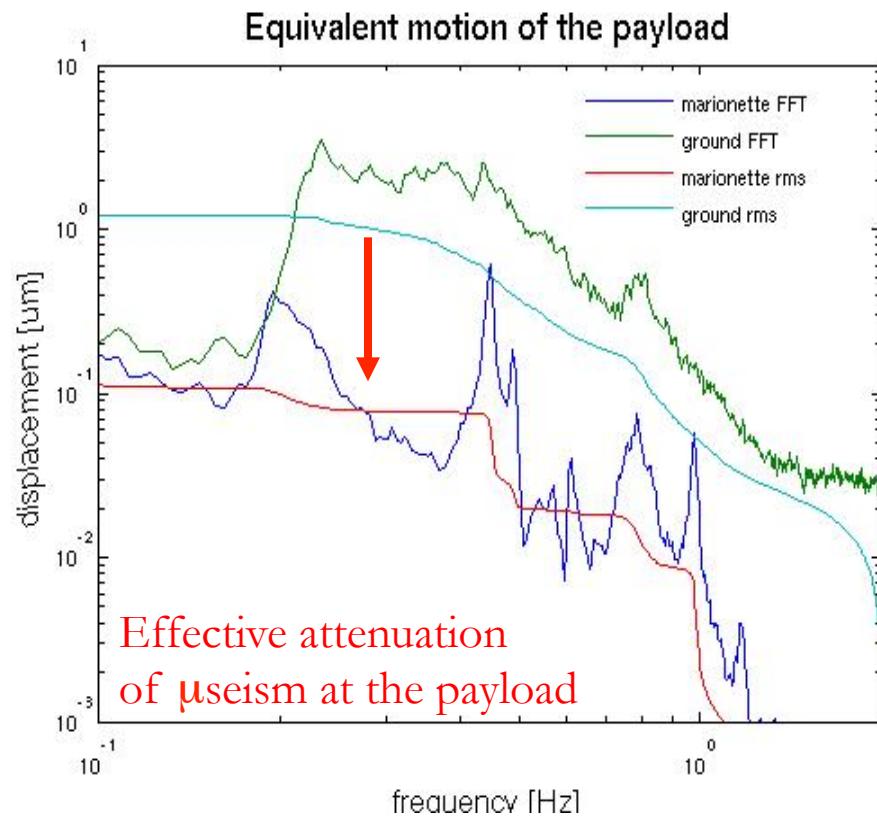
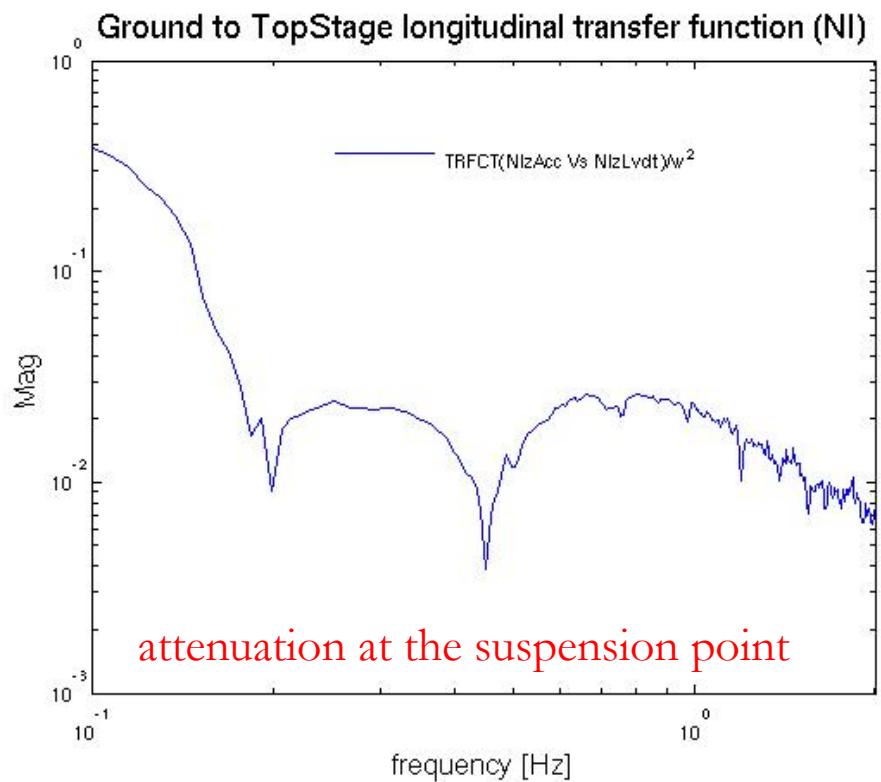
Reduce Position/Acc crossover frequency

"Reduce" x_s

on-fly tuning using two different blending filters (digital)



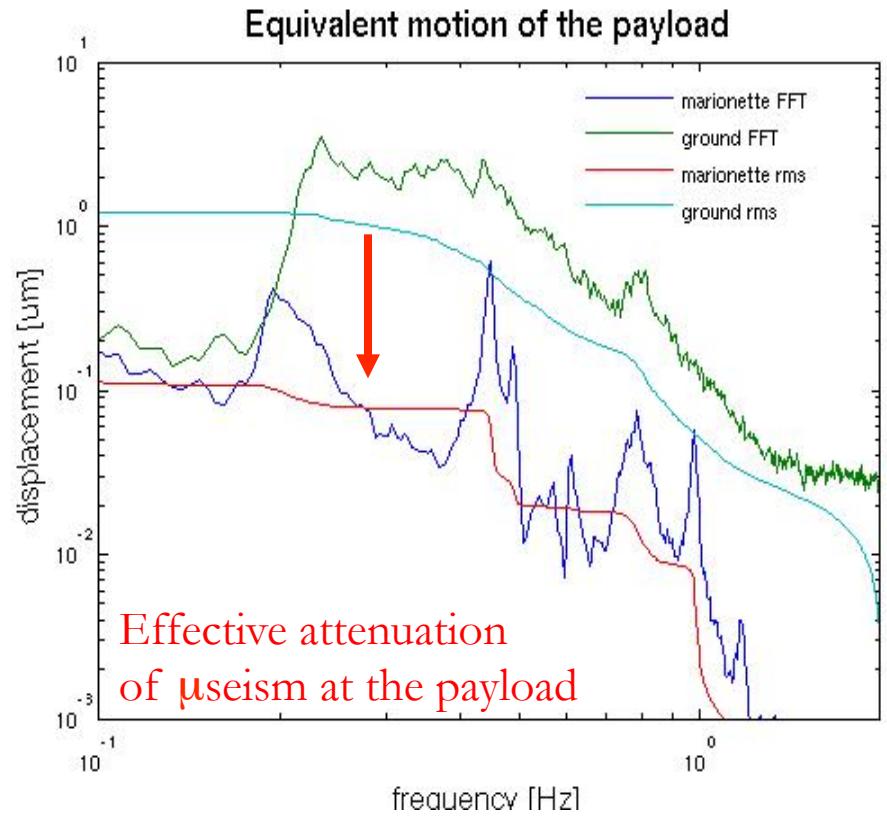
μ Seism disturbance attenuated downstream (=>the concept of Global Inverted Pendulum Control)



ITF lock force applied to the marionette is used to correct the residual payload motion, whose rms above 100 mHz is ~ 1 order of magnitude smaller than the ground motion.

μ Seism disturbance attenuated downstream (=>the concept of Global Inverted Pendulum Control)

The reconstruction provides an answer to the question:
what would be the payload (test-mass) displacement due to sea μ seism without SuperAttenuator ?



Controlling IP using passively isolated test-mass as reference position is a method to reduce the impact of seismic re-injection through LVDT sensors placed at the top-stage, i.e.

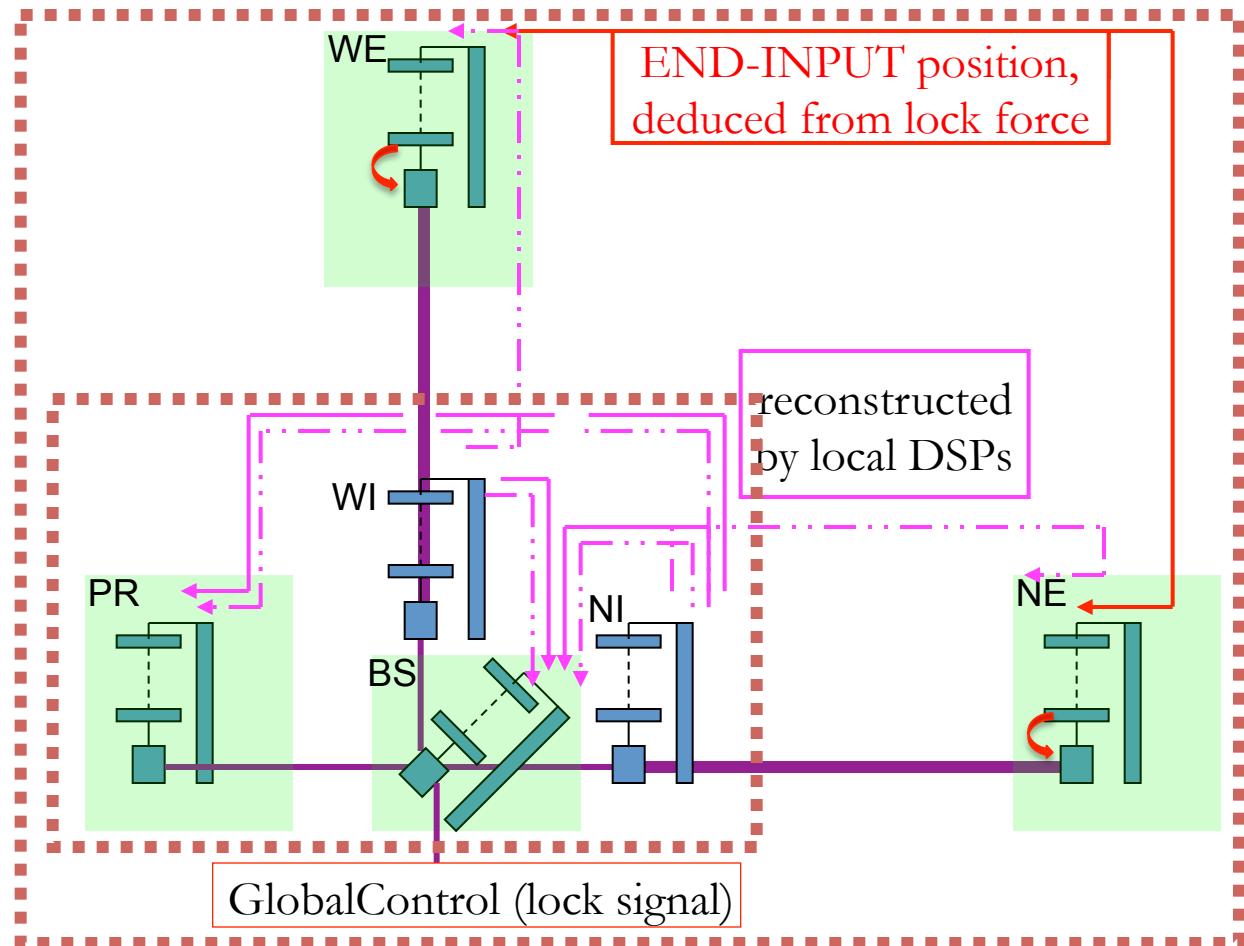
- safe increase cross-over between position/acceleration sensing
- evasion of tilt re-injection through accelerometers at LF

μ Seism-Free platform: Global Inverted Pendulum Control

μ seism is **incoherent** along the arm baseline
 $\Rightarrow \mu$ Seism reduced at **END suspension top-stages** by using position referred to

also the acceleration is recombined \rightarrow OK

μ seism is **coherent** in the central area
 μ Seism-Free control signals reconstructed with respect to **INPUT mirrors (μ SF)**

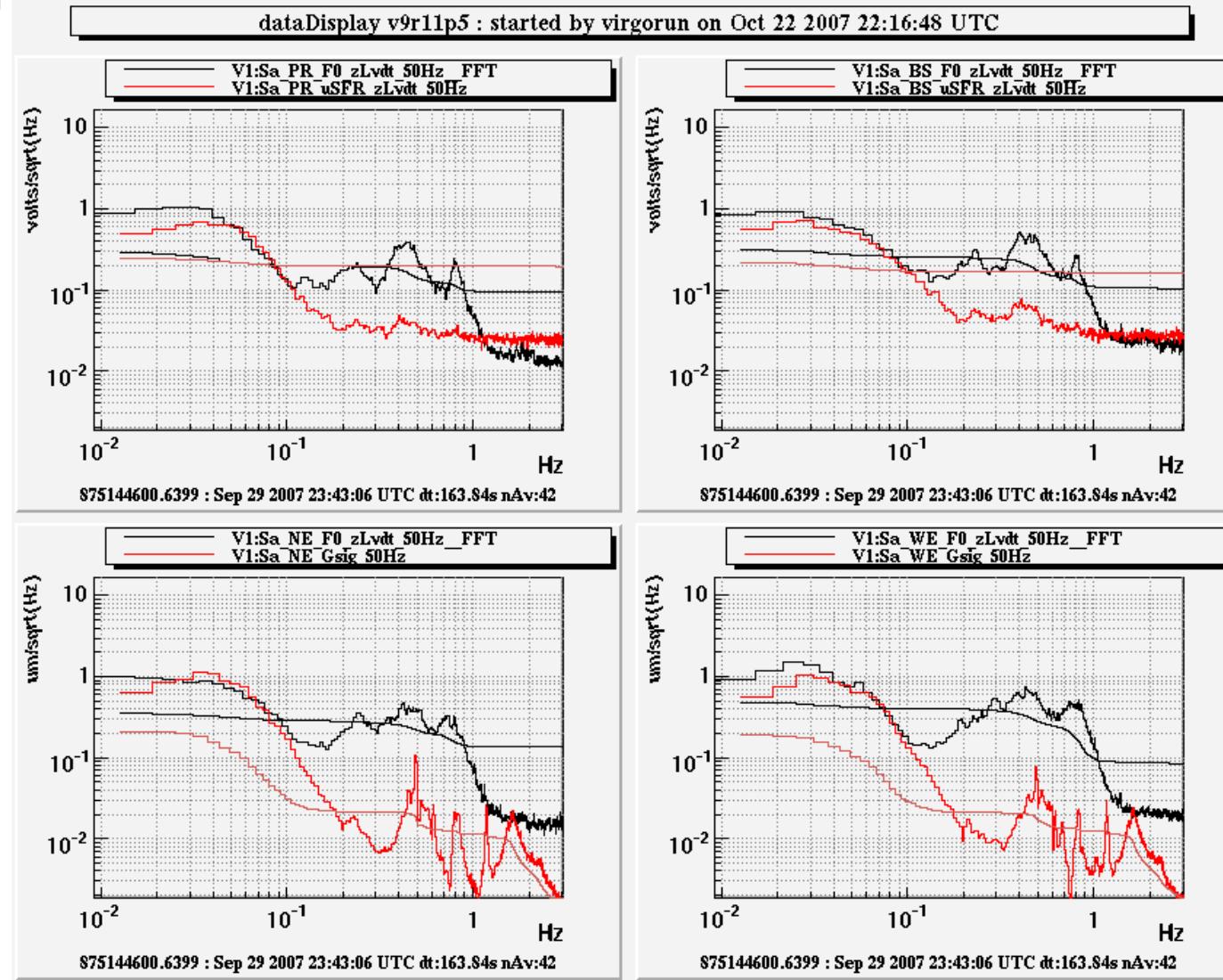


INPUT TOWERS USED AS REFERENCE

μ Seism evasion strategy: an example



INPUT mirror suspensions used as reference

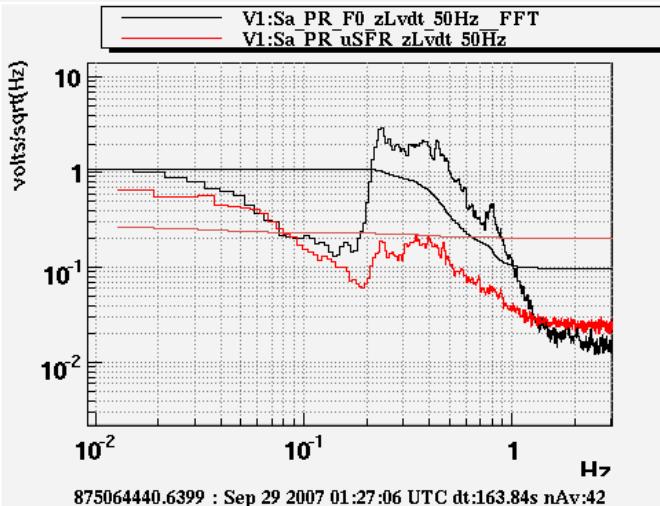


μ seism: rejection VSR1start-VSR1stop

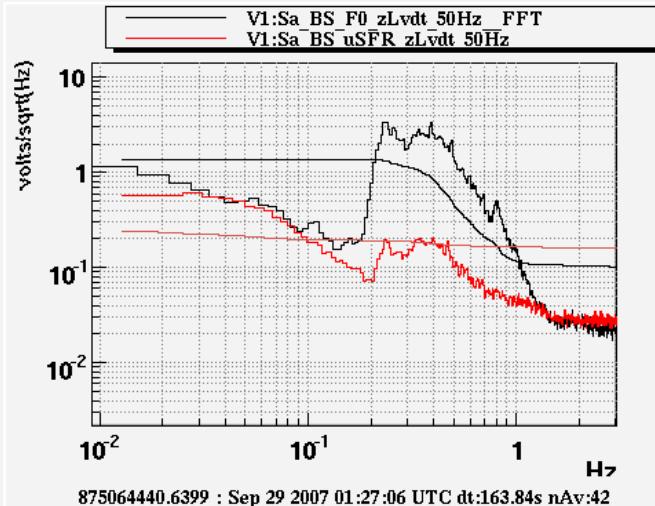
sea

INPUT mirror suspensions used as reference

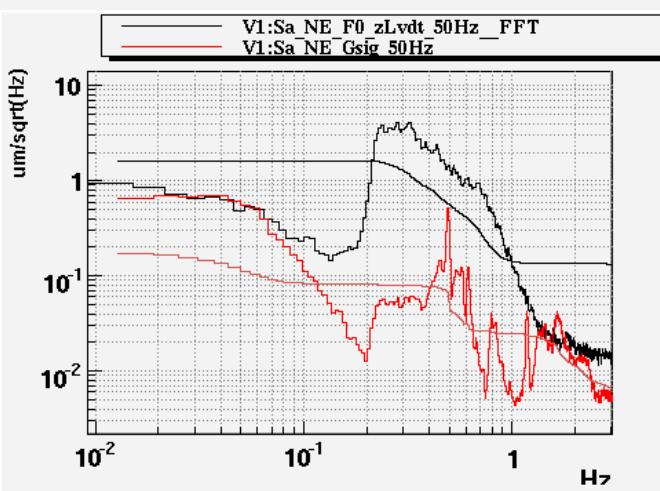
dataDisplay v9r11p4 : started by virgorun on Oct 22 2007 15:21:19 UTC



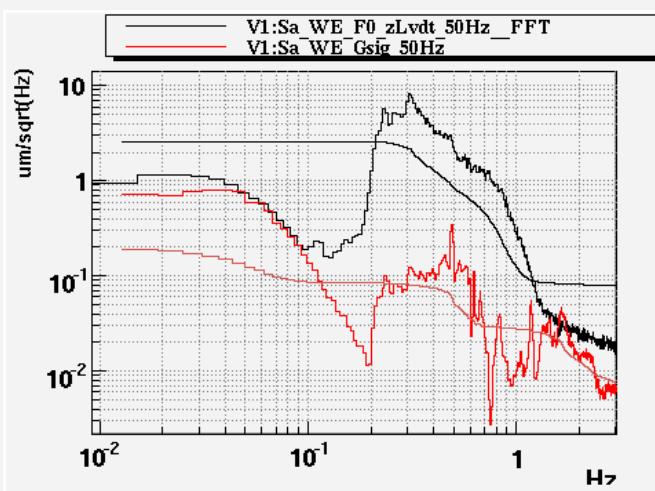
875064440.6399 : Sep 29 2007 01:27:06 UTC dt:163.84s nAv:42



875064440.6399 : Sep 29 2007 01:27:06 UTC dt:163.84s nAv:42



875064440.6399 : Sep 29 2007 01:27:06 UTC dt:163.84s nAv:42



875064440.6399 : Sep 29 2007 01:27:06 UTC dt:163.84s nAv:42

local LVDTs, used in-loop sense and re-inject μ seismic noise

Combined channels:
 μ SFR (μ Seism-Free Reconstruction, the noise is coherent because central area suspensions are close each other)

+

GIPC (Global-Inverted-Pendulum Control, for 3-km-separated susp.)

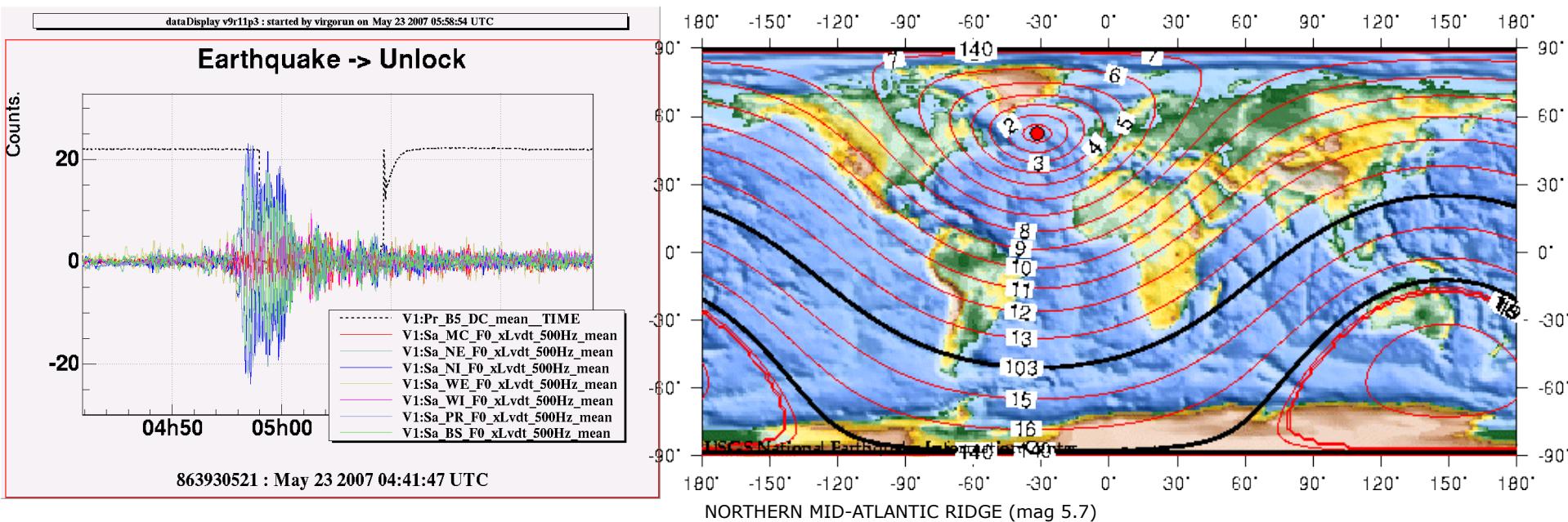


Global Inverted Pendulum Control (GIPC)
VS
EarthQuakeGuardian (EQG)

Before implementing the use of differential acceleration in global IP control, the system was more fragile as waves from far EQ reached the site.

As long as the disturbance is at low frequency and localized, GIPC is very effective (cars, jumping visitors, “bombing”, wind...)

As the disturbance becomes “common” (earthquakes...), non perfect GIPC may play a negative role



This was the trigger point that pushed to develop a more robust interferometer

Earthquake Guardian (EQG) implementation (I), VSR1 (2007)



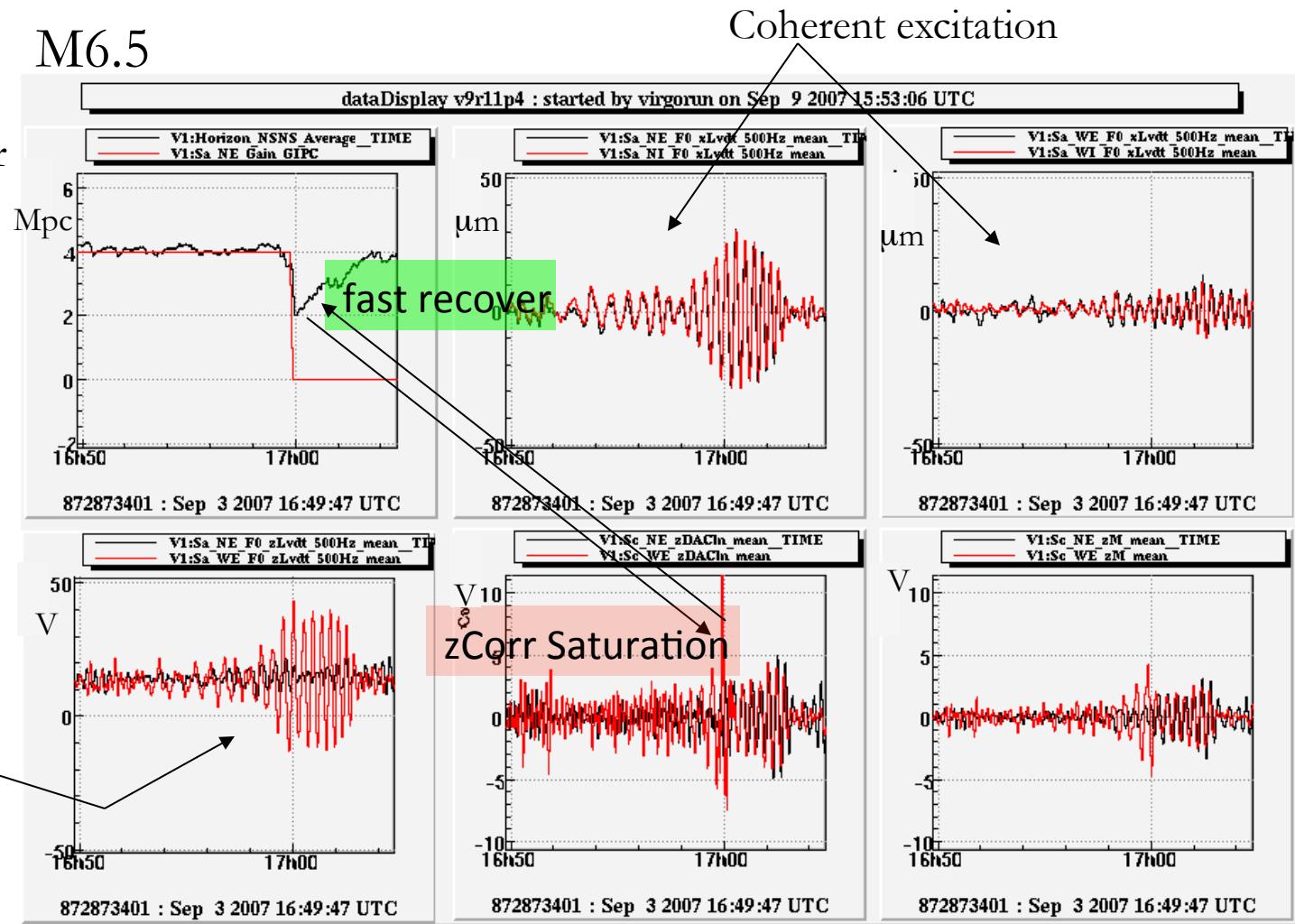
M6.5

GIPC instability during coherent excitation over 3-km base (far EQ)



An automated Guard to disable GIPC: EQG

Top-stage corr. from locking



4-min to recover the lock instead of 30-40 min without EQG

Earthquake Guardian (EQG) implementation (II), VSR1 (2007)

Comparison of two EQ events with similar local amplitude

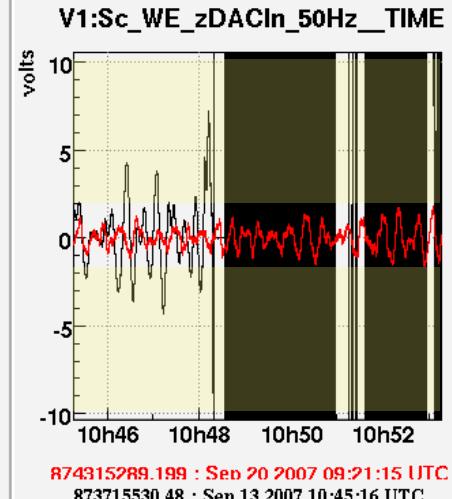
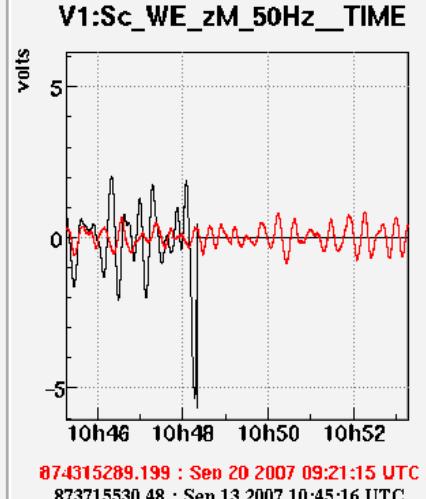
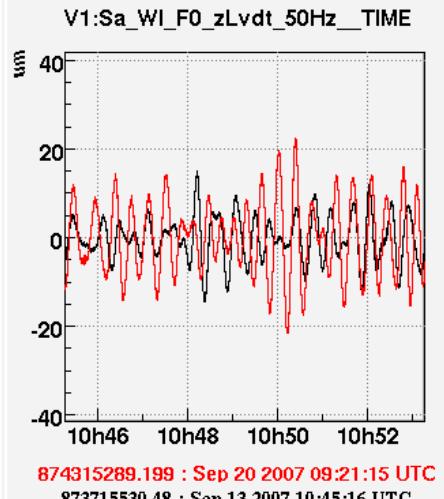
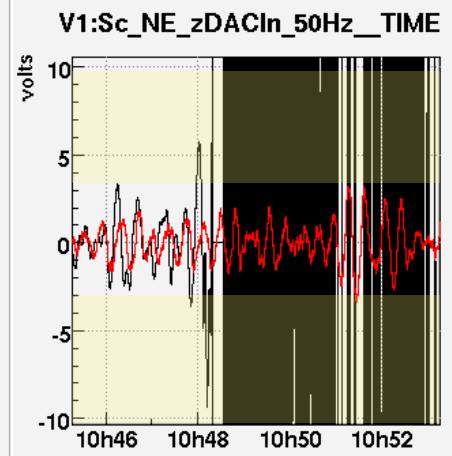
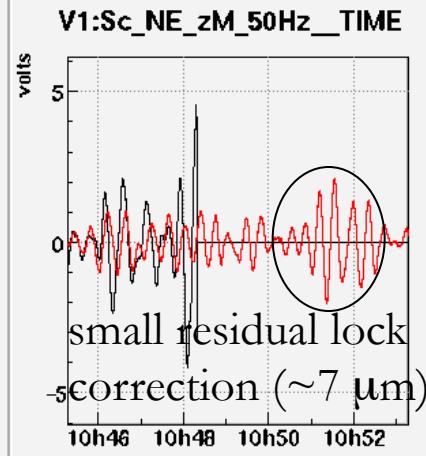
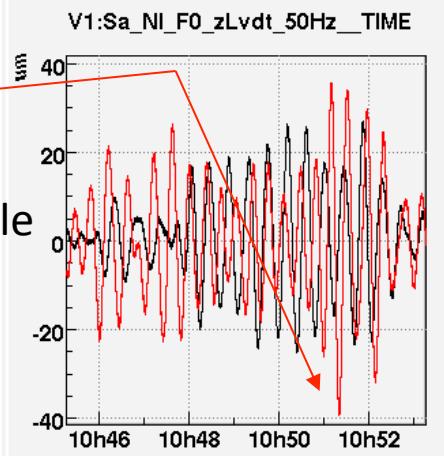
dataDisplay v9r11p4 : started by virgorun on Sep 20 2007 10:41:55 UTC

40 μm peak

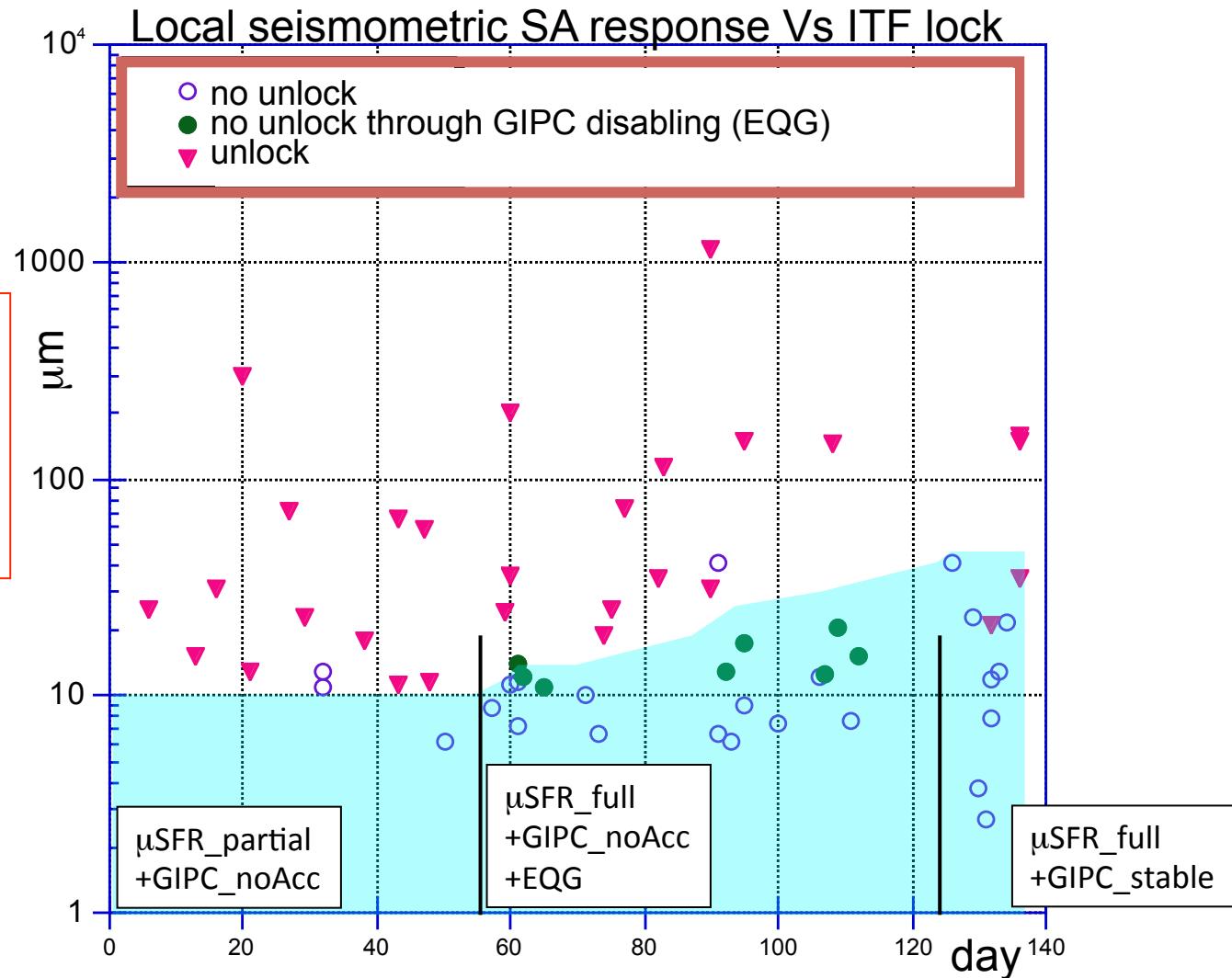
Before making GIPC stable
we had mirror control
saturation as IP
approached 20 μm

The system
is much more
robust .

Correction
dynamics more
than doubled.



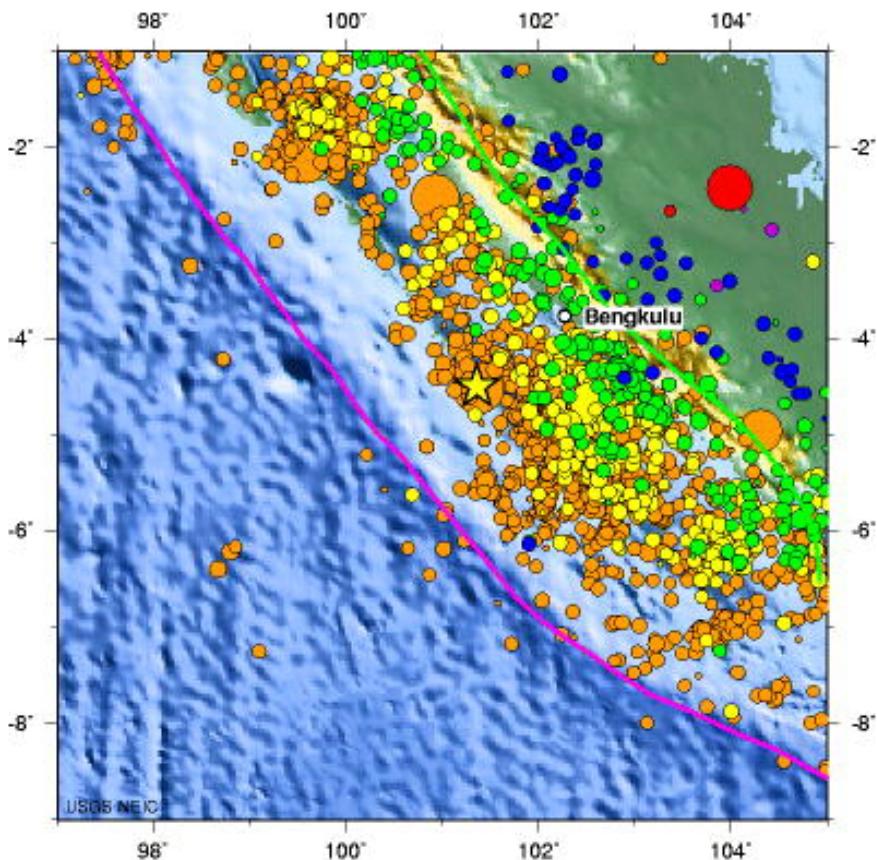
Lock robustness against EQs improvements during first run



Magnitude 8.5 SOUTHERN SUMATRA, INDONESIA

Wednesday, September 12, 2007 at 11:10:26 UTC

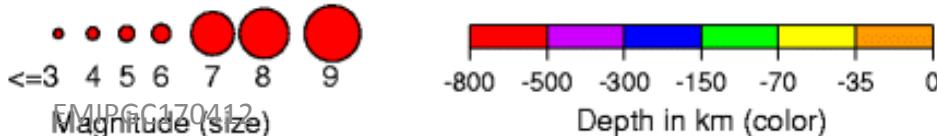
Historic Seismicity



SOUTHERN SUMATRA, INDONESIA

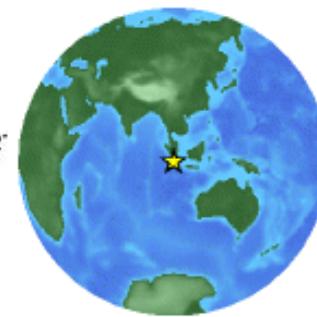
2007 09 12 11:10:26 UTC 4.50S 101.36E Depth: 34 km, Magnitude: 8.4

Seismicity 1990 to Present



Major Tectonic Boundaries: Subduction Zones -purple, Ridges -red and Transform Faults -green

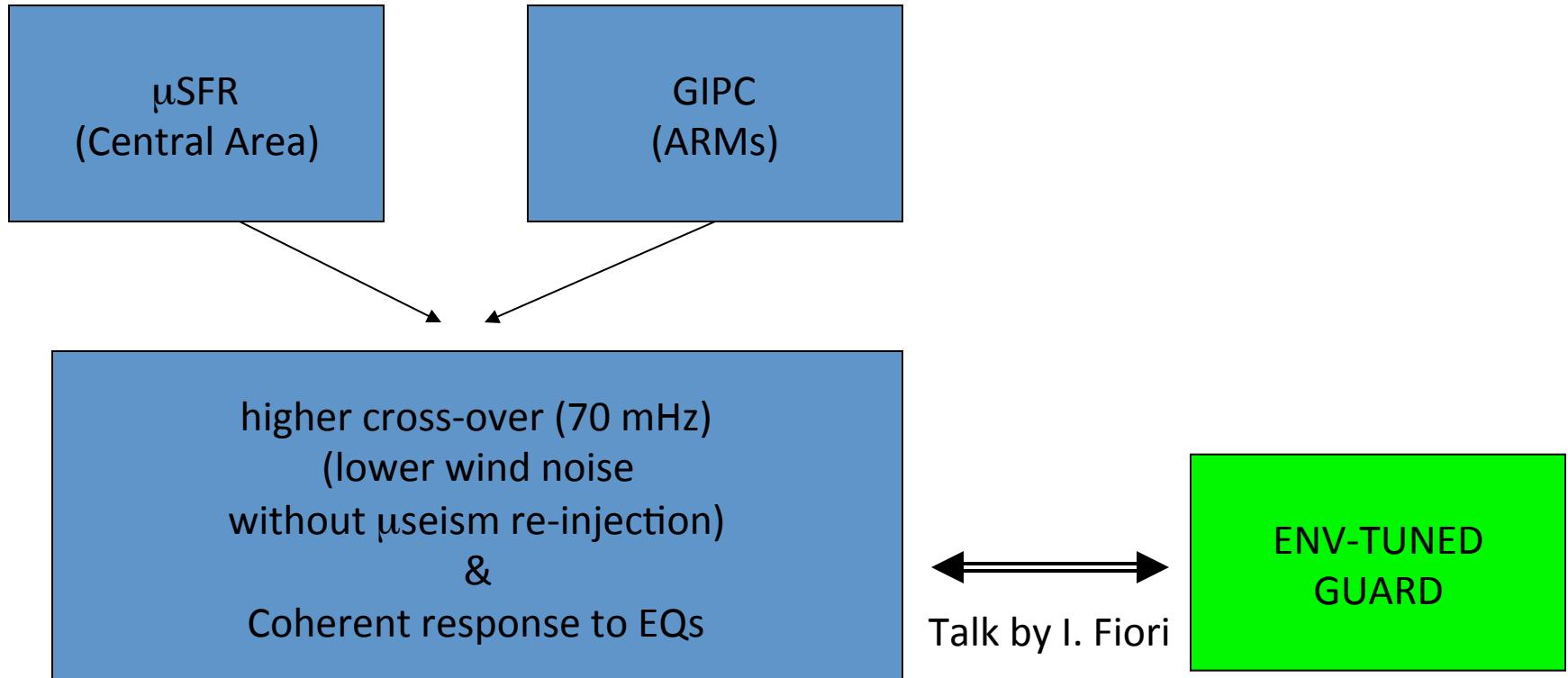
Typical candles for testing the response of the system



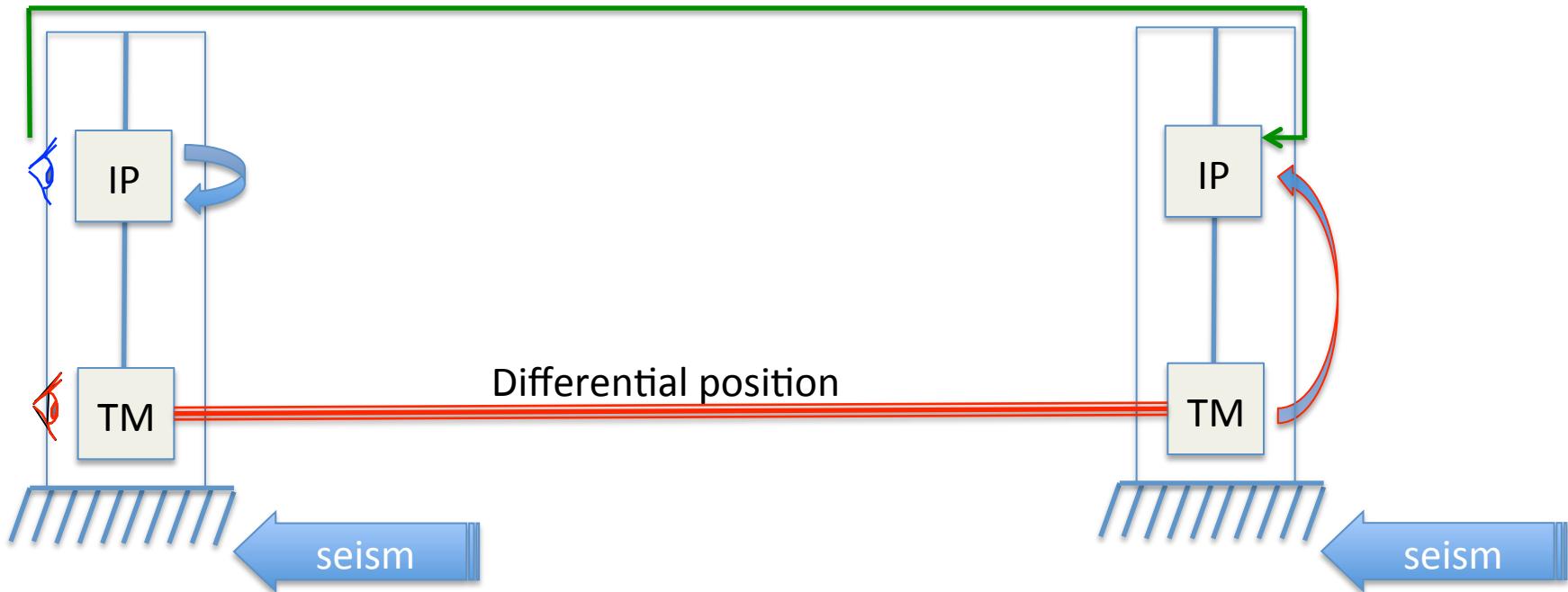
EQ producing at the site shakes comparable to those due to far sources with $M>6.5$ are critical for ITF operation.

Top-stage control strategies involving suspension operation **as-a-whole** improve disturbance rejection capability.

EQ GUARD is a monitor of the coherent response of far suspensions



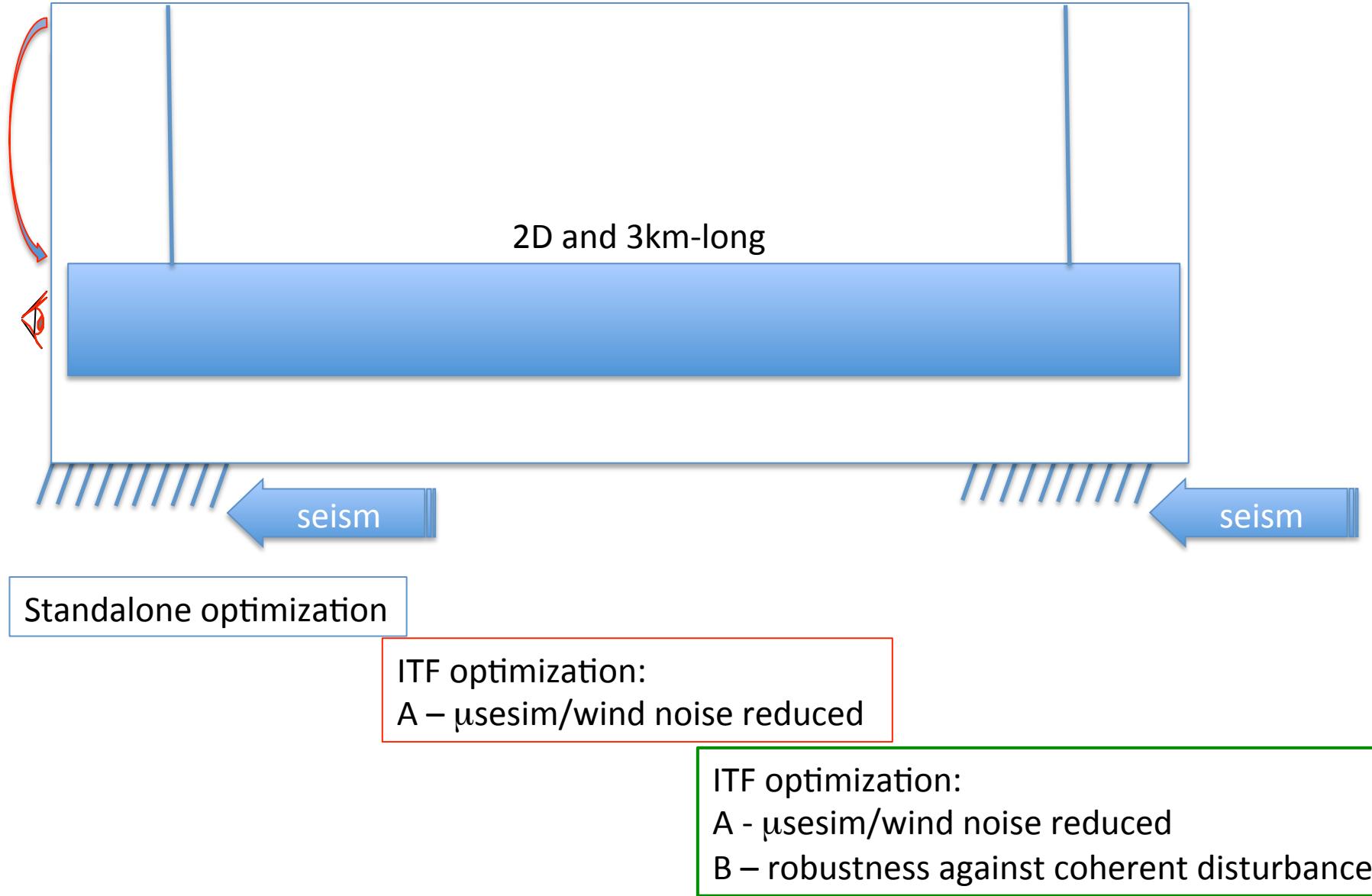
Differential acceleration



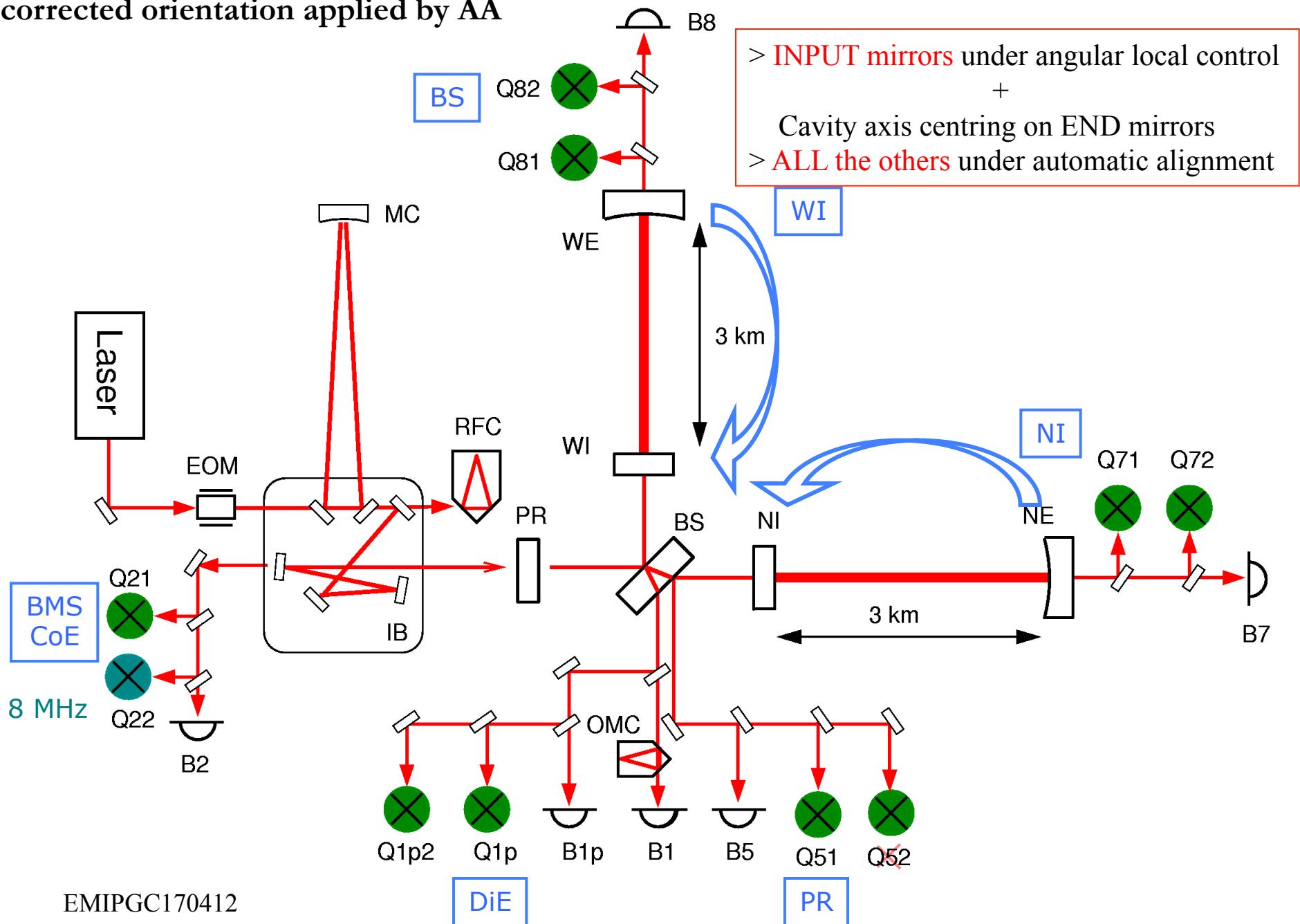
Standalone optimization

ITF optimization:
A – μ sesim/wind noise reduced

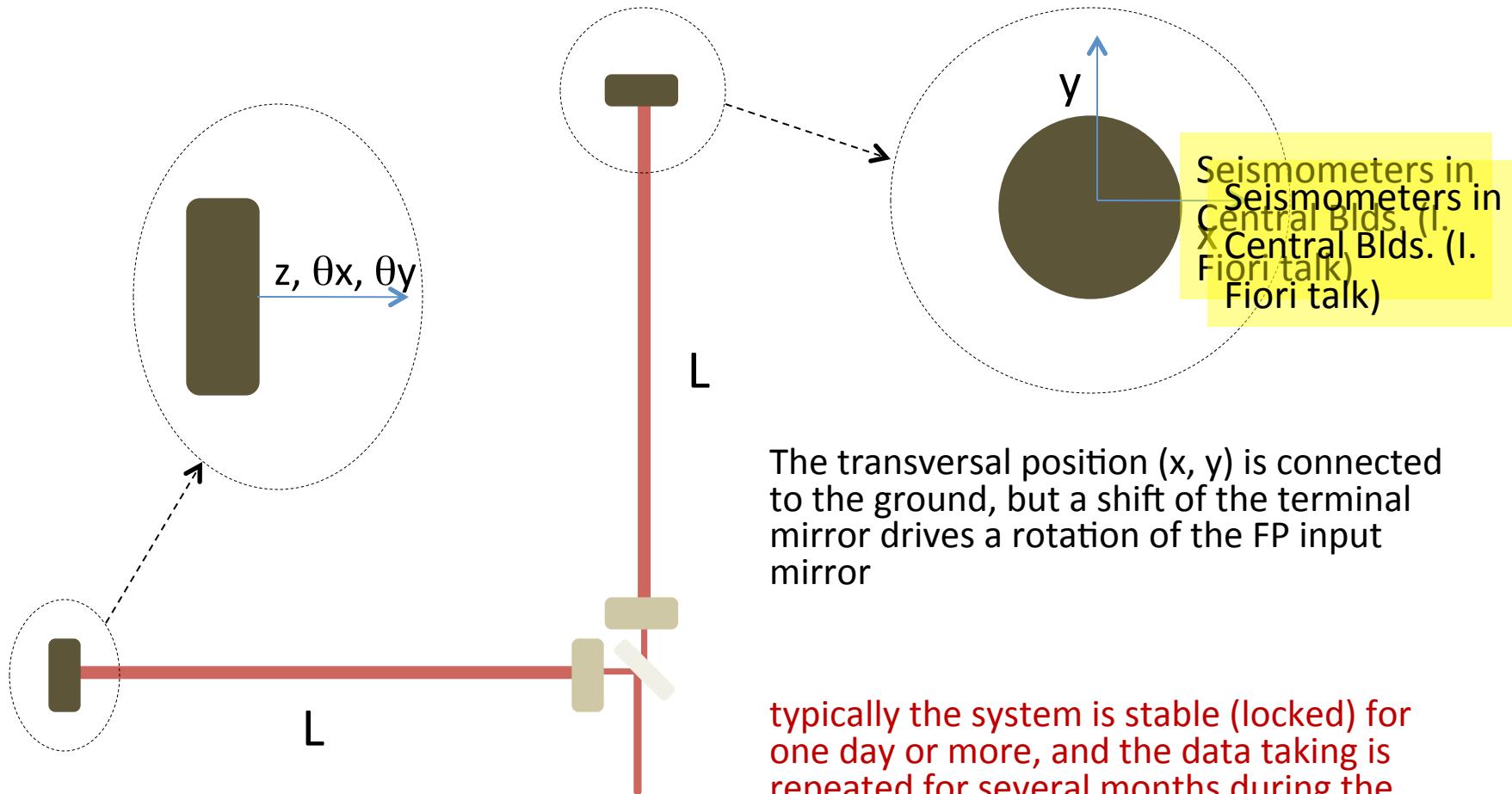
ITF optimization:
A - μ sesim/wind noise reduced
B – robustness against coherent disturbance



automated-alignment (AA). Local control signals (optical levers) at low frequency read corrected orientation applied by AA



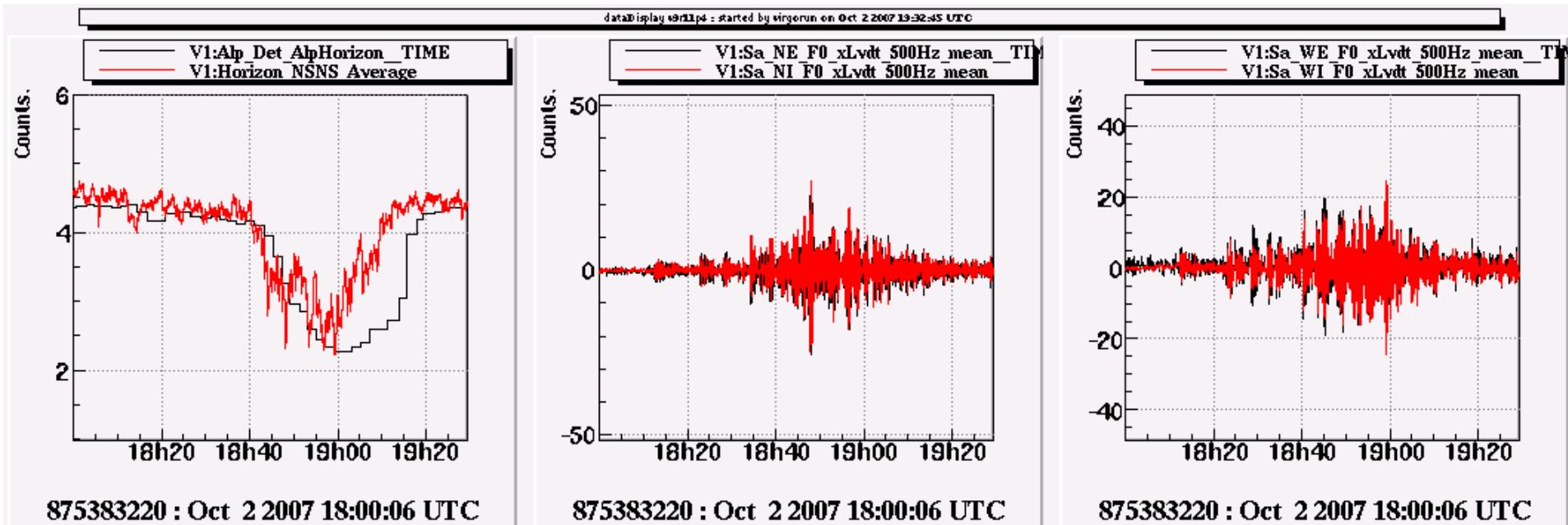
Relative position of the test masses, concerning the longitudinal displacement (z) and the orientation of the mirror surfaces (θ_x , θ_y), are completely disconnected from the ground motion.



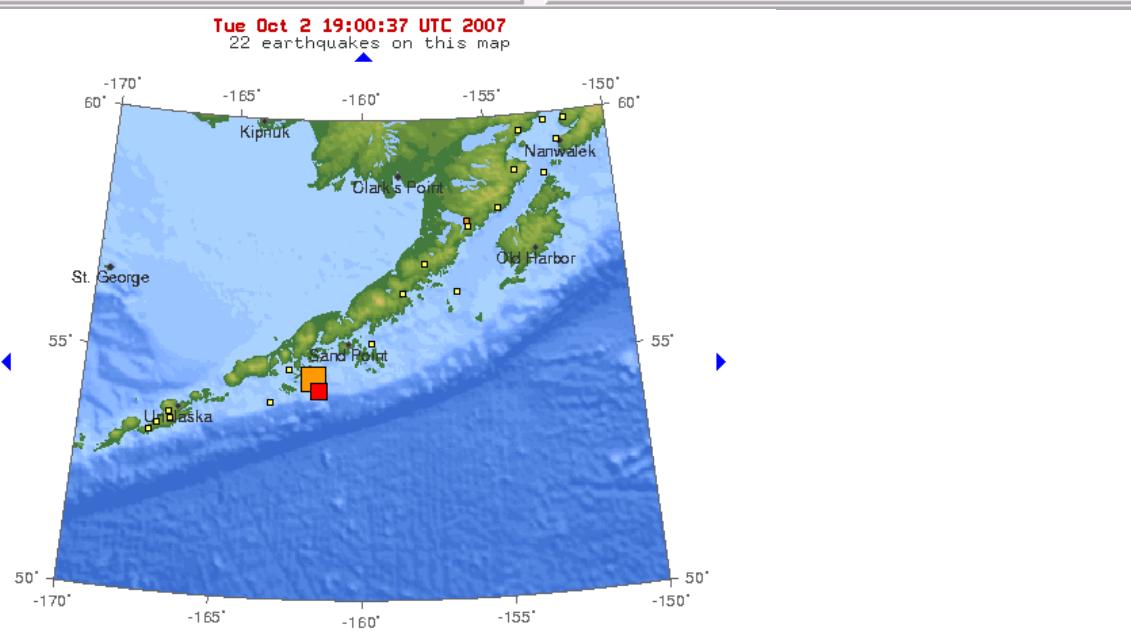
The transversal position (x, y) is connected to the ground, but a shift of the terminal mirror drives a rotation of the FP input mirror

typically the system is stable (locked) for one day or more, and the data taking is repeated for several months during the scientific runs, with a duty cycle > 80%

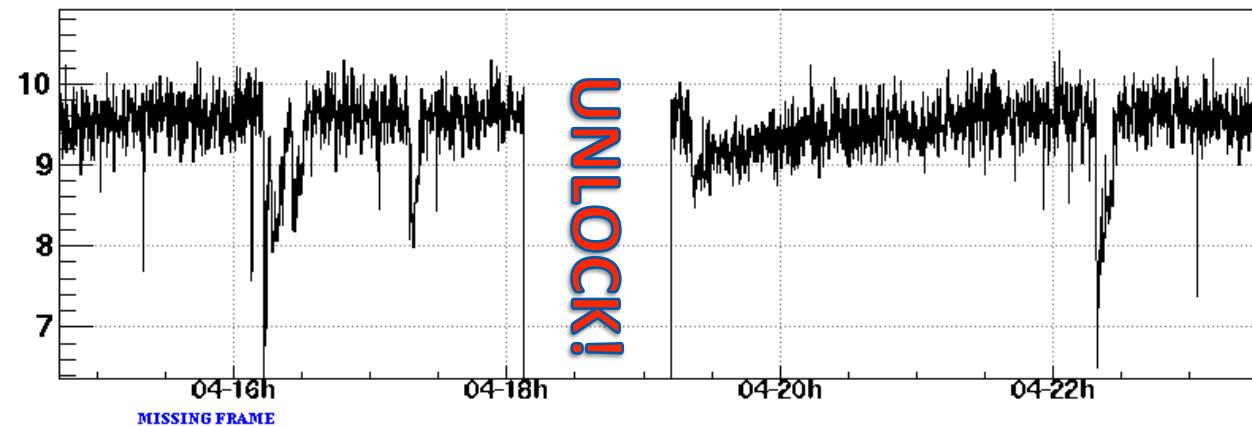
Example (I) of seism measurement using the ITF (detection horizon worsened)



Even if the ITF lock is maintained,
It undergoes to lower sensitivity
period during which GW detection
horizon is lower.

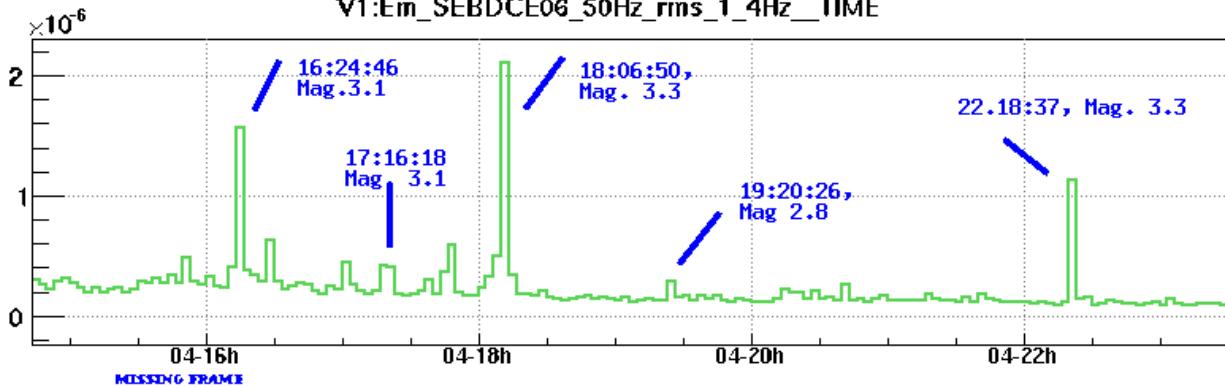


V1:HorizonTF_NSNS_TIME



The horizon drops

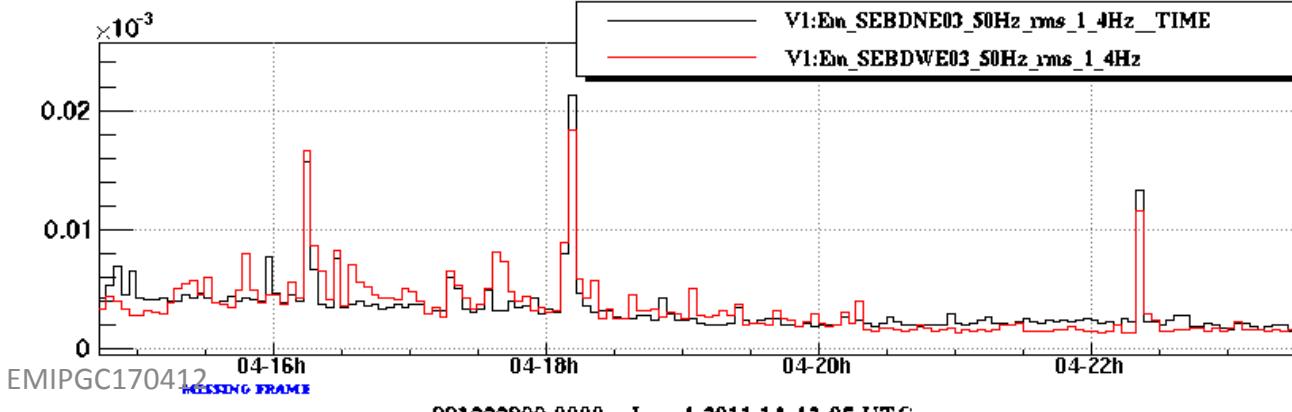
V1:Em_SEBDCE06_50Hz_rms_1_4Hz_TIME



Seismometers in Central Bldgs. (I. Fiori talk)

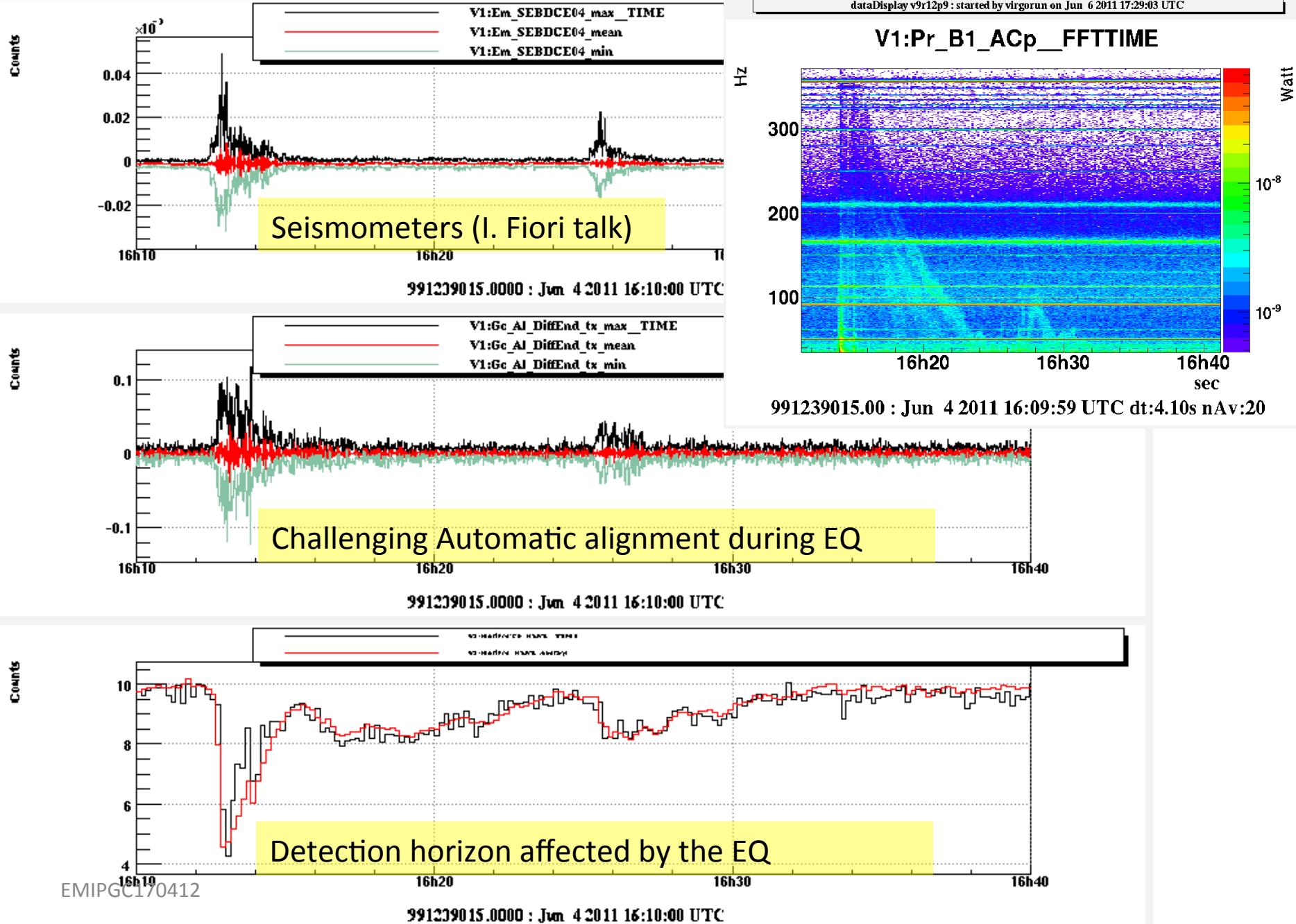
V1:Em_SEBDNE03_50Hz_rms_1_4Hz_TIME

V1:Em_SEBDWE03_50Hz_rms_1_4Hz

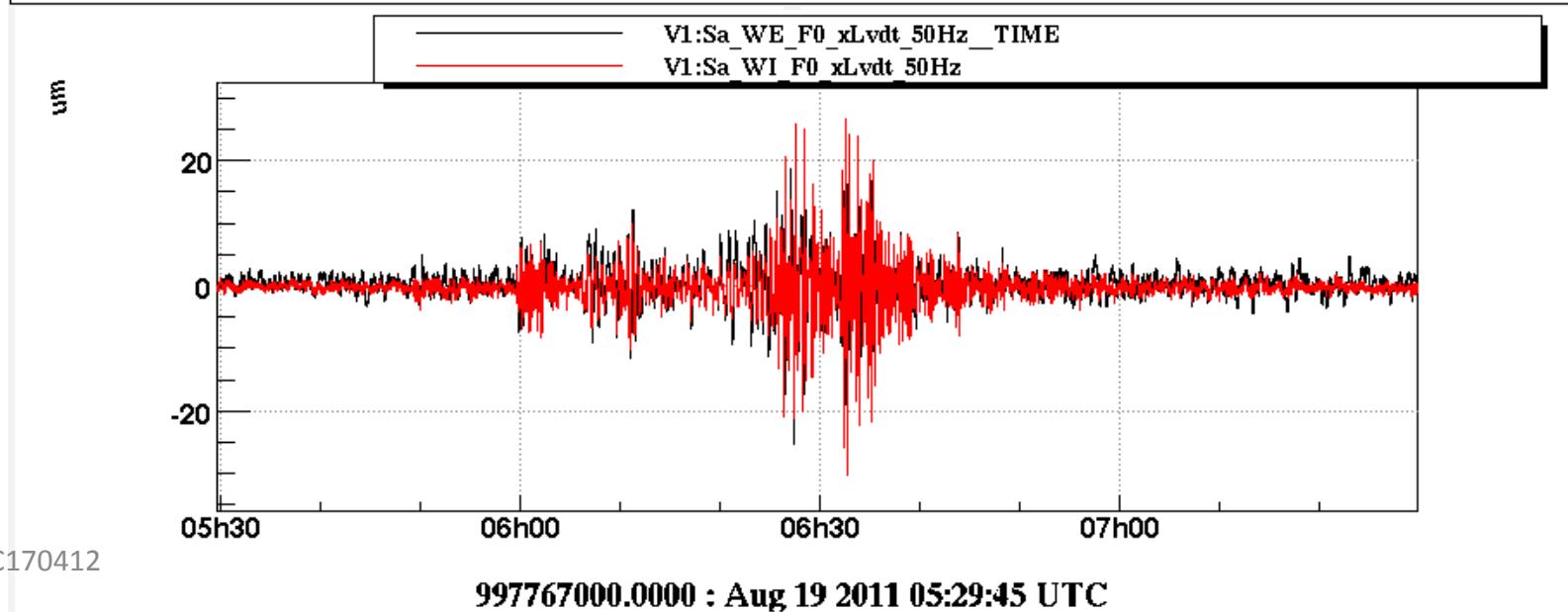
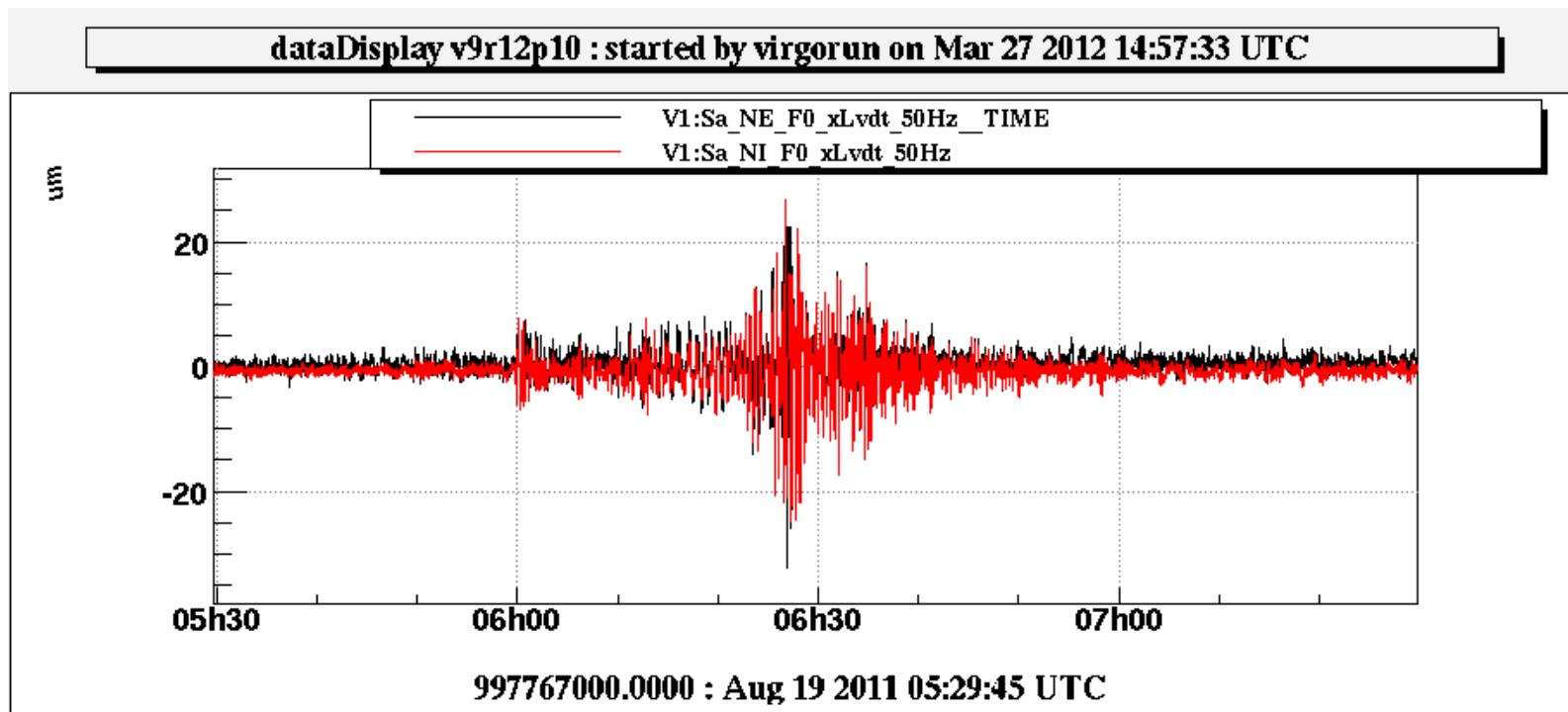


Seismometers in terminal Bldgs. (I. Fiori talk)

dataDisplay v9r12p9 : started by virgorun on Jun 6 2011 18:18:10 UTC

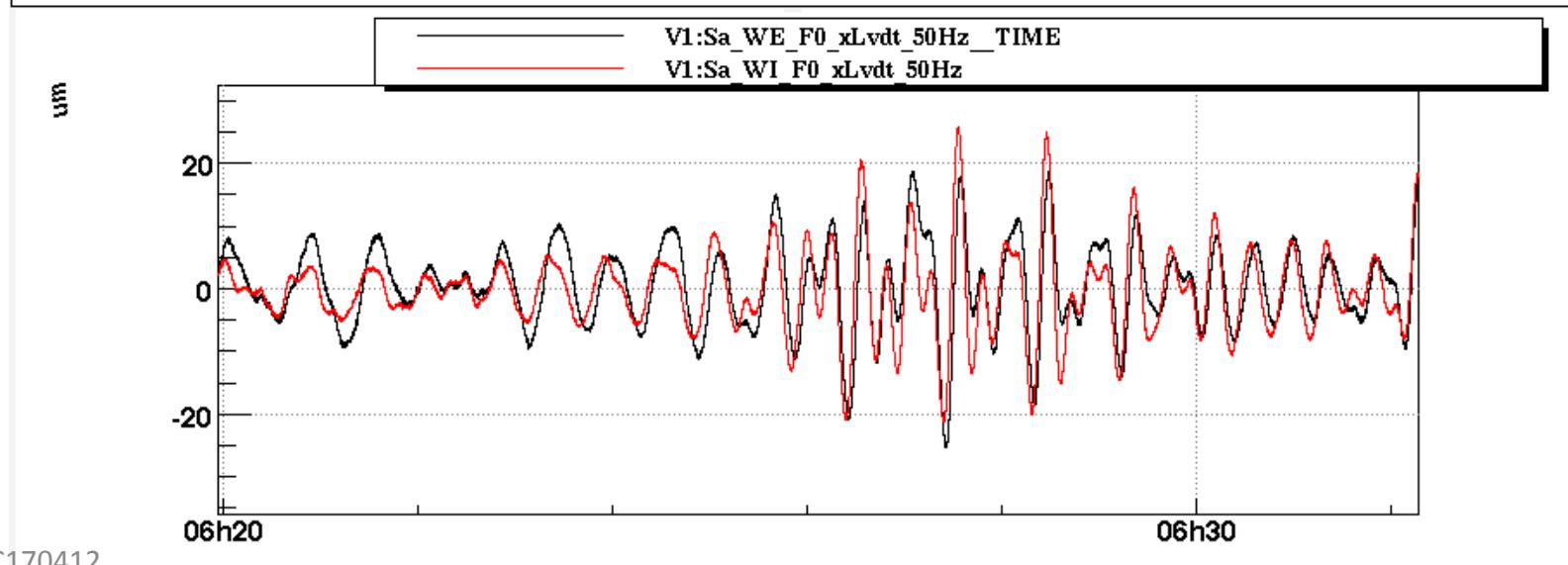
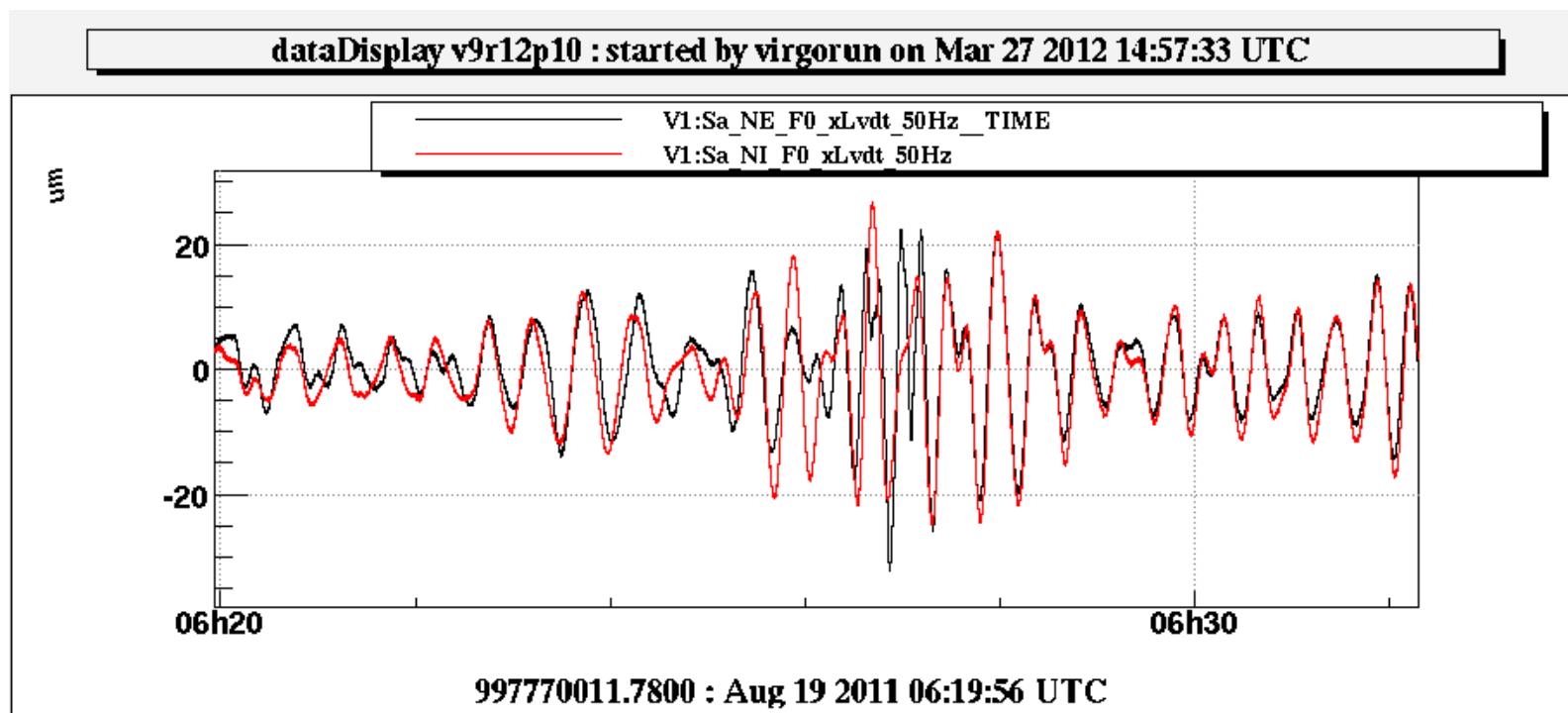


Example (II) of seism measurement using the ITF



EMIPGC170412

Example (II) of seism measurement using the ITF (zoom)

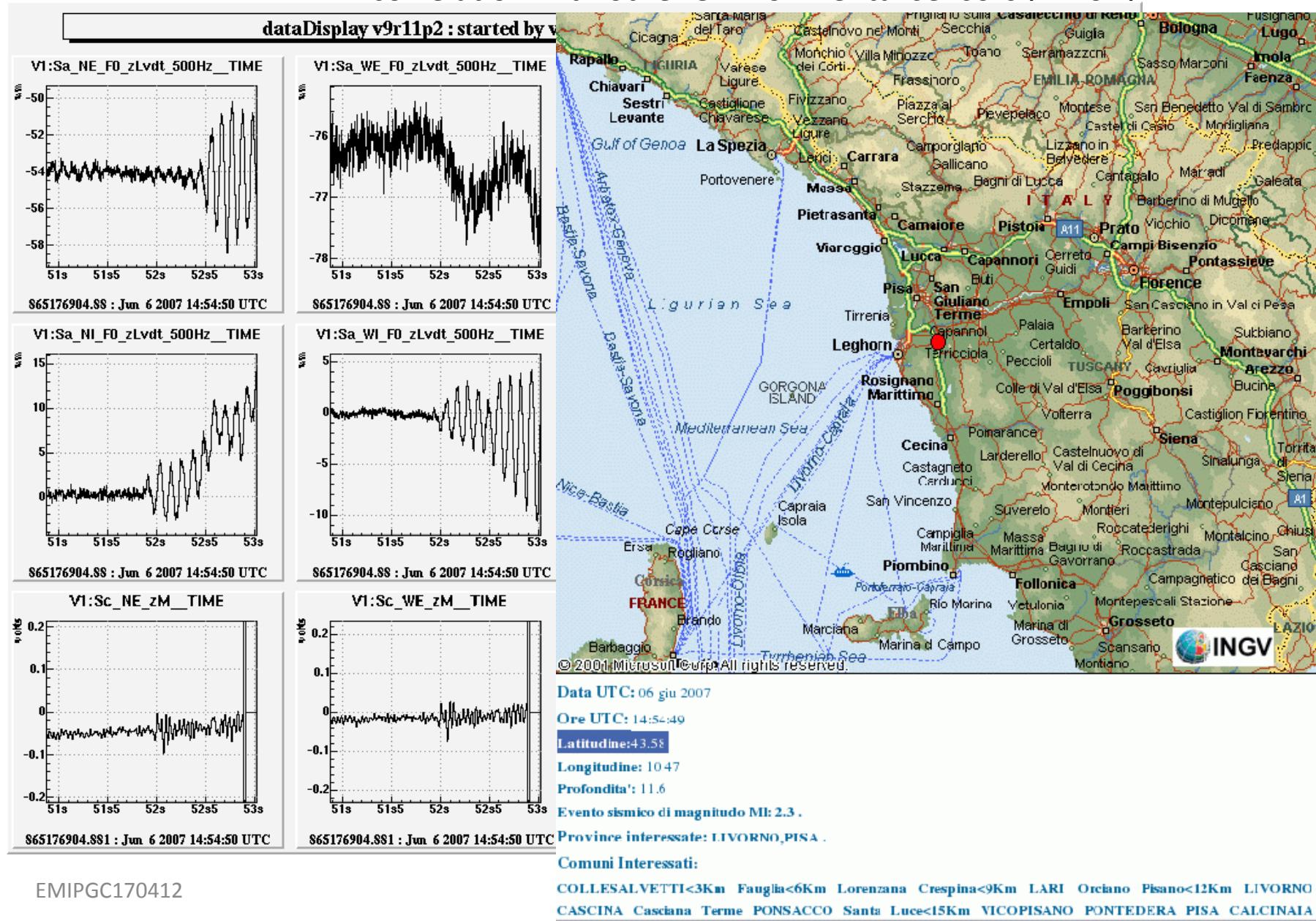


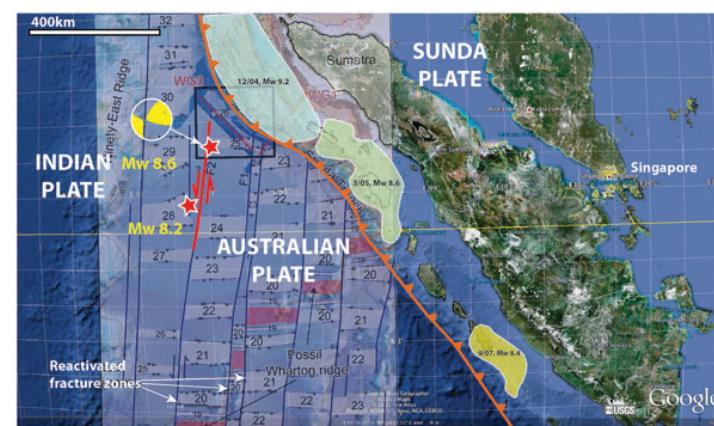
EMIPGC170412

997770011.7800 : Aug 19 2011 06:19:56 UTC

EQG method analyses correlation at 3 km so that, very close seismic events (< 10-20 km) causing incoherent excitation are not detected by EQG

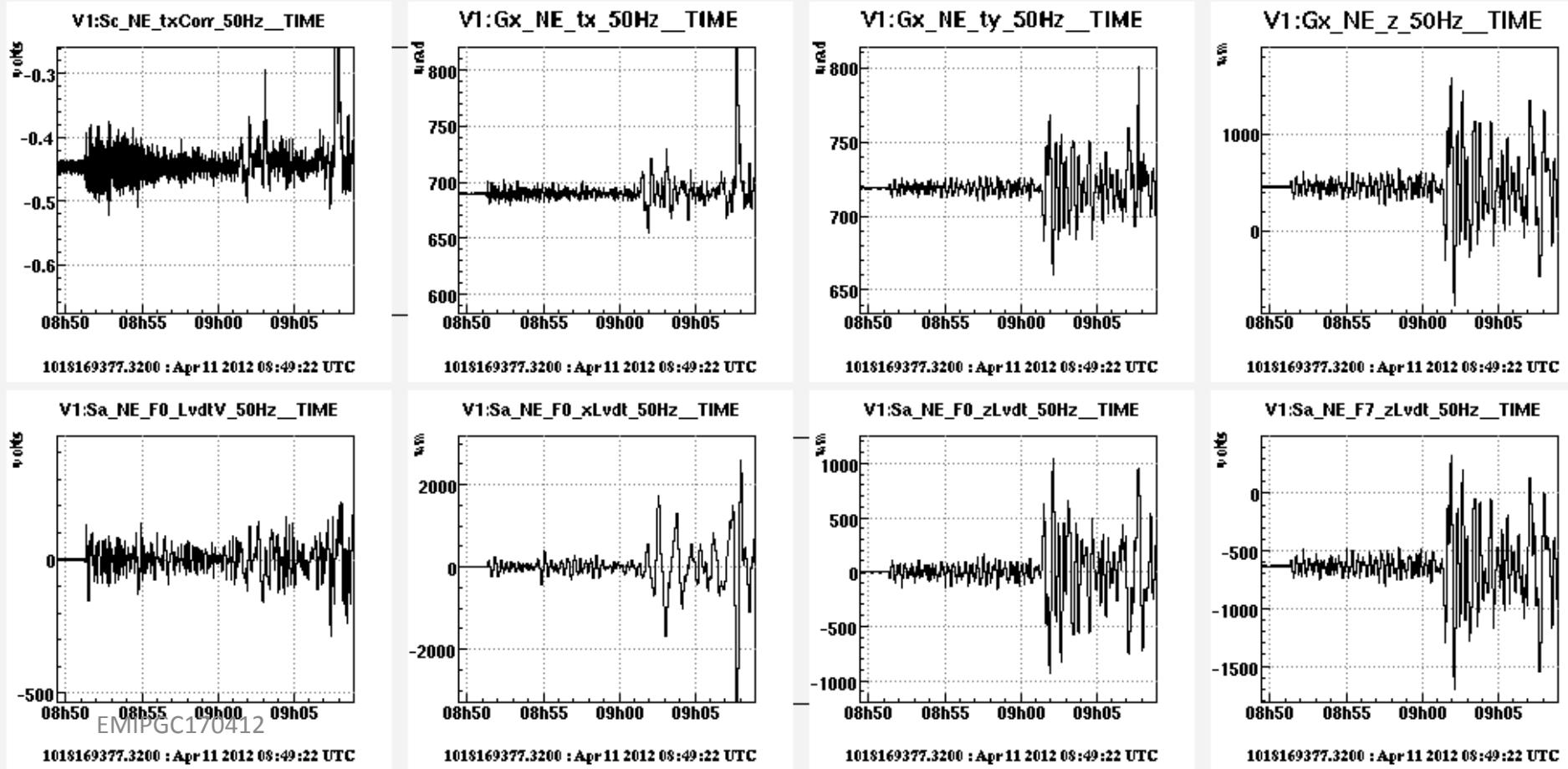
→ correlation with other environmental sensors (I. Fiori)





Example of standalone seism measurement using a single suspension (Sumatra 11 Apr/2012, NE suspension)

dataDisplay v9r12p10 : started by virgorum on Apr 15 2012 18:13:13 UTC



Tilts

Interesting tilt studies can be performed

- 1) by comparing Automated Alignment signals with respect to local control
- 2) through tilt correction signals

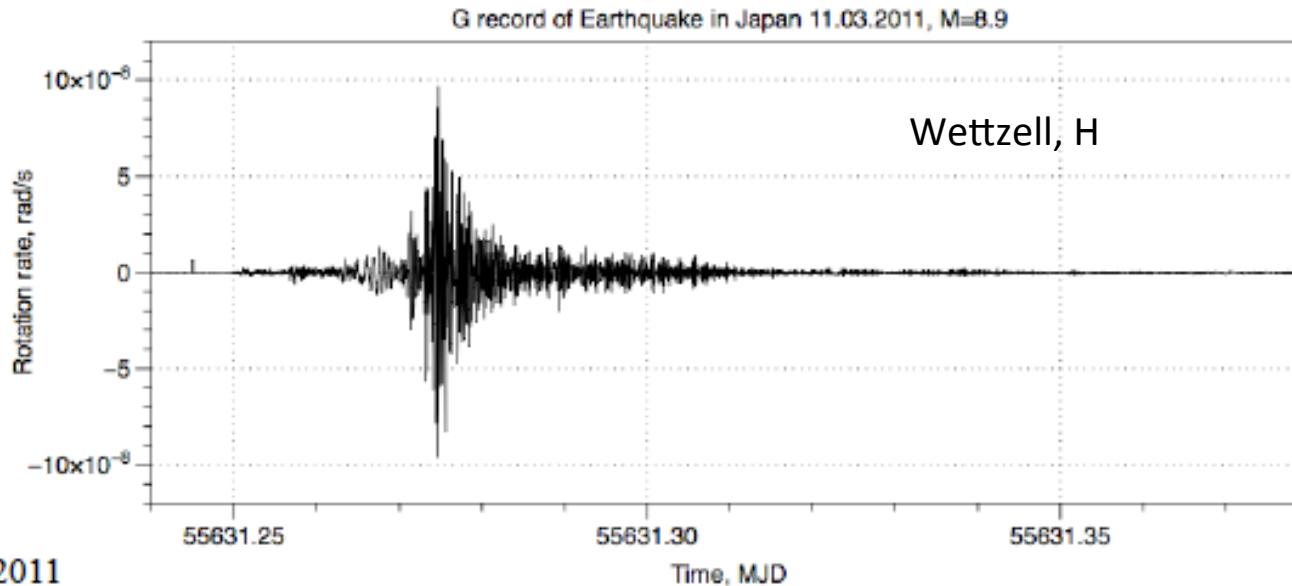
Disentanglement between local tilt due to local deformation/drifts and gravimetric

Vector orientation is difficult (see V. N. Rudenko) but it deserves some dedicated study.

Tiltmeters are a key feature of next generation of suspensions at least to cleanup acceleration sensing.

Tilt sensors : the Gyrolaser

VIR-0255A, INFN Pisa



Observation of the
Reyleigh wave
produced by an
Earthquake

Interesting tilt studies can be performed

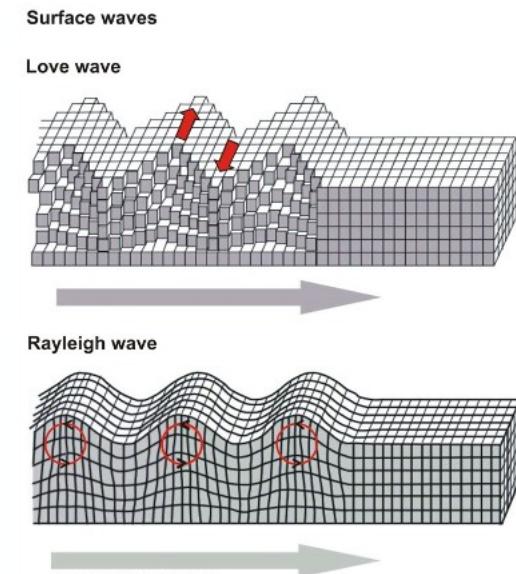
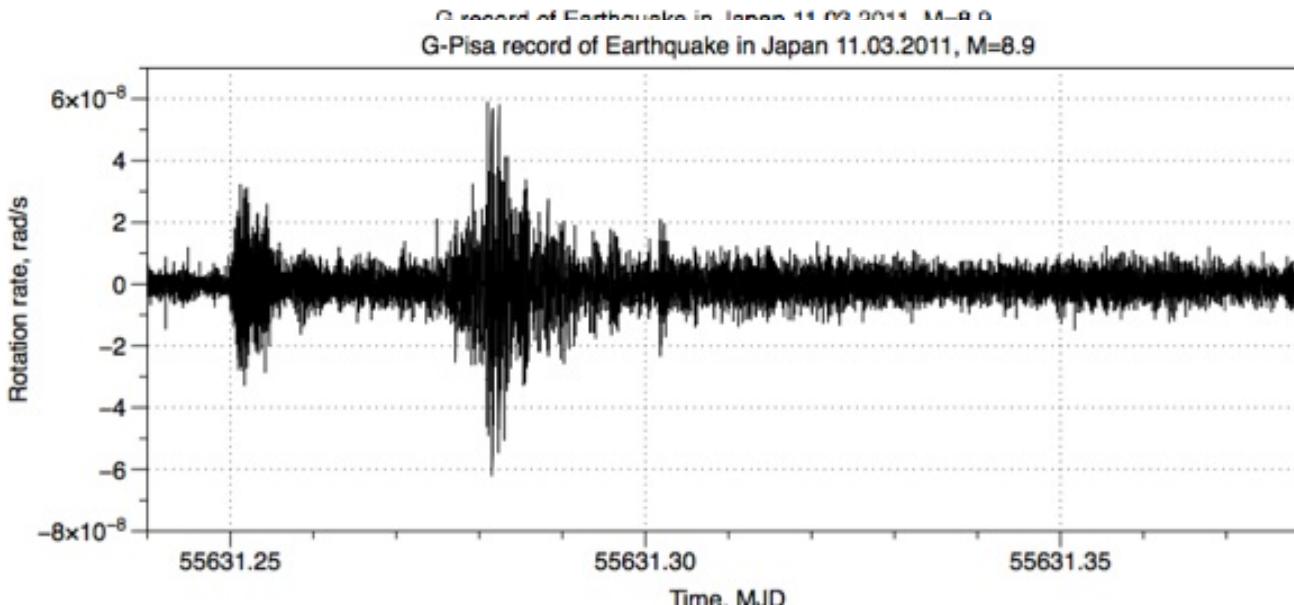
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acceleration sensing.

Tilt sensors on ground : the Gyrolaser

VIR-0255A, INFN Pisa



conclusions

- Along the horizontal plane of the ITF Virgo behaves as a whole, namely as biaxial closed-loop accelerometer whose floating mass is 3km-long L-shaped rigid bar.
- Axes angles are adjusted in order to keep the the operation point.
- Vertical d.o.f of suspensions are not correlated during the operation and can be exploited in correlation to other environmental signals.