Topics in simulation and DA for GW interferometers: the VIRGO case

- The VIRGO super-attenuator: a introduction
- Why a mechanical simulation
- How the simulation is set up
- The comparison with real data, and how these are analyzed
- Latest results on suspension performances
- How the simulation is helping for locking studies

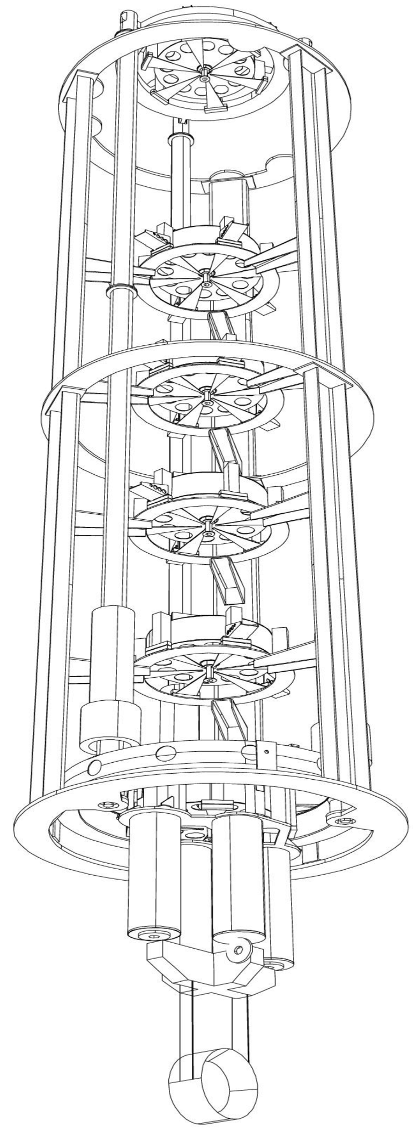
Andrea Viceré
LIGO Laboratory, Caltech

(with many thanks to M.Barsuglia, L.Di Fiore, G.Losurdo)

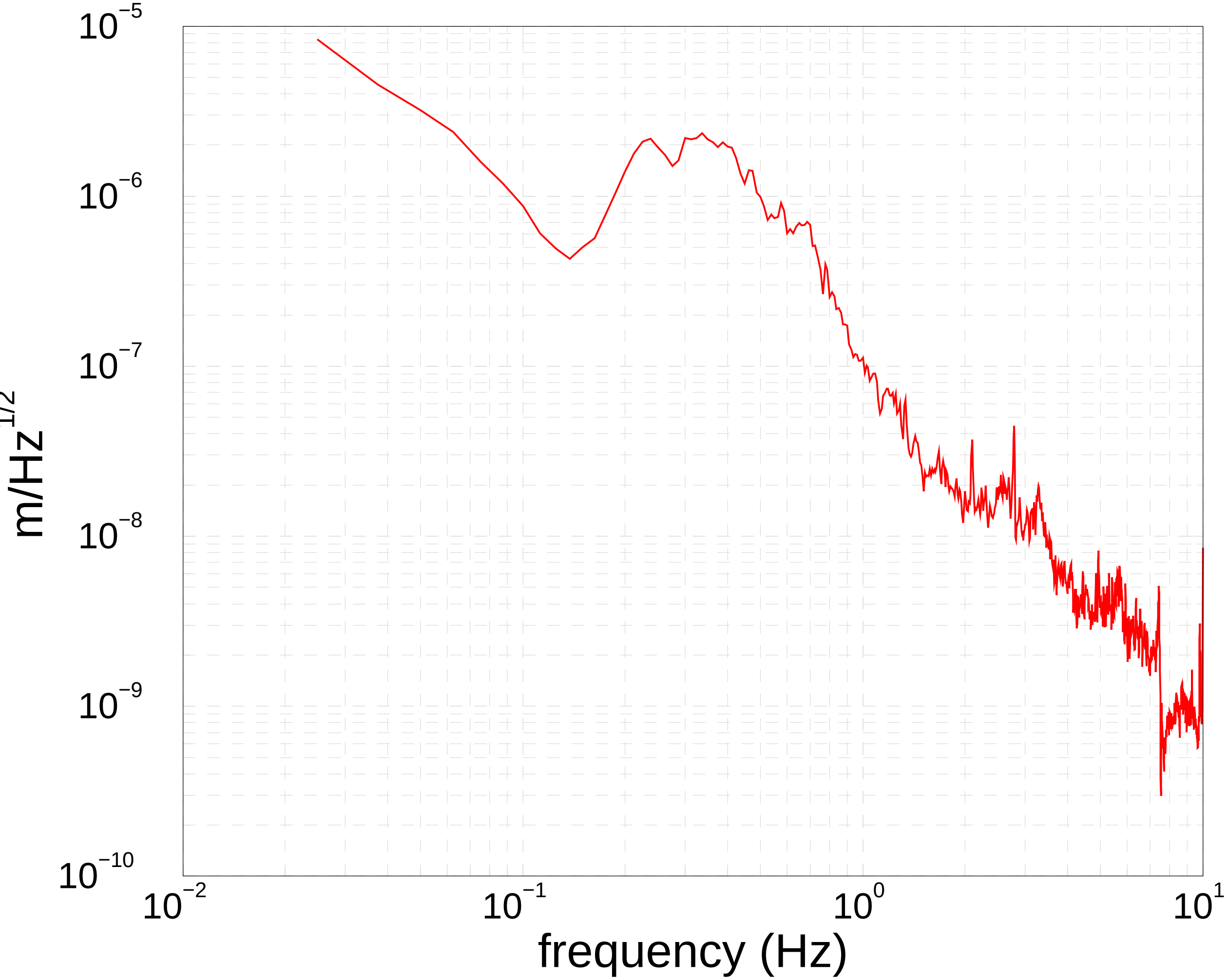
A VIRGO Super Attenuator

- An inverted pendulum for low frequency control
- 6 seismic filters (in all DOFs)
- 1 longitudinal-angular control stage (the marionetta)
- 1 longitudinal control stage (the reference mass)

- The system has a double role
  - Filtering out the seismic noise
  - Actuate on the mirror position

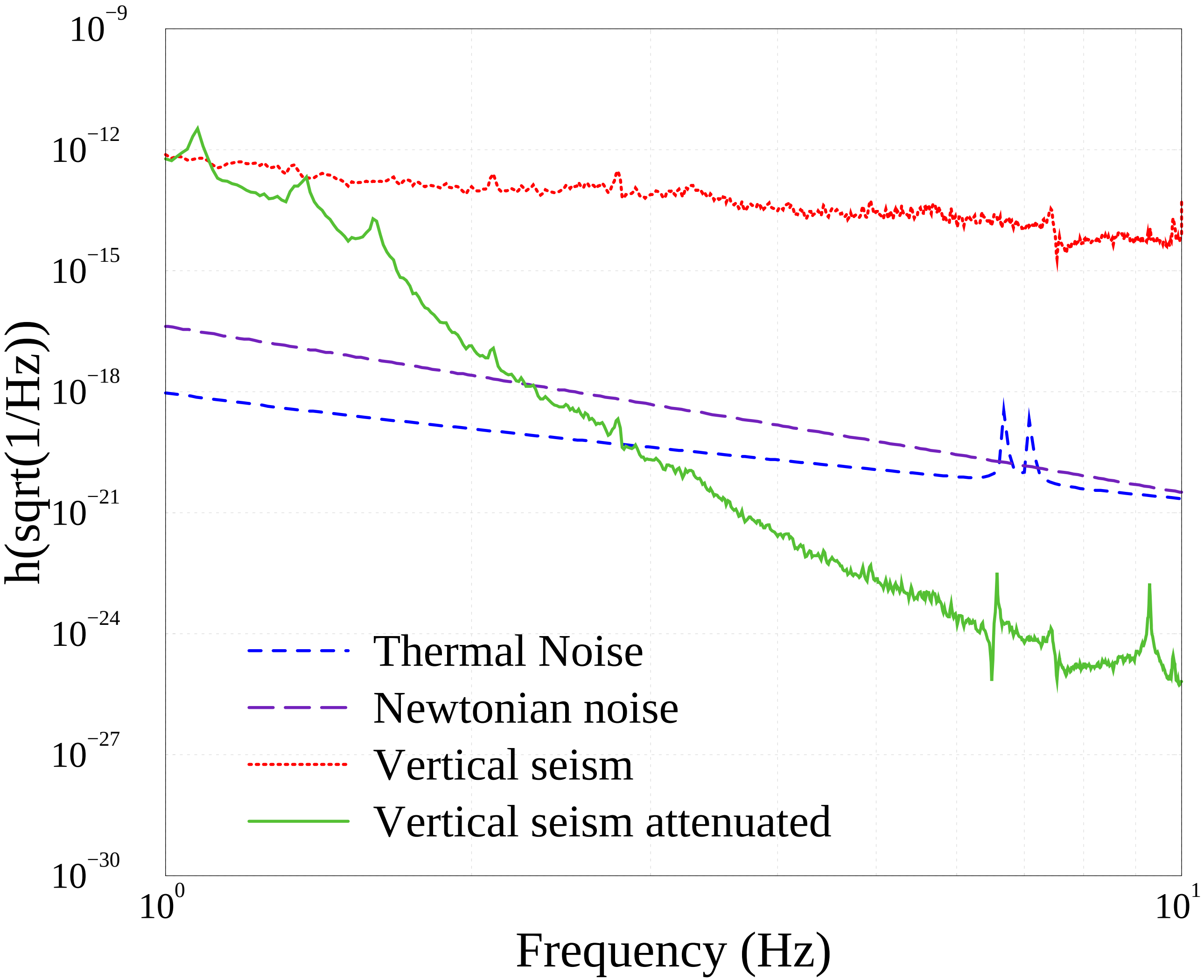


Why so many stages?



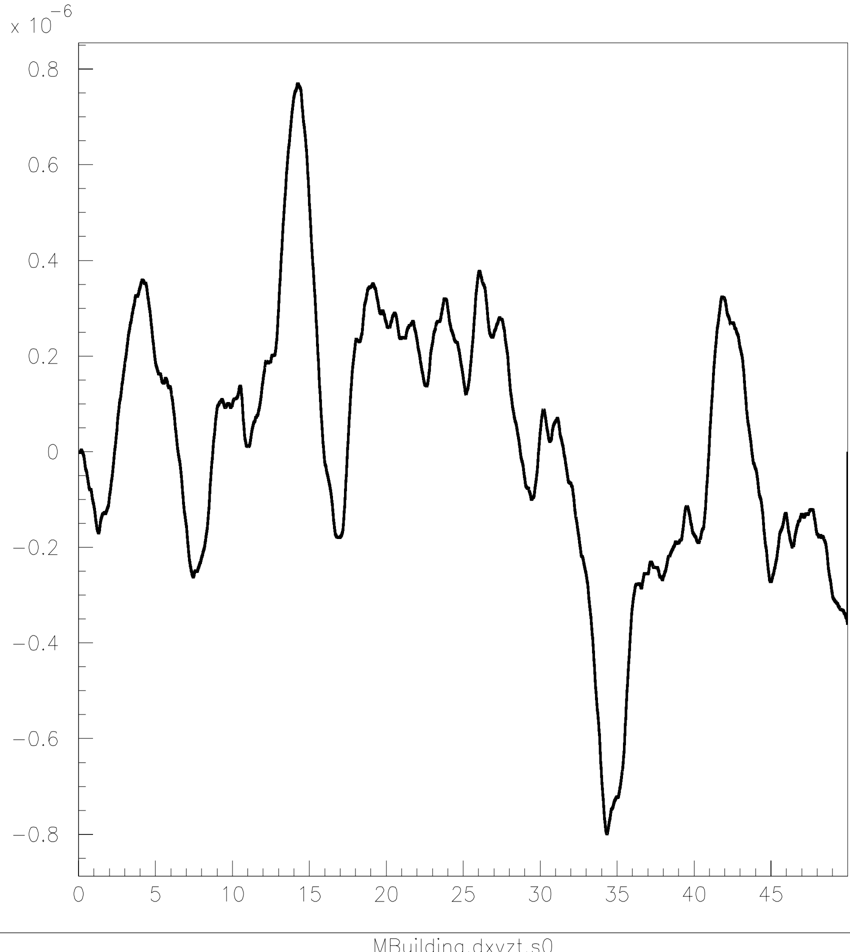
- Seismic noise measured in Cascina
  - » Quiet day!
- Several sources of noise in the area!
  - » 1 airport at 20 Km
  - » 2 railways within 10 Km
  - » 1 super highway
  - » 2 highways
  - » Several crowded roads

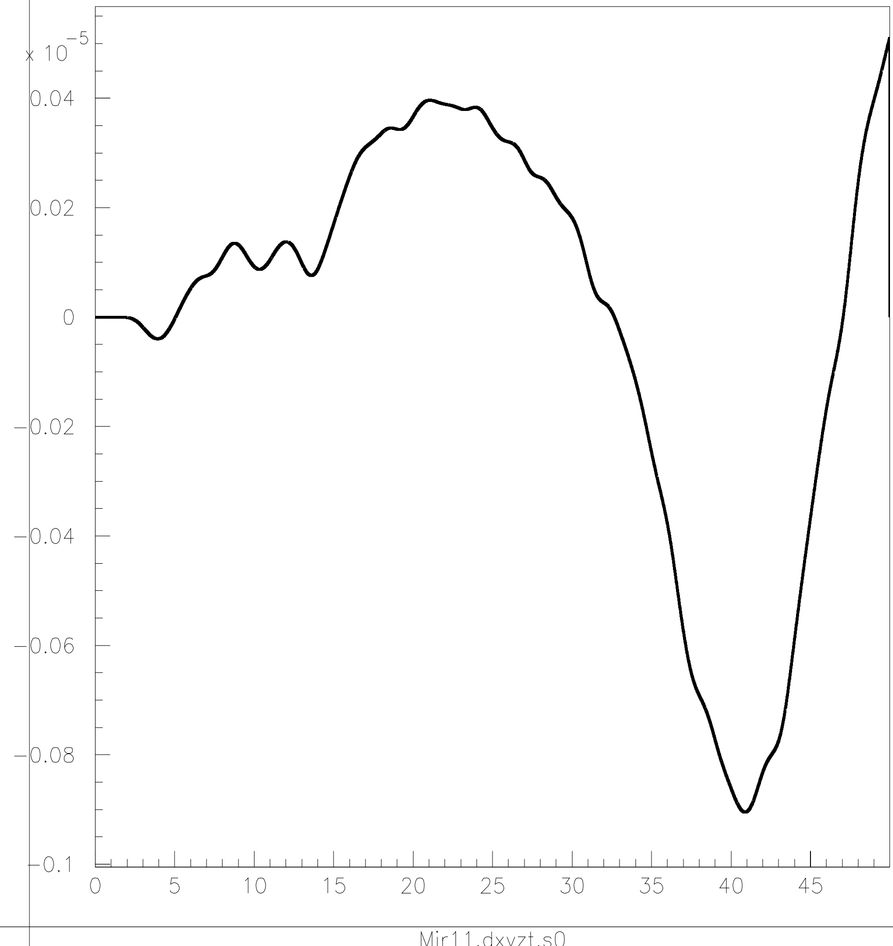
Attenuation goals



- Vertical seism is dominant
- On paper, above 3÷4 Hz the noise should become dominated by other sources
- The choice is to achieve this goal only by passive means.

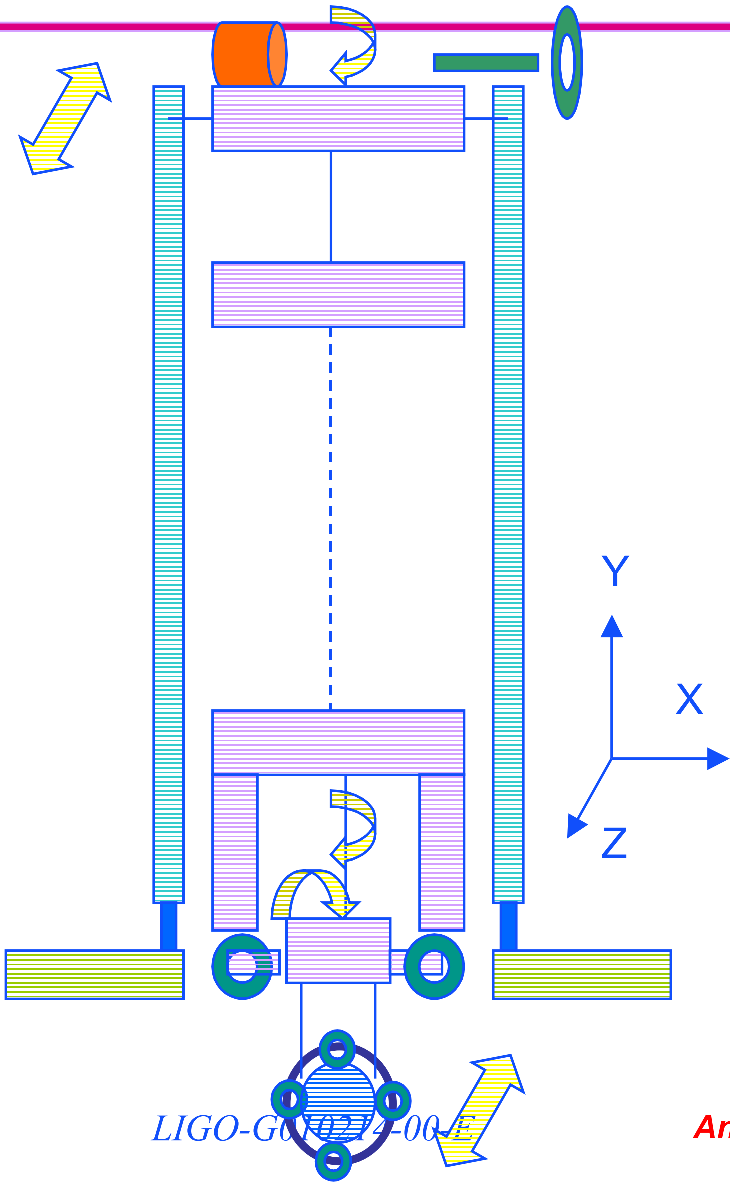
Price to pay: LF amplification





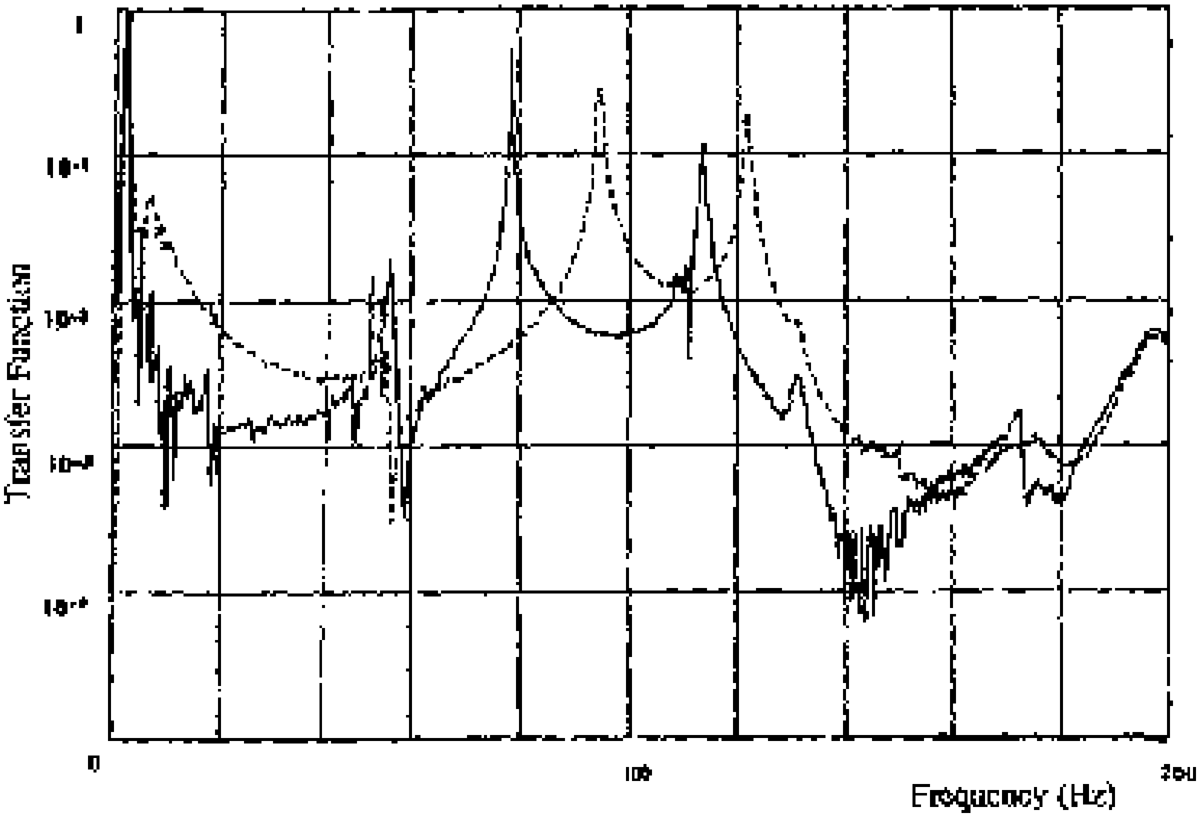
- **Left**: ground motion **Right**: mirror motion → control requirements

The SA as a control device



- Three sensing devices
  - » LVDT sensors on top of the IP
  - » Accelerometers …
  - » The interferometer itself
- Three actuation stages
  - » Below 5 Hz, coils on the IP
  - » In the range 5, 20 Hz, from the marionette
  - » In the upper range, from the reference mass
- Hierarchy of forces → hierarchy of noises
  - » Avoid large forces applied directly to the test-mass

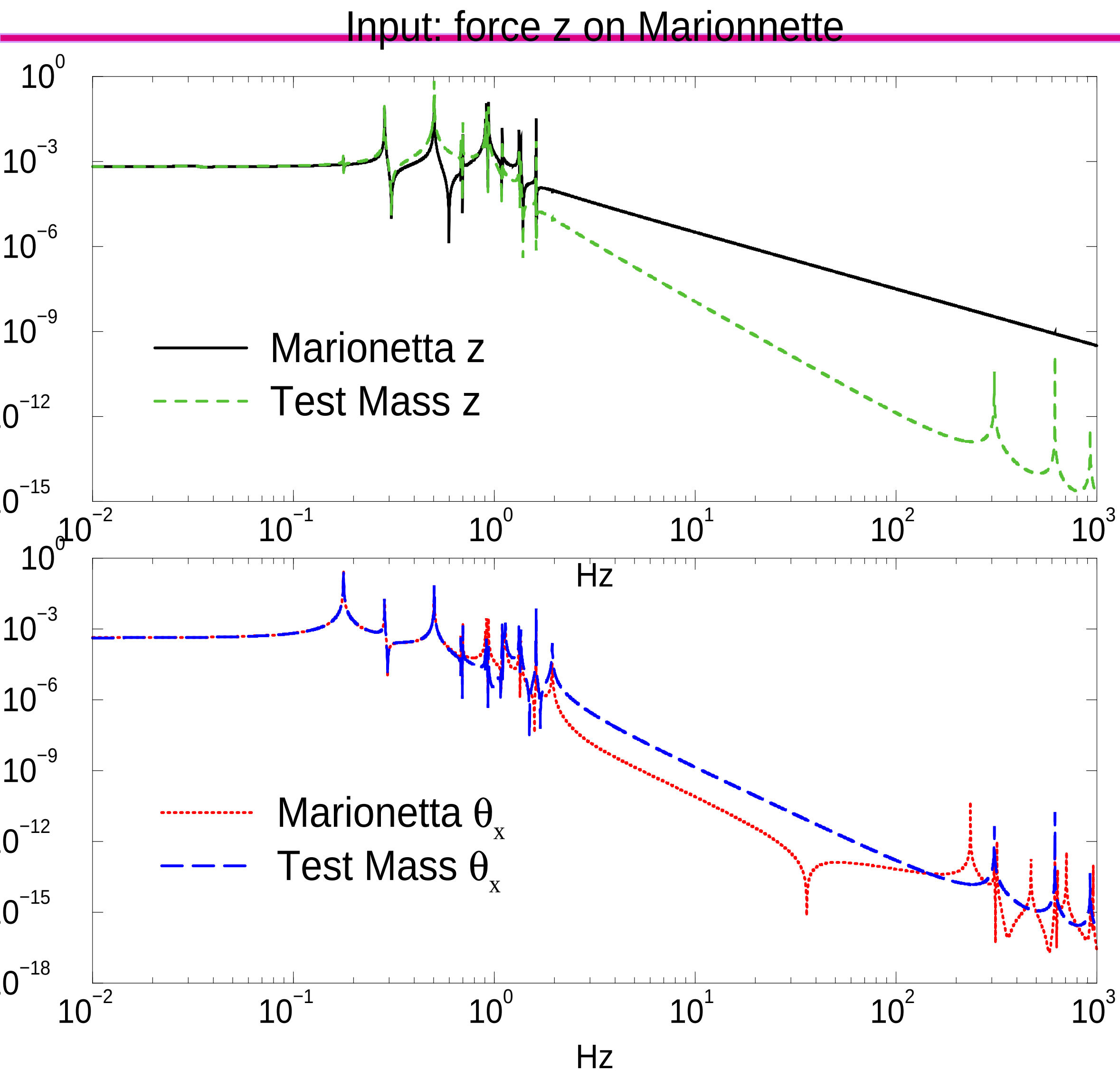
Why a mechanical simulation?…



- In the plot, the vertical TFs of a seismic filter
  - » The two curves correspond to two options for the fundamental frequency.
- What happens when chaining several such elements?

R.Flaminio, S.Braccini

What one would like to know

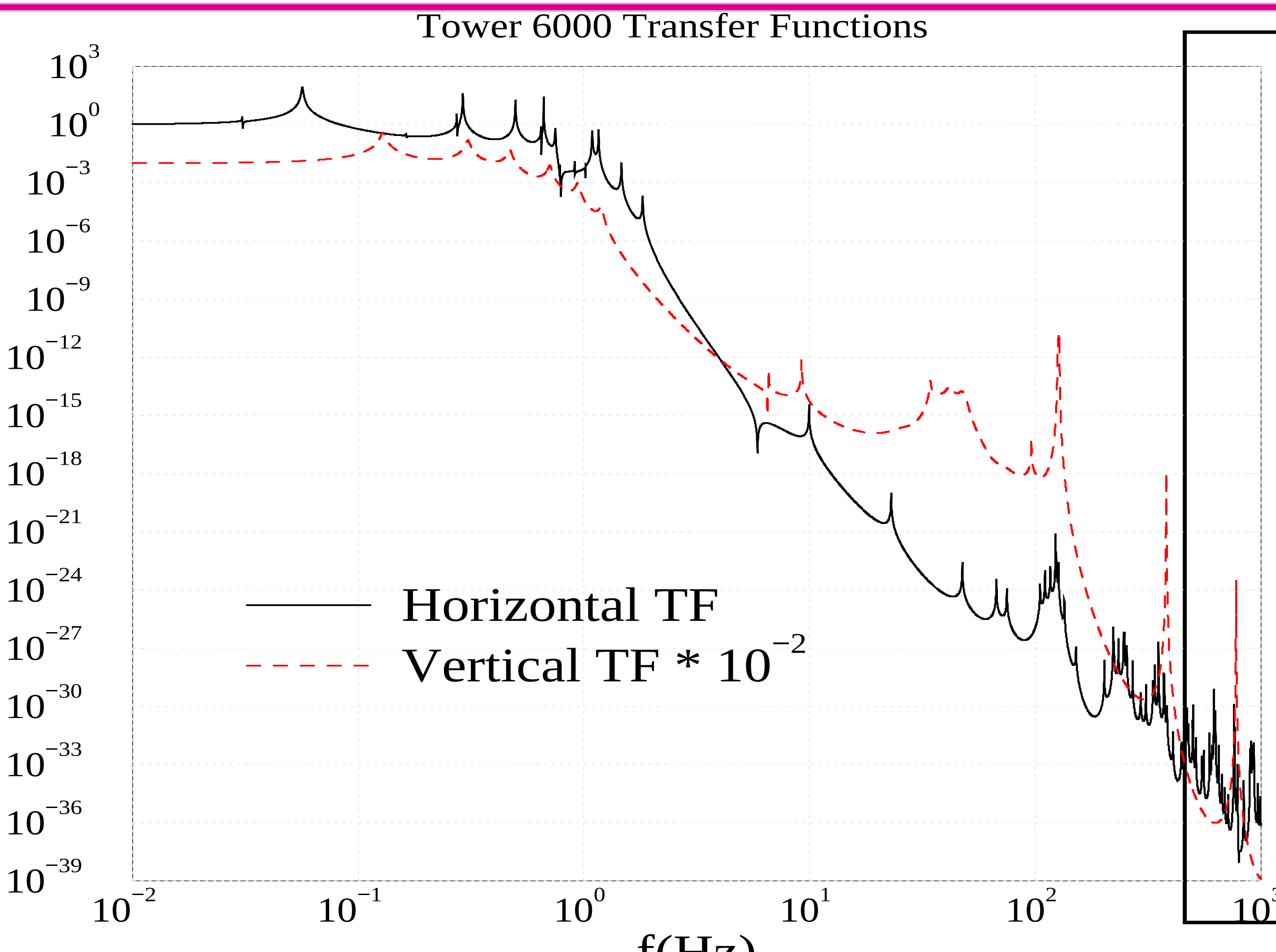


- In the plot, some of the (simulated) TFs which are relevant in controlling mirror position
- The design of control filters depend on these TFs.
- A complex system: one needs
  - A good model, and
  - direct measurements

Model scope and requirements

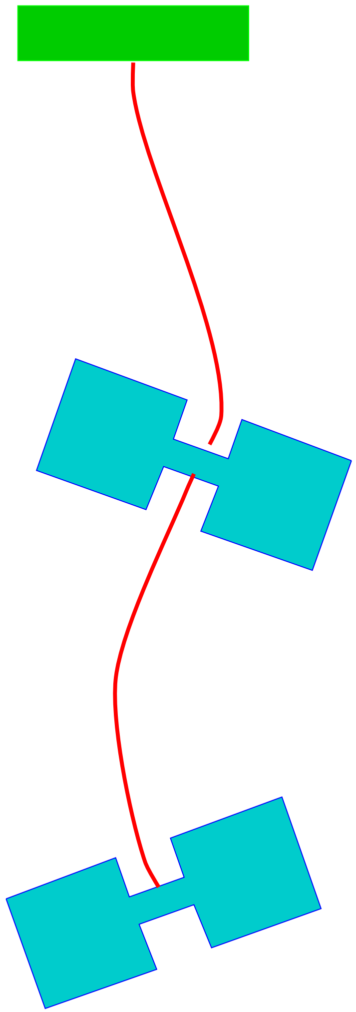
- Assess attenuation performance in the detection band [4Hz – 10 kHz]
  - Help in deciding where improvement is needed
  - Requires modeling of the internal modes of elastic elements
  - Limit: only the ITF shall be able to fully validate the results!
- Predict the motion of test masses
  - Due to noise inputs (seism, thermal noise …)
  - Under the influence of control forces
- Provide a time domain model
  - Needed to integrate with optics and study lock-acquisition
  - Simple: as few DOF as possible to keep simulation time within reasonable limits
  - Neglect internal modes

Is this strategy consistent?



- Low frequency structure relevant for control studies
- High frequency structure important for noise in detection band.
- The “gap” in between guarantees that it makes sense to use a simplified model for control.

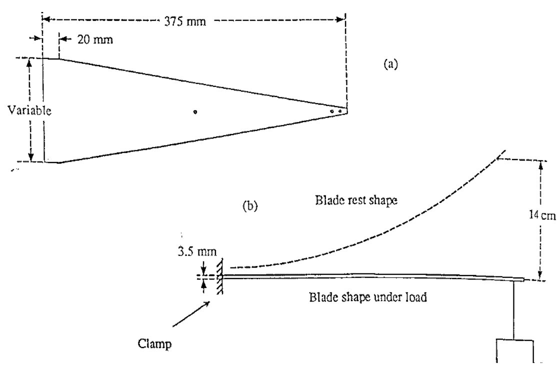
Model construction



- Describe elastic elements
  - » Only those relevant in the frequency band of interest!
- Keep the model simple
  - » Possibly limit to a effective potential representation

$$U = \frac{1}{2}\int_0^L EI\left[x''(z,t)\right]^2 + T\left[x'(z,t)\right]^2 dz$$

  - » Neglect higher order modes (violins) for control studies, keep them otherwise.

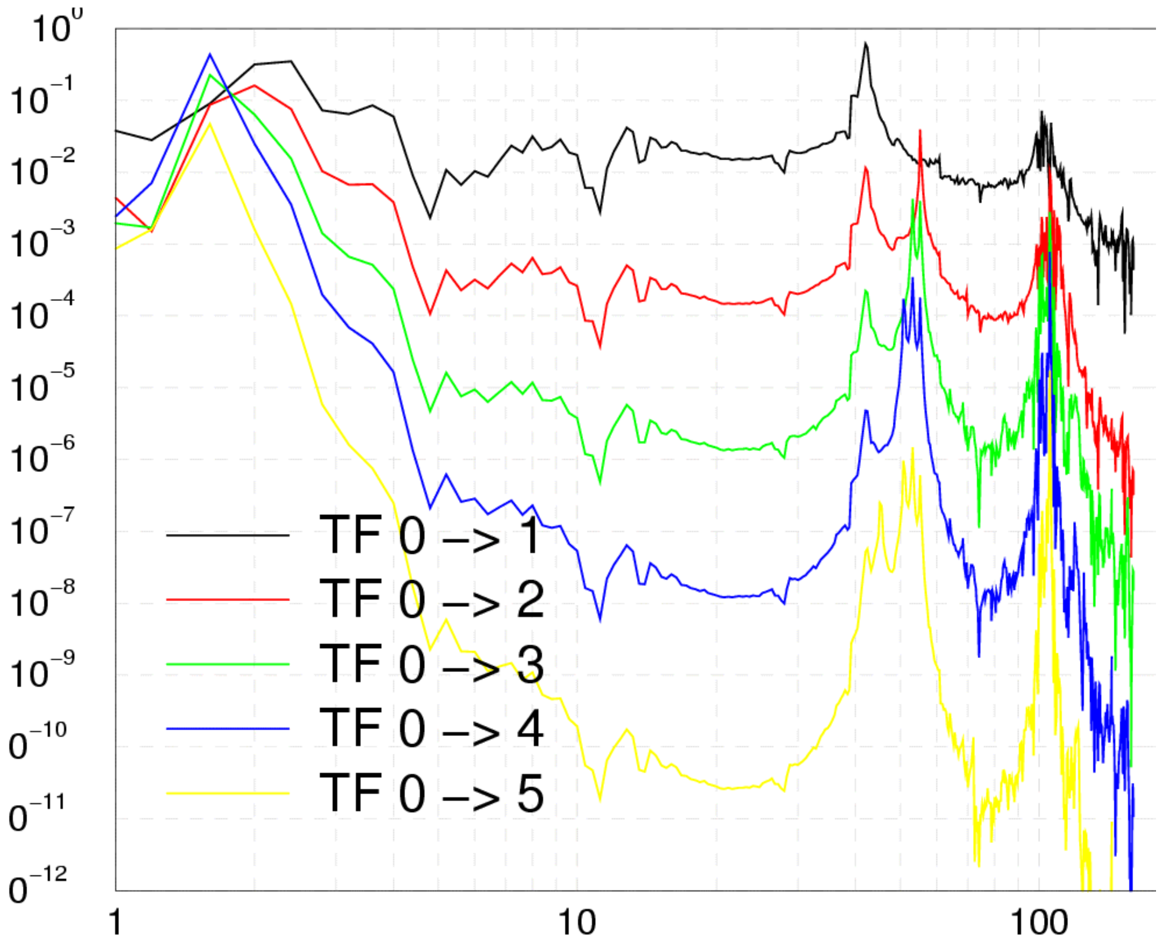


Left: VIRGO blades for vertical attenuation

Simulation parameters and tuning

- In VIRGO we chose to start from *physical* parameters
  - » Masses, characteristics of wires and blades, strength of magnets …
  - » Some are better known, other are actually approximate
- An alternative approach would have been to see the mechanics as a black box
  - » One could define it as a MIMO model and then fit its parameters
  - » Advantage of generality, but total loss of contact with the instrument
- The tuning is a typical (hard) inverse problem
  - » Physical parameters as a basis
  - » Mode identification to select subsystems
  - » Parameter tuning using mode characteristics and TF measurements

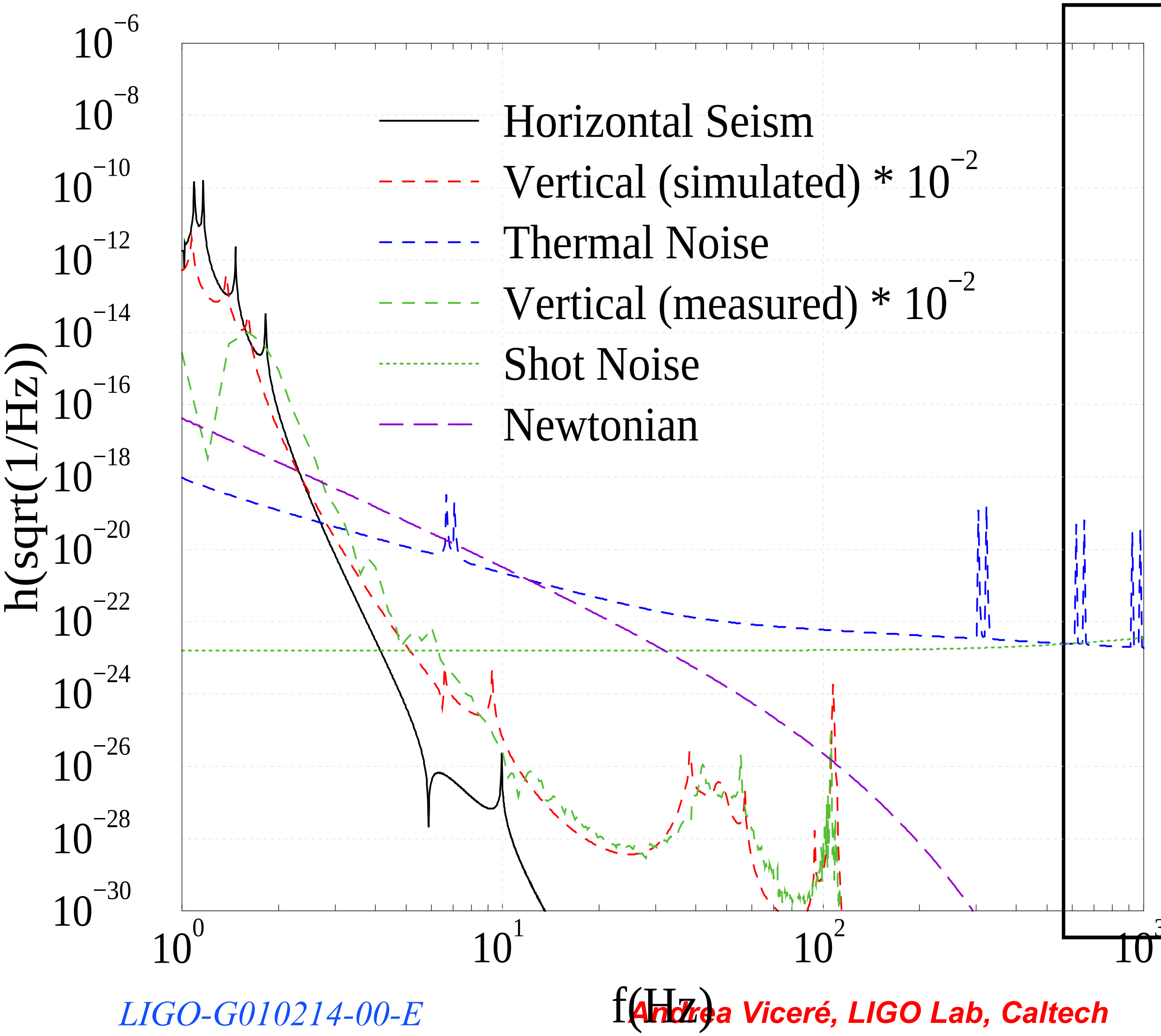
Example: vertical performance



S.Braccini et al

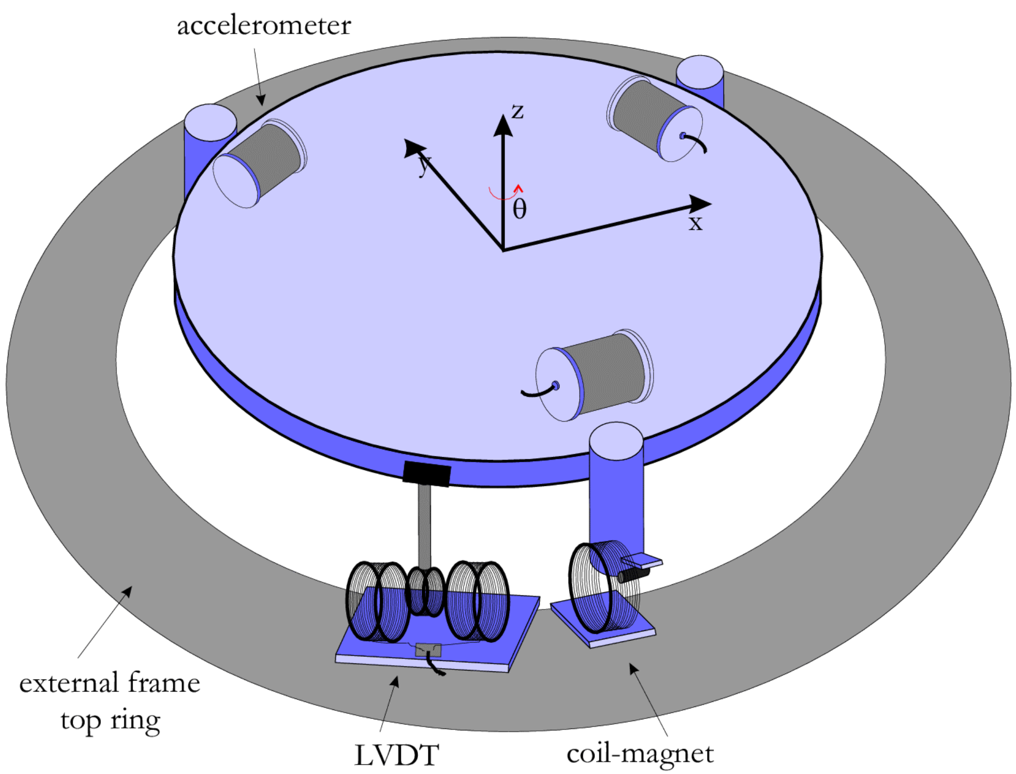
- Impossible to measure the entire SA chain TF !
  - » Only the ITF shall have the sensitivity needed
  - » Possible to measure stage by stage
- Compose the partial SA TFs to obtain the full one

Seismic noise and sensitivity



- Vertical seismic noise dominates over horizontal, in the detection band
- The stage-by-stage measurement agrees with simulation → confidence that no effect has been forgotten
- Blade resonances come close to the sensitivity curve, in quiet conditions: for safety, in the Cascina suspensions they have been damped.

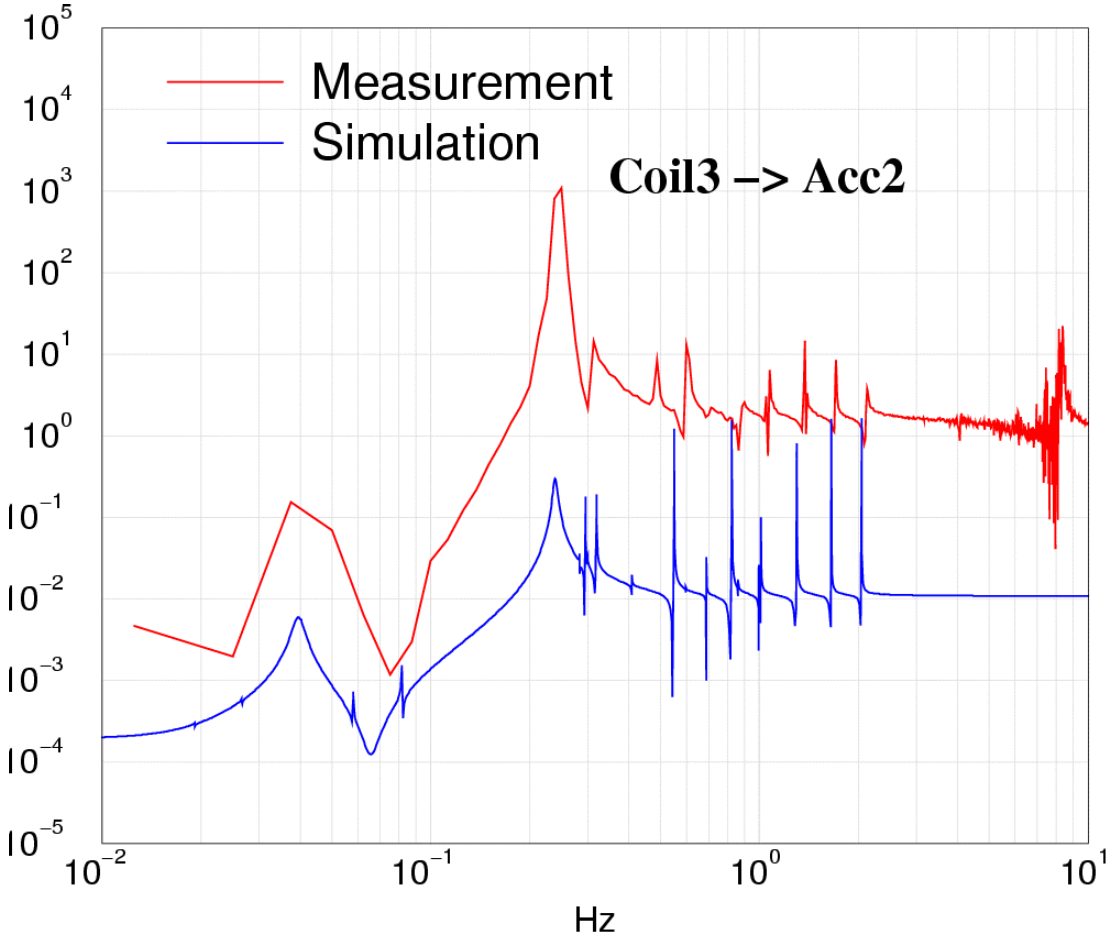
Passive isolation is not enough



Courtesy G.Losurdo

- At low frequency the SA is an "amplifier"
- An array of sensors picks up the motion, where is larger, and feedbacks it.
  - » Below 10÷20 mHz the system is "locked" to the ground
  - » In the [20mHz, 5Hz] it is locked to the inertial frame
- How this system performs?

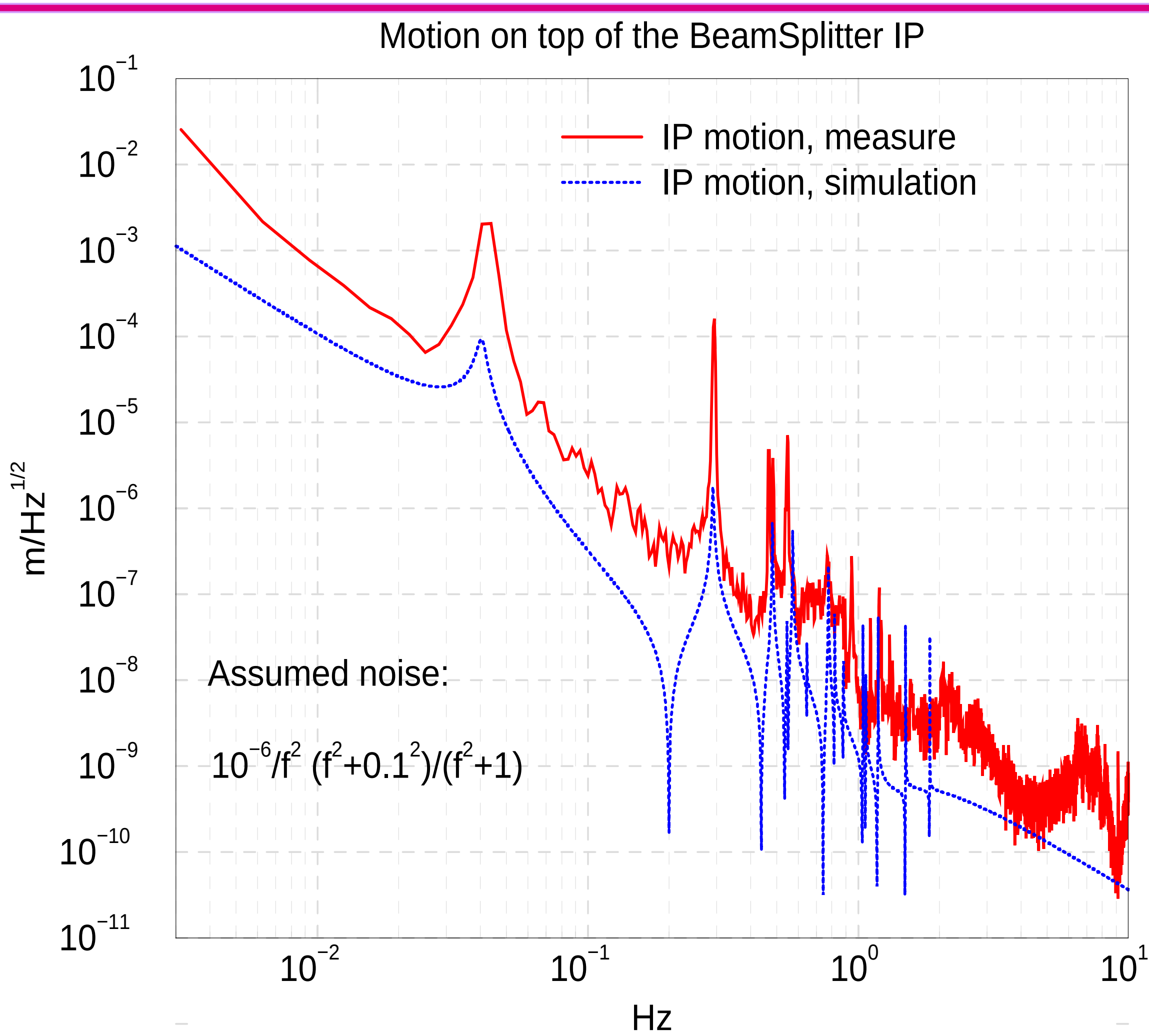
Actuator response



- On top of the IP the sensors allow to measure the response to control forces
- The simulation can be tuned to reproduce the main features.

Data: courtesy by A.Gennai

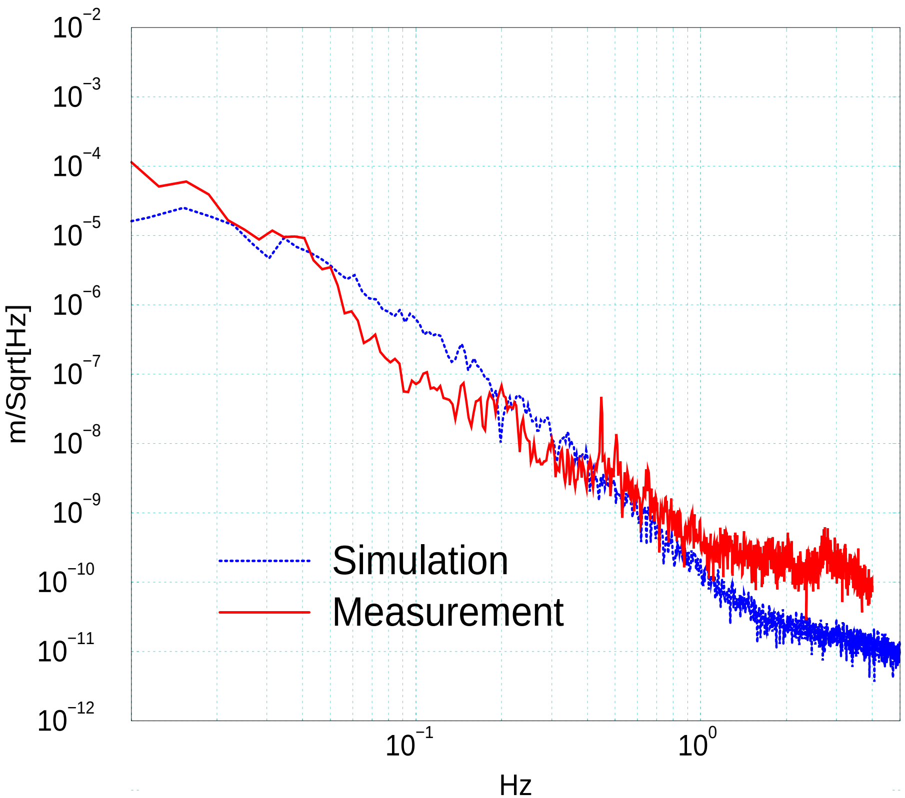
Response to seism: open loop…

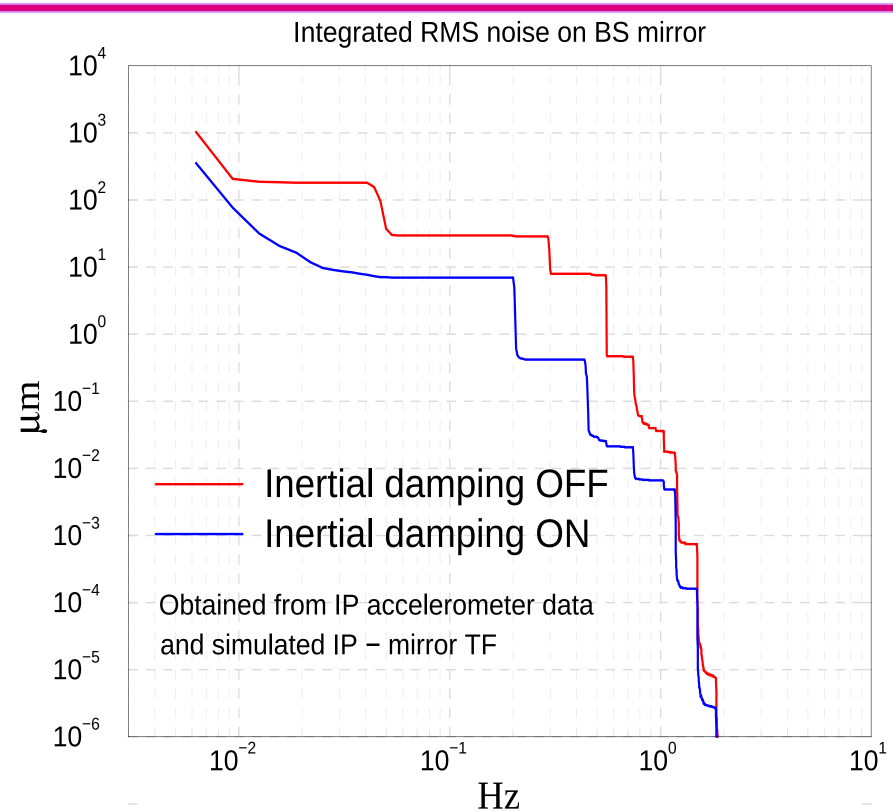


- Assuming a model for the noise, the IP motion can be estimated.
- The absolute scale is wrong, but the main features are reproduced

Data: courtesy by G.Losurdo

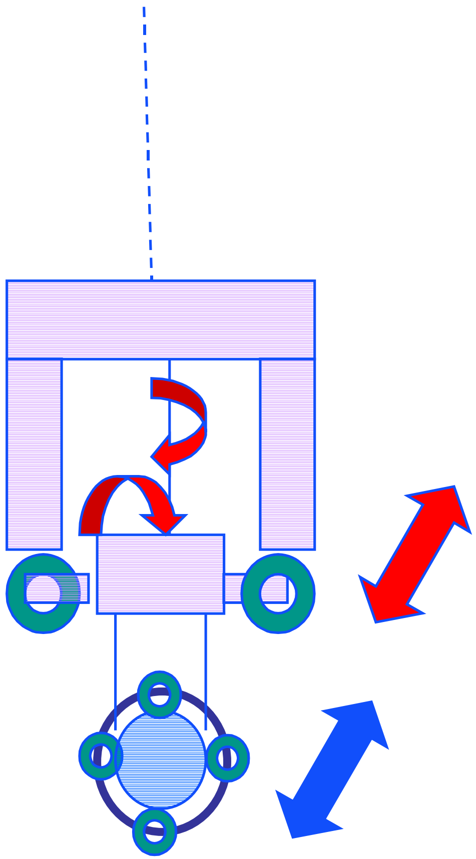
…closed loop





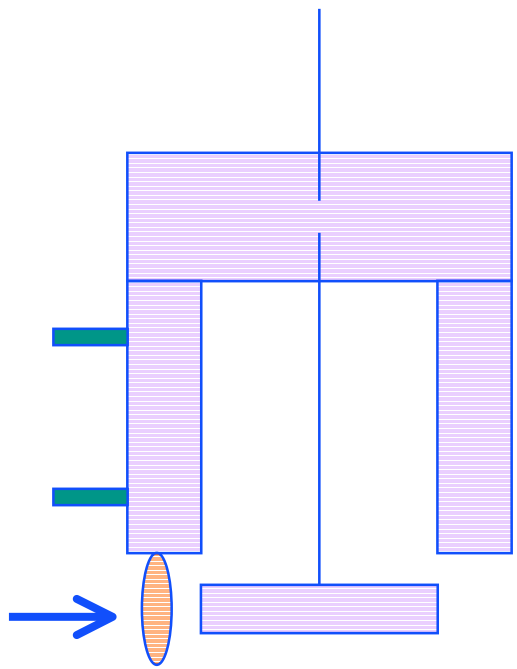
- **Left**: simulation and measurement on top of the IP
- **Right**: the residual *predicted* RMS on the test mass, using as input the *measured* motion on top of the IP

Next step: steer the mirror



- Force response from the reference mass is simple
  - Just the response of a pendulum
- More complex is the response from the marionette
  - This stage is *necessary* for yaw and pitch, and *desirable* for coarse longitudinal action
- Problem: not easy to tune the simulation parameters
  - Poor inputs
  - No permanent sensors to monitor the motion of the elements.

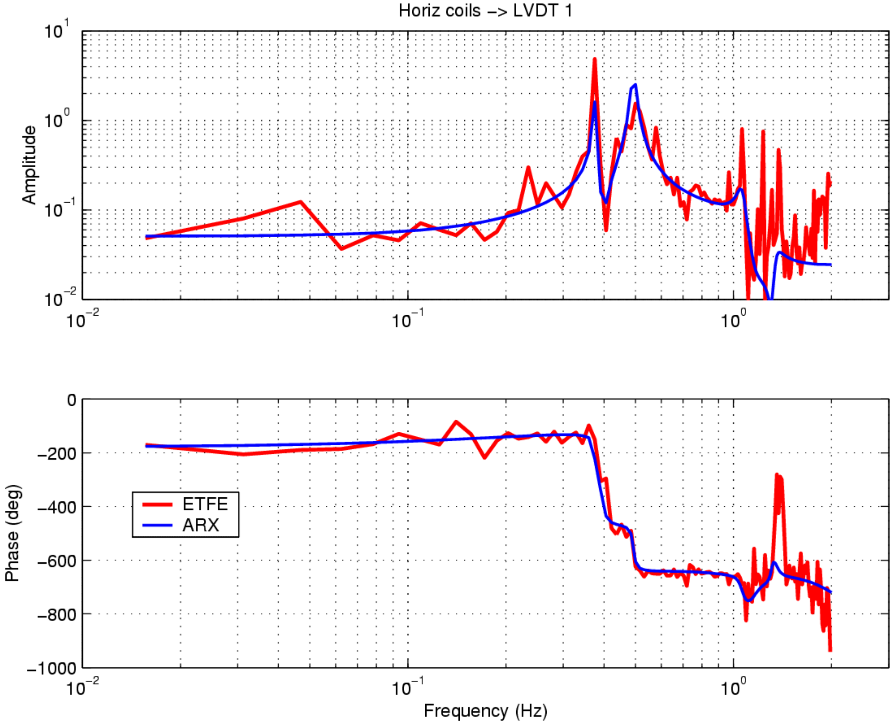
A system identification problem…

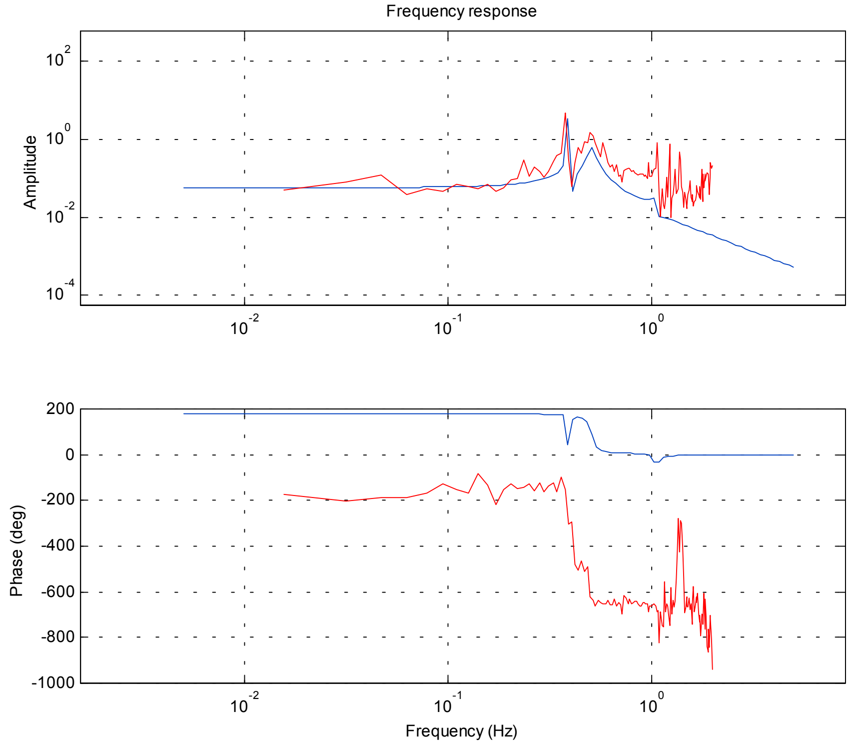


- Isolate the less known element: the steering filter
- Suspend and add a mock payload
- Actuate using the standard coils
- Read the motion in 3D using small LVDTs mounted on its surface
- Register inputs and outpus, compare with the model and tune its parameter

With A.Di Virgilio et al.

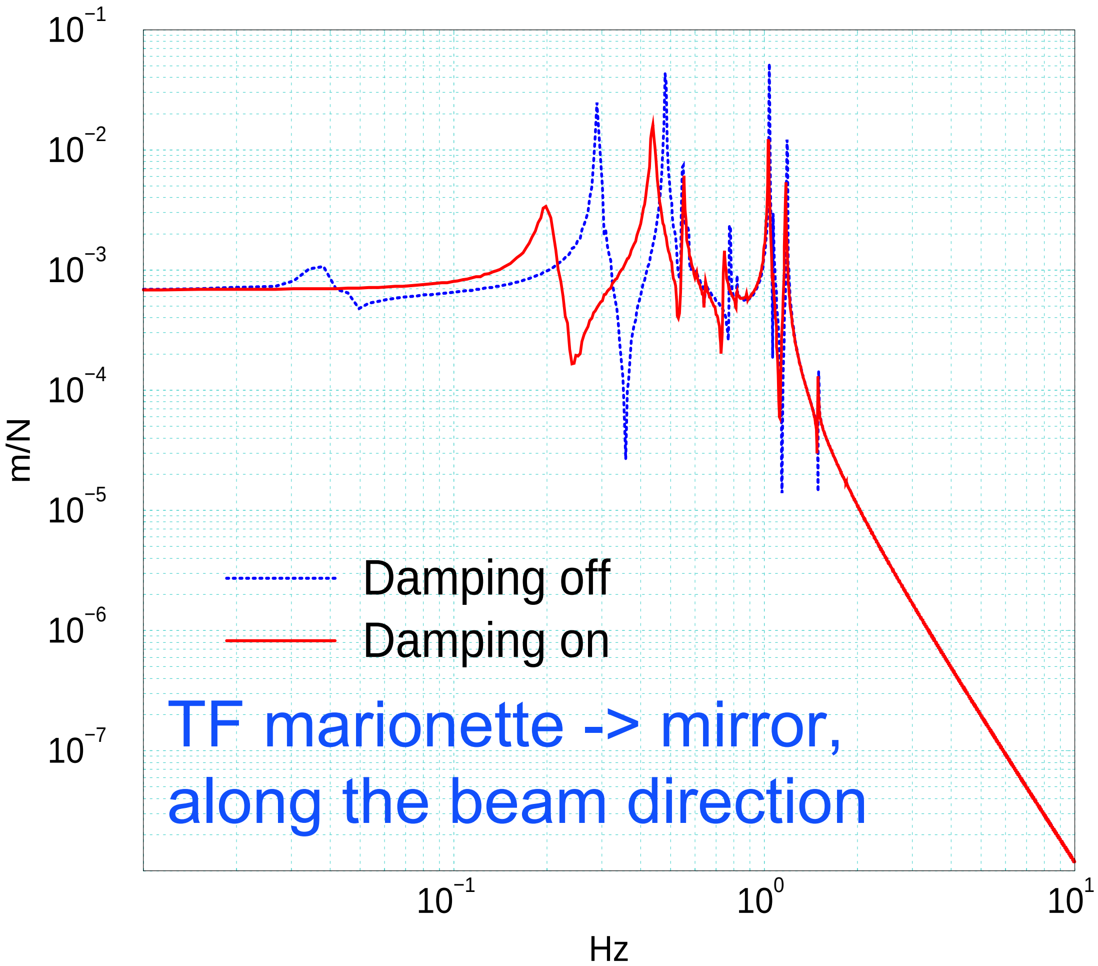
…with some difficulties





- **Left**: a fitted linear model between inputs and outputs successfully fits the output spectrum → good data quality
- **Right**: a model based on physics gives a less successful fit → extra DOF are excited, which the model ignores.

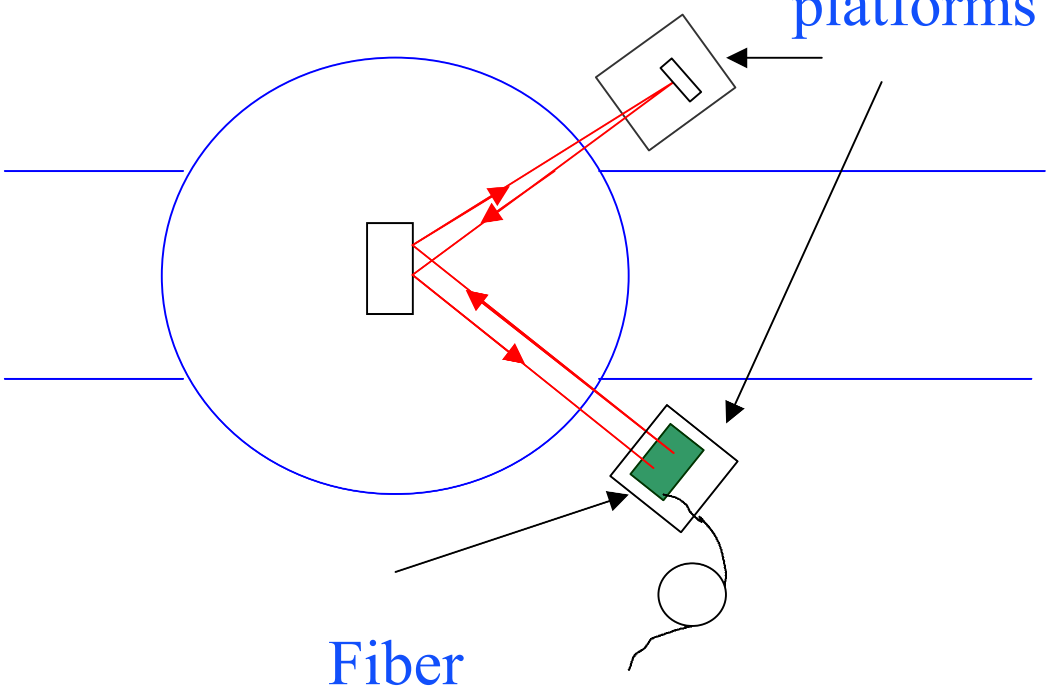
More accuracy is needed



- To be able to reach high gains, transfer functions like this are needed with good accuracy
- The pole/zero structure depends on the gain of the inertial damping!
- A (well tuned) model is indispensable to build an adaptive control loop

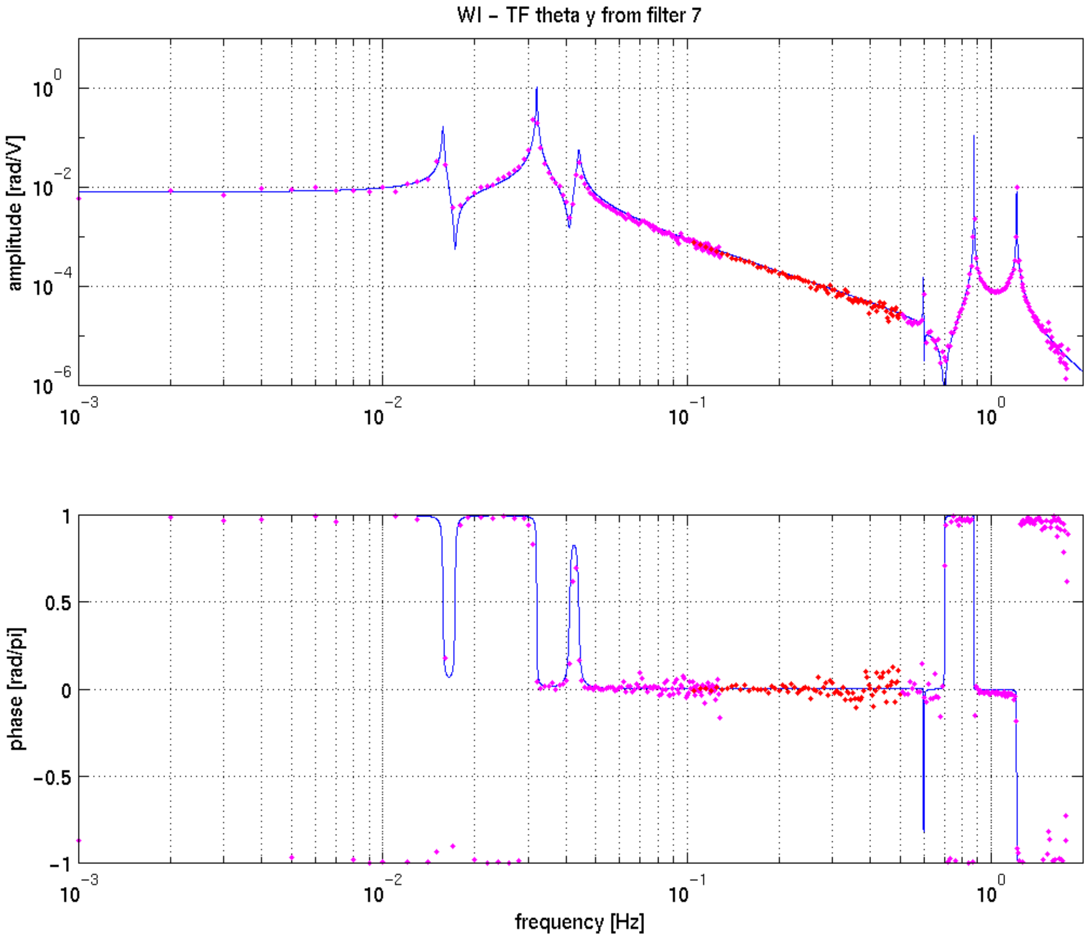
TF measurement: the "lavatrice"

L.Di Fiore, E.Calloni et al.



- A fiber Mach-Zender interferometer
- Angular motion by beam translation, using a PSD, in open loop.
- Longitudinal motions picked up by fringe interference, in closed loop, using a PZT to lock the interferometer
- A single stage suspension is sufficient to reduce the seismic noise at a level which allows TF measurements.

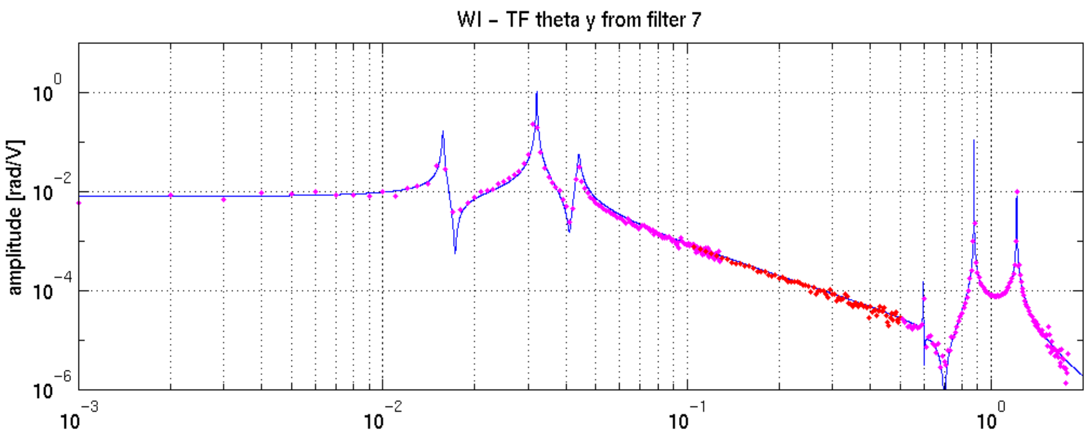
Angular (yaw) TF on West Input

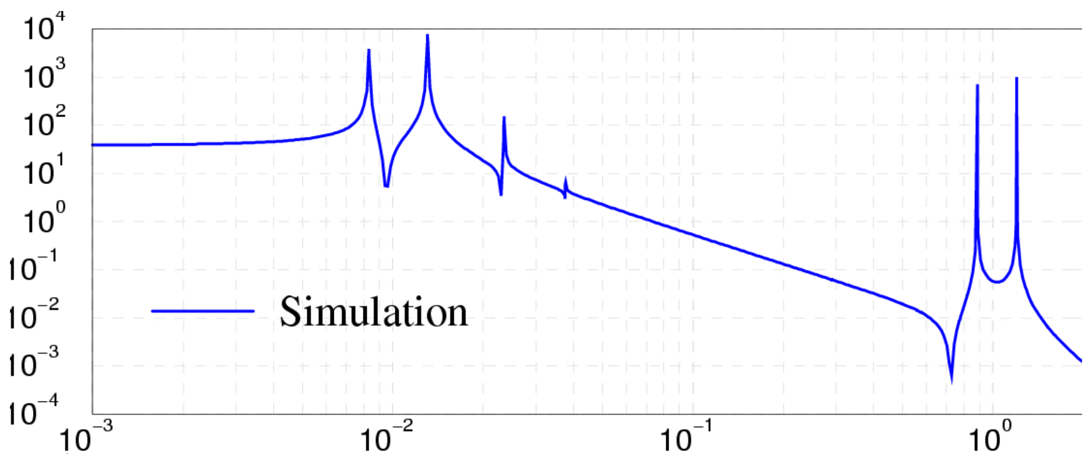


- The color of the data points is related to different runs, with different levels of input force.
- The line is NOT the simulation, but a zero/pole fit to the data!!
- The measurement is taken with inertial damping on, to have some control on the mirror position

Exp. Data: L.Di Fiore

Still the yaw, against simulation

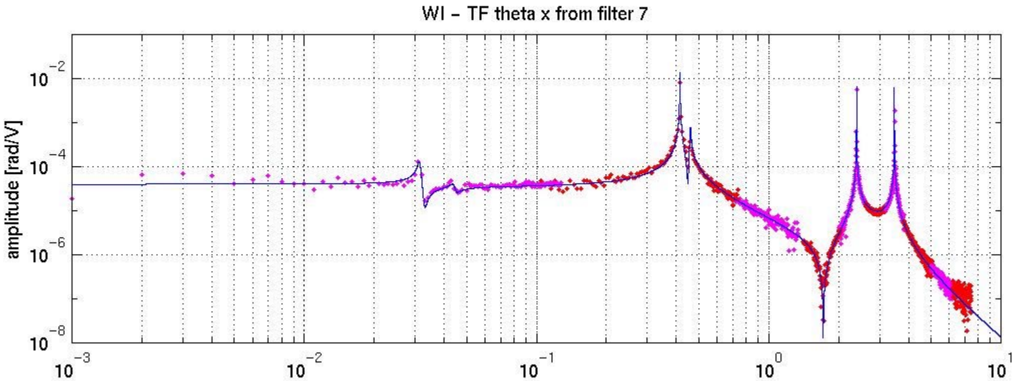


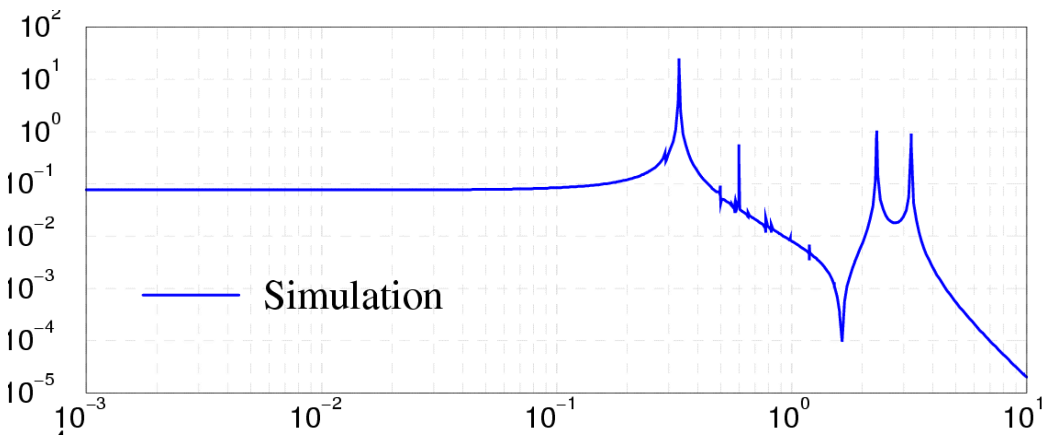


- Main features ok
- Low frequency resonances shifted: wrong momenta of inertia for the filters.
- After tuning, one expects good agreement …

Exp. Data: L. Di Fiore

Pitch motion

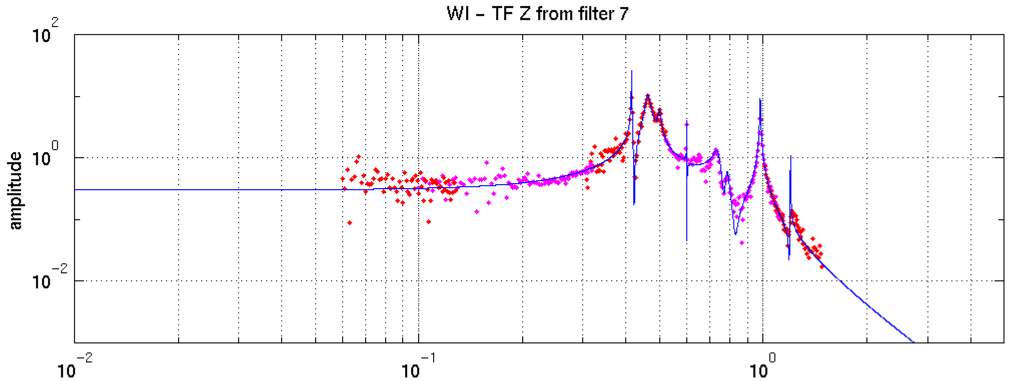


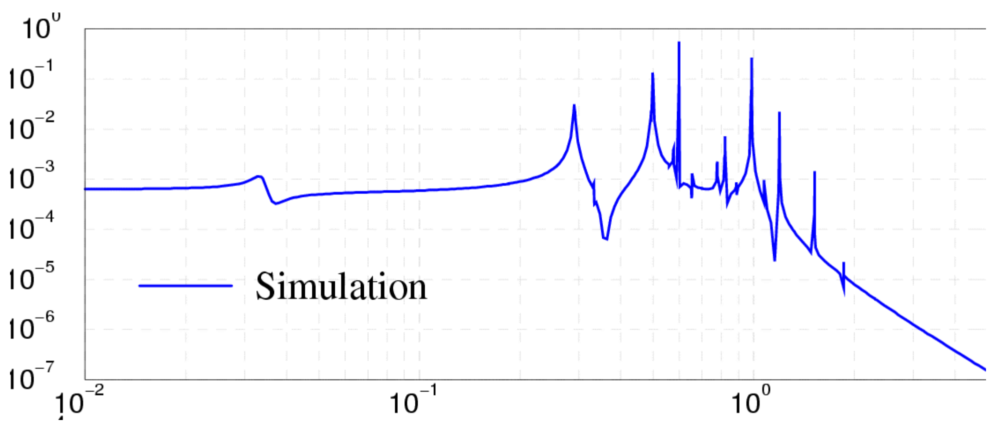


- Similar scenario: reasonable agreement, some tuning to be done.
- Note the zero/pole at 30 mHz in the experimental data: it is a mixing with longitudinal motion.

Exp. Data: L. Di Fiore

Longitudinal TF from steering filter

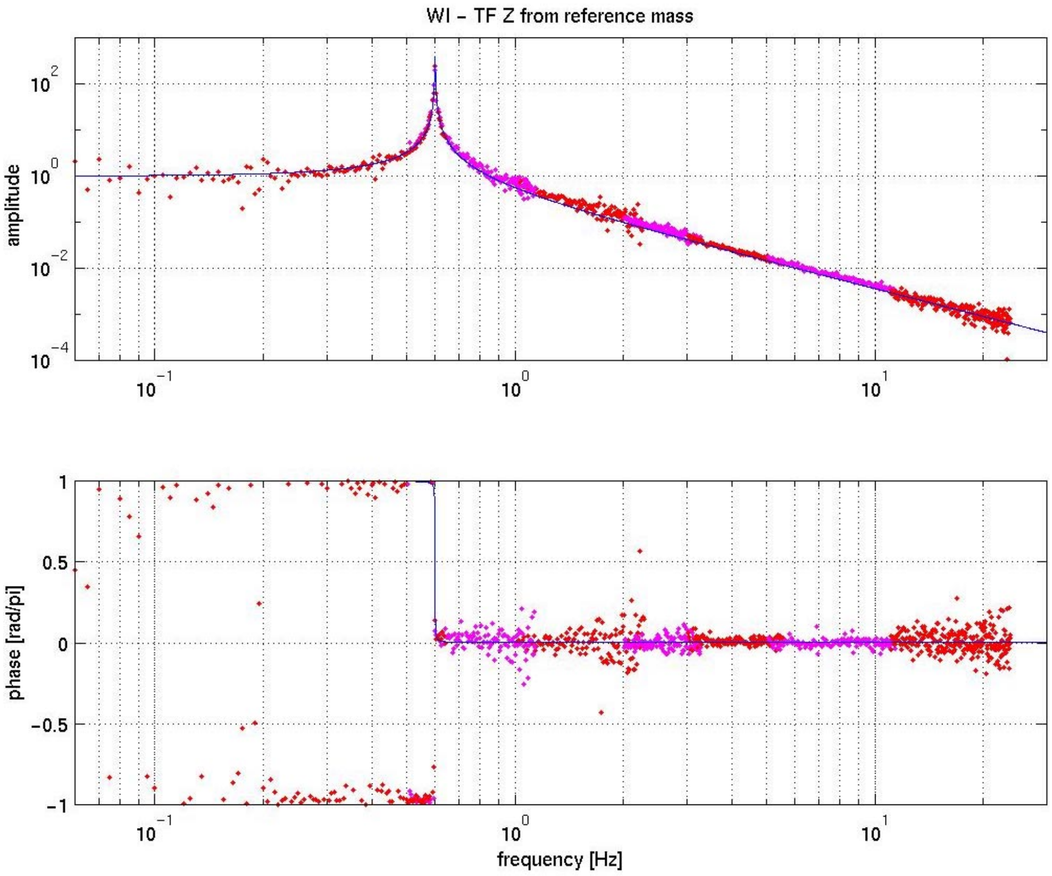




- Quite a large disagreement … still some tuning work is required!
- Note however that this TF is less critical for the CITF: the noise level allows to lock from the reference mass

Exp. Data: L. Di Fiore

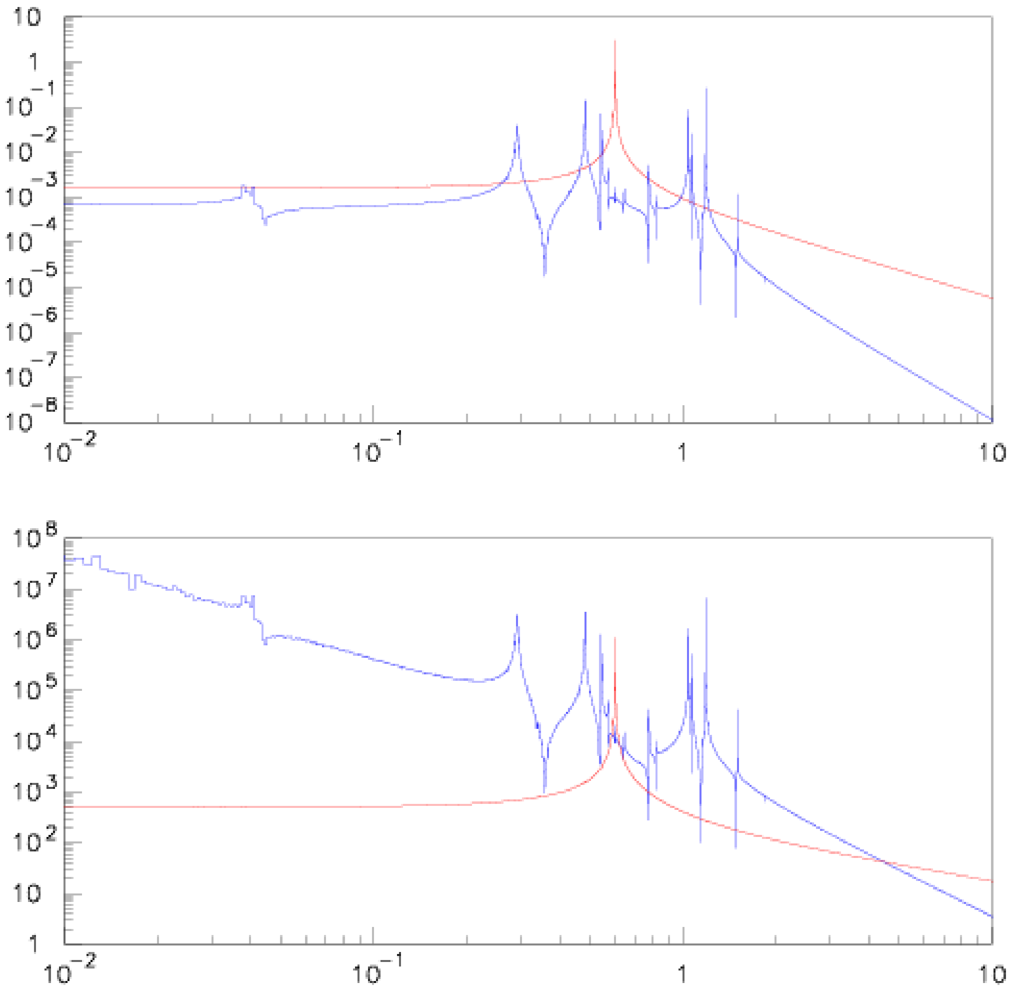
From the reference mass



- No surprises, and no need to compare with the simulation.
- Note however that the Q factor cannot be deduced from this curve: the measurement time was limited

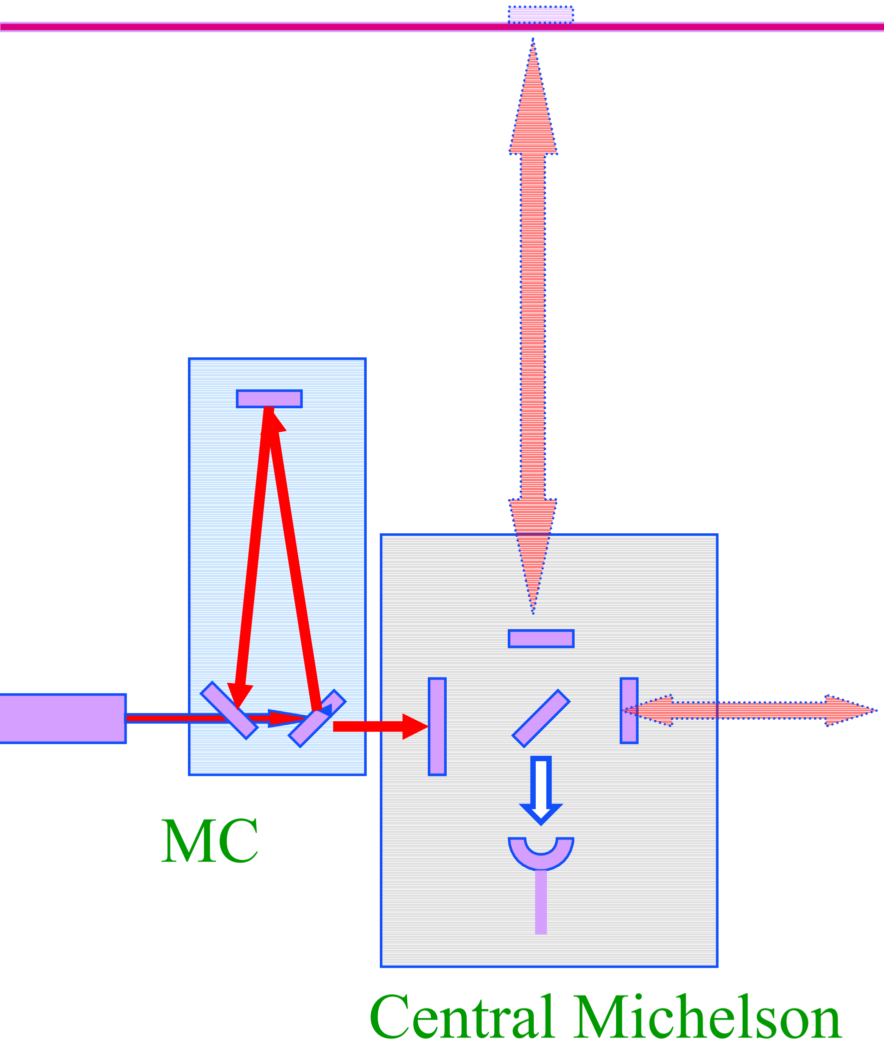
Exp. Data: L. Di Fiore

Mirror longitudinal control



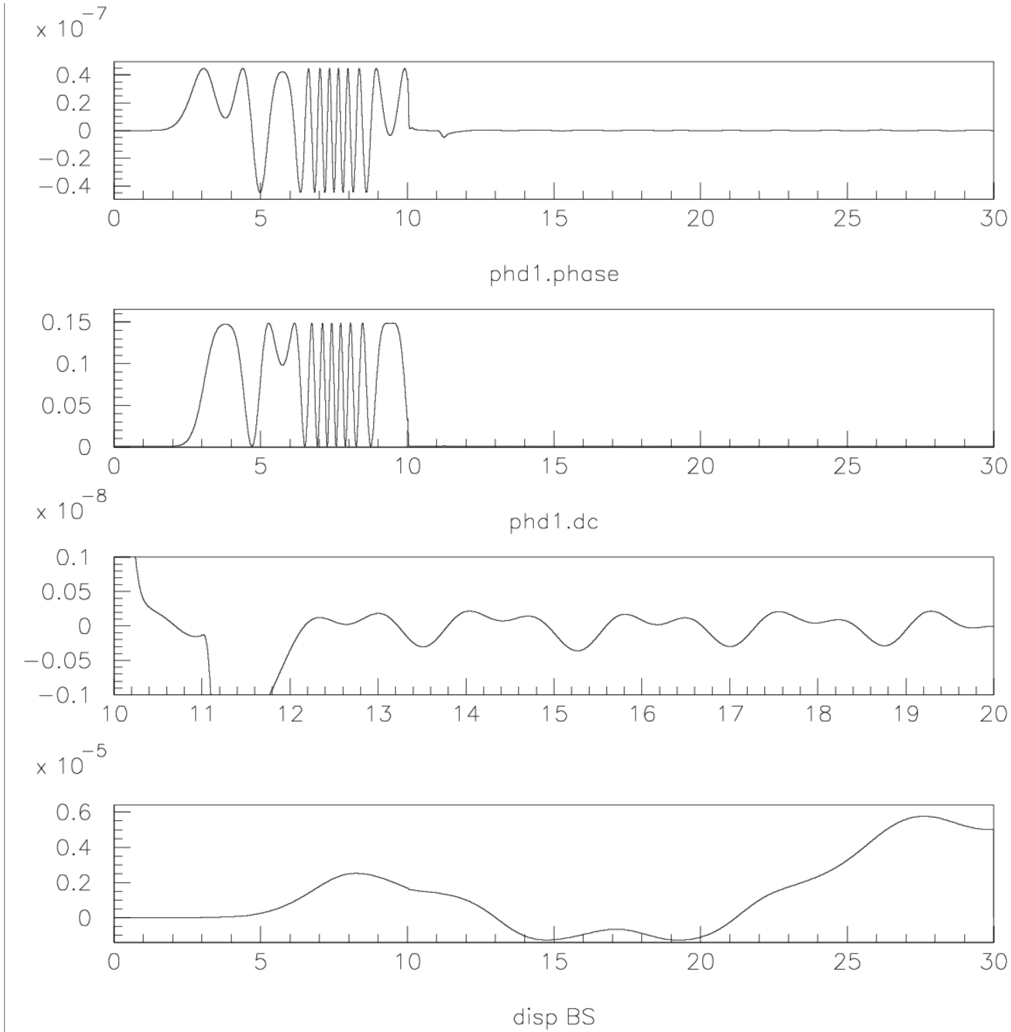
- » Should use both marionette and reference mass
- » Simple filter on the marionette, plus compensator for poles and zeros.
- » Unity gain set around 30 Hz
- » Include saturation and digitization effects, electronic noise in DAC and ADC …

Central InTerFerometer locking



- While long arms are being build, VIRGO exercises locking in the central Michelson and the CITF
- Currently the MC and the Michelson are operated as separated ITF.
- Once both are locked, they shall be operated as a single instrument, until the arms are commissioned

Example: lock acquisition



- Simple Michelson (VIRGO CITF configuration)
- Longitudinal control using both marionetta and reference mass
- Initial experiments, still with a low gain
- “d1” is the dark fringe photodiode,
- Suspensions, optics, locking filters, all is simulated within the *SIESTA* package
- **Soon in reality!**

Courtesy of M.Barsuglia