Optical bench Seismic Isolation System (SAS) Prototyped for the HAM chambers of the Advanced LIGO Interferometers

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Benjamin Abbott(1), Yoichi Aso(3), Valerio Boschi(1,4), Dennis Coyne(1), Riccardo DeSalvo(1), Carlo Galli(5), Gianni Gennaro(6), Alex Ivanov(1), Szabolcs Marka(3), David Ottaway(2), Virginio Sannibale(1), Alberto Stochino(1,2,4)), Chiara Vanni(5),

1) LIGO Laboratory, Caltech, Pasadena, CA; 2) LIGO Laboratory, MIT, Cambridge, MA

3) Columbia University, NY; 4) University of Pisa, Italy;

5) Galli e Morelli, Lucca, Italy; 6) PROMEC, Bientina, Italy

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LIGO-G070695-00-E

Summary

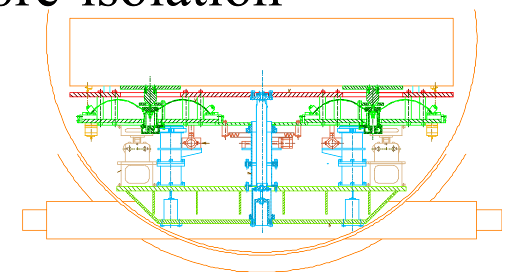
- Motivations for the SAS pre-attenuator

- HAM-SAS prototype
- System Performances
- Platform Controls

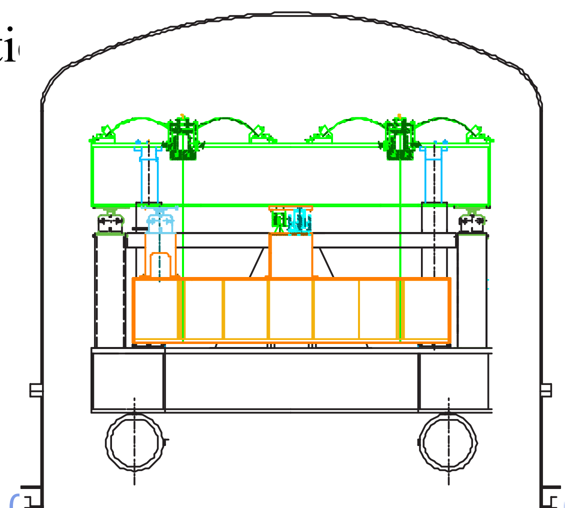
- Conclusions

Design motivations

- Concerns about the complexity, lack of redundancy, long term reliability and cost of the baseline LIGO seismic pre-isolation system, HEPI + ISI.



- HAM chambers version prototyped
  - the most difficult as:
    - Optical table is supported from below the center of mass
    - Difficult installation in cramped space below opti
  - BSC version much simpler and easier to realize
    - All key points tested by the HAM prototype



- Design targets to eliminate concerns:

Design targets: 1

- Instrument reliability:
  - Completely UHV compatible sensors and actuators (coils)
  - No in-vacuum active circuits
  - No in-vacuum pressurized volumes to avoid internal leaks
  - Redundancy of sensing and actuation for immunity from single point failures
- Complexity reduction:
  - Single passive attenuation stage replacing all three active stages of baseline design
  - Mitigation of cradle effect by geometrically separated horizontal and tilt d.o.f.
  - Higher tolerance of lower payload rigidity

Design targets: 2

- Ultra High Vacuum environment protection:
  - Actuation power limited to100 mW max.
    for intrinsic protection against overheating and UHV pollution
- Tolerances and registering:
  - Wide tolerances and registering of critical dimensions (ease of ass.)
  - Designed to withstand 200^{o}C component baking and
    120^{o}C post assembly baking
    - for UHV protection and guaranteed system stability
- Rigidity and controllability:
  - Large frequency ratio (≥100) between suspension resonances and internal resonances:
    - Optimal plant for positioning controls, and for possible future active attenuation upgrades

Design targets 3

- Tunable payload design:
  - To optimize for different loads and possible future upgrades
- Earthquake damage protection:
  - 10 mm stoke protection in all d.o.f. (Olympia 5 mm)
- Cost:
  - Single stage reduces costs by >0.25 to 0.5 M$/unit (HAM/BSC)
    - (5 BSC units and 5 HAM units for each interferometer)
- Fast turnaround:
  - Started production in July 2006, tests stopped in April 2007

Target achievement

- The project evaluation dead time arrived before commissioning could be completed
- the LIGO project was forced to make a decision to stay with the baseline as the HAM-SAS had not demonstrated meeting all requirements by the deadline.
- Some of the data reported below was collected after the deadline

Target achievement

- Commissioning and testing stopped prematurely
  - no time for implementation of Center Of Percussion compensators
  - no time for fine alignments and low frequency resonance tuning
  - Little time for robustness and long term drift and stability measurements and ease of use/integration studies
- The Measured performance is:
  - in agreement with simulations of the system at the tested level of implementation
  - close to requirements/targets
- Means to improve performance have been identified and give high likelihood of being able to achieve requirements/targets with
  - the implementation of the components not yet implemented
  - further testing/development

Key mechanical features

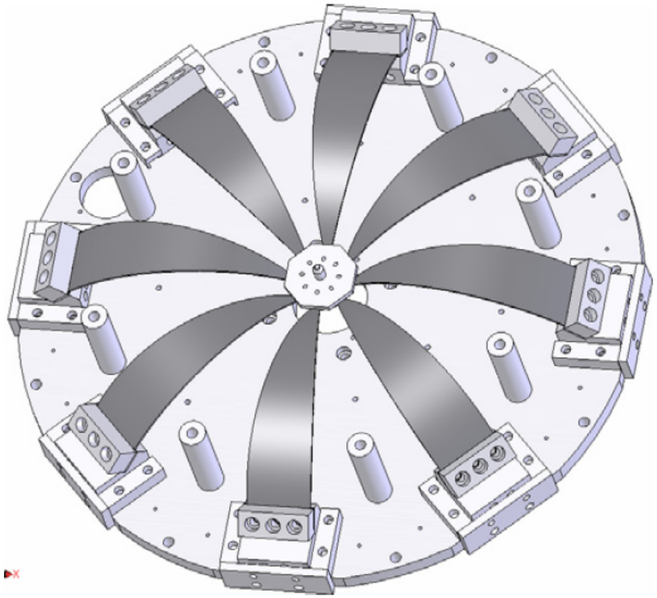
- Designed primarily as a passive attenuation unit
  - Design similar an accelerometer inertial mass.
    - Soft support flexures to reach the lowest possible resonance freq.
    - Isolation performance limited by the flexure material characteristics, equal to the sensitivity of the best seismometers
- Minimally active controls, mainly for static positioning and suspension resonance suppression
  - (But plant optimized also for active attenuation)
- four-legged Inverted Pendulum table for the horizontal degrees of freedom (two translations and yaw)
- four GAS filters in the vertical degrees of freedom (vertical translation, pitch and roll)

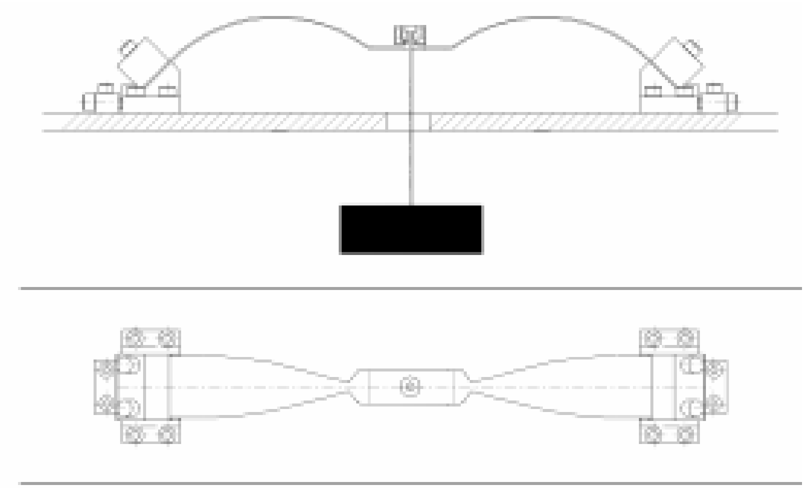
Fundamentals of Passive Mechanical Filter

- Low resonant frequency:
  - ⇨ early attenuation roll-off (<100 mHz)
  - ⇨ small control force requirements (~mN)
  - ⇨ Naturally vanishing resonances $Q \propto \omega_0^{\,2}$
- Center of Percussion Effect compensation:
  - ⇨ high frequency attenuation improvement (x10)

SAS Passive vertical Mechanical Filters

Vertical Isolation: Geometric Anti-Spring Filter (GAS)





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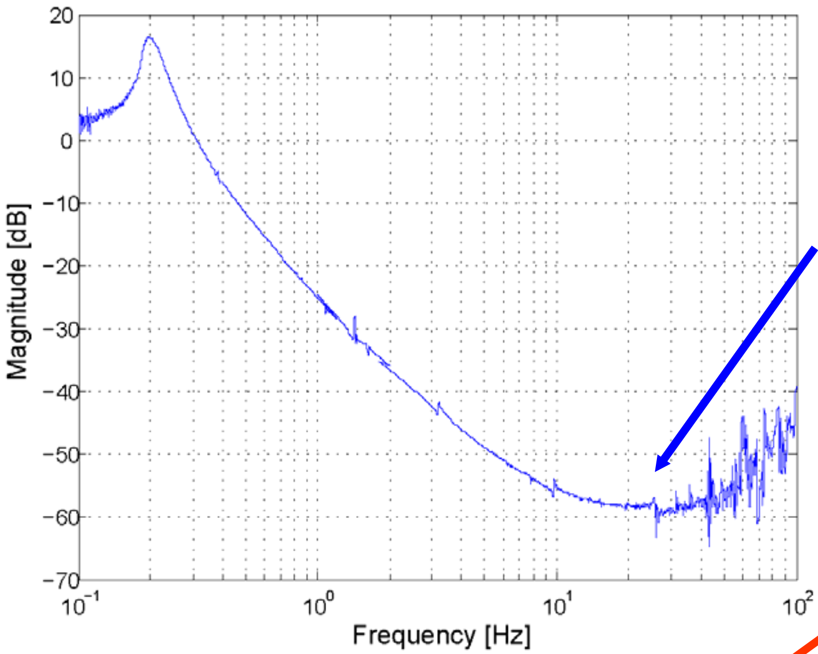
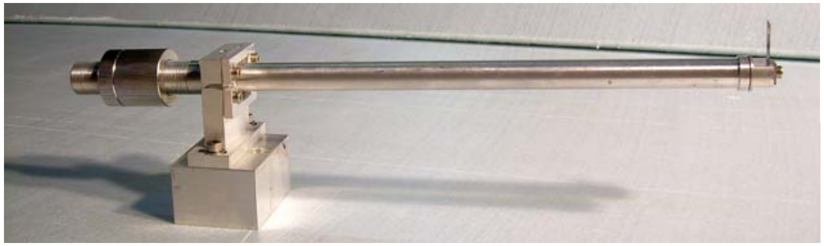
SAS Passive vertical Mechanical Filters



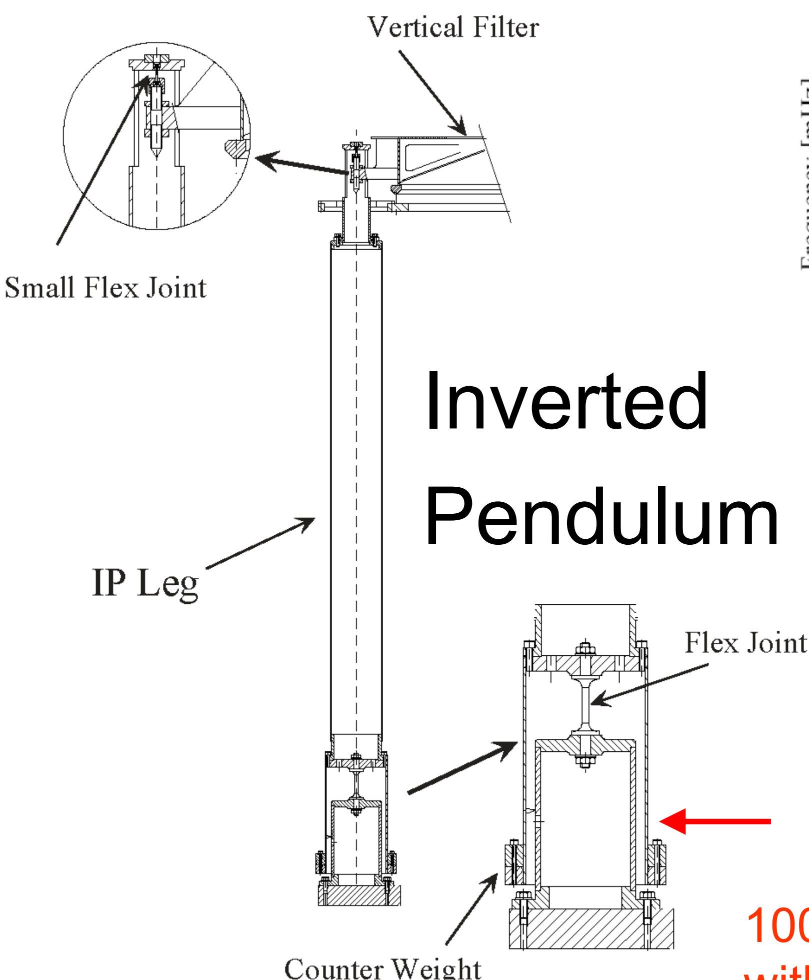
- -60 dB naked filters
- -80 dB with Center Of Percussion compensators

$$H_z(\omega) = \frac{\omega_0^2(1 + i\phi) + \beta\omega^2}{\omega_0^2(1 + i\phi) + \omega^2}$$

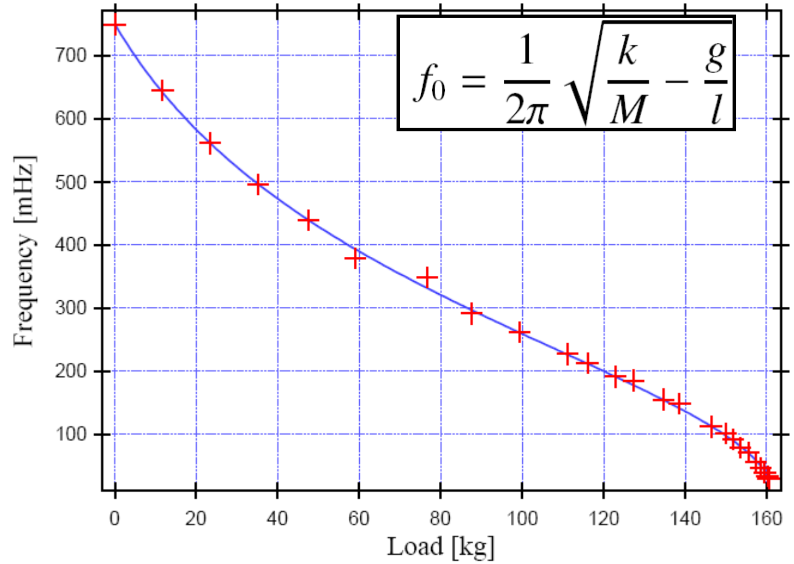


[A. Stochino, et al., Nucl. Instr. and Meth. A (2007), in press: doi:10.1016/j.nima.2007.06.029]

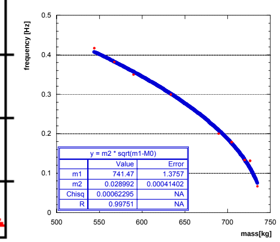
SAS Passive horizontal Mechanical Filters



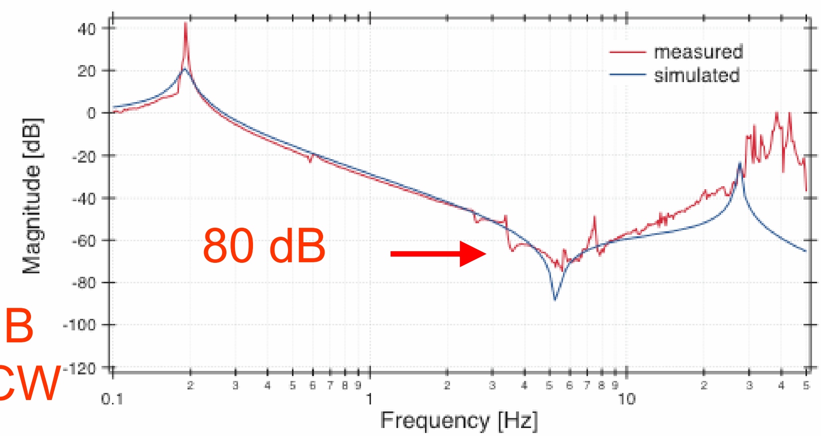
Inverted Pendulum



Frequency vs Load

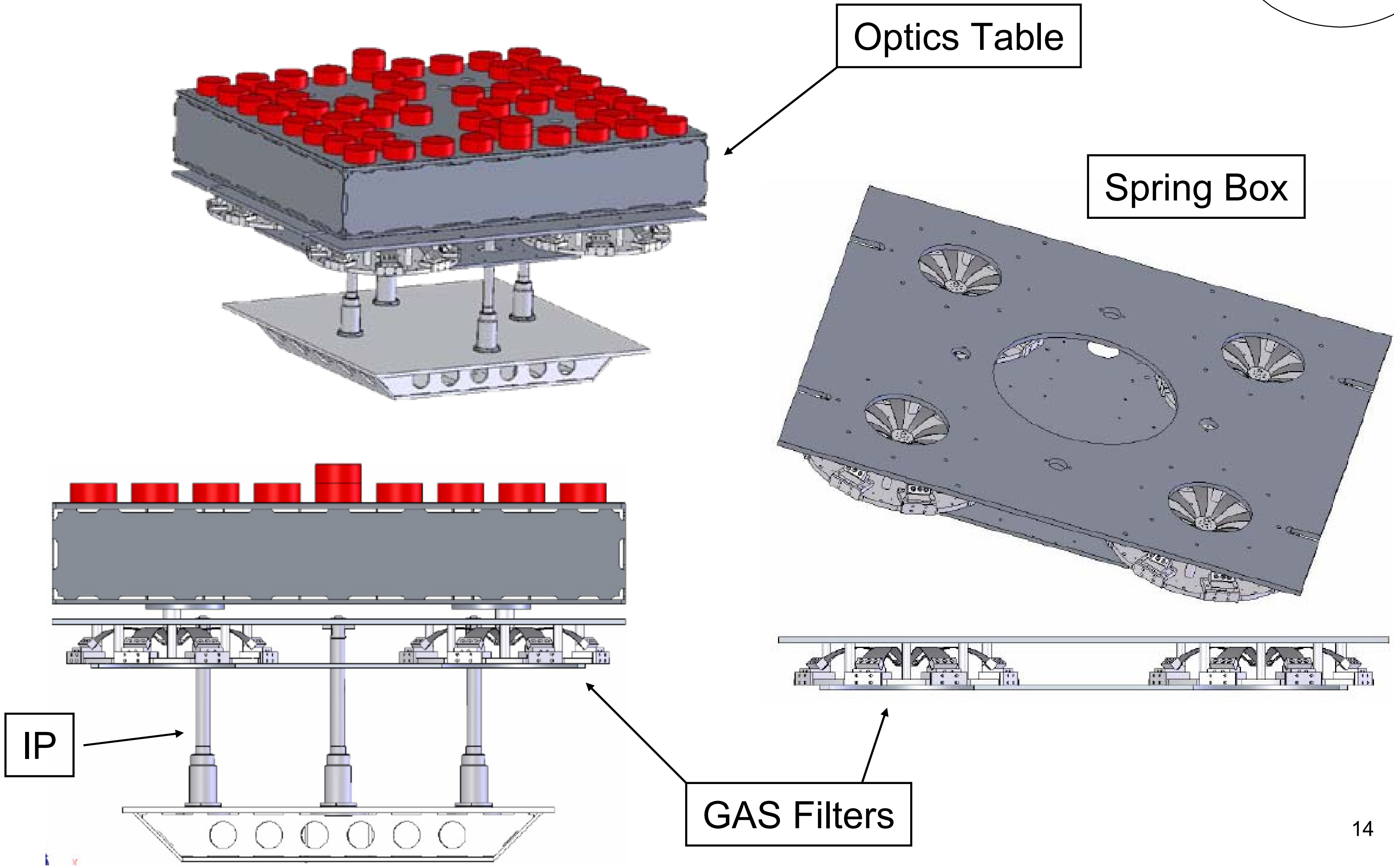


transmissibility

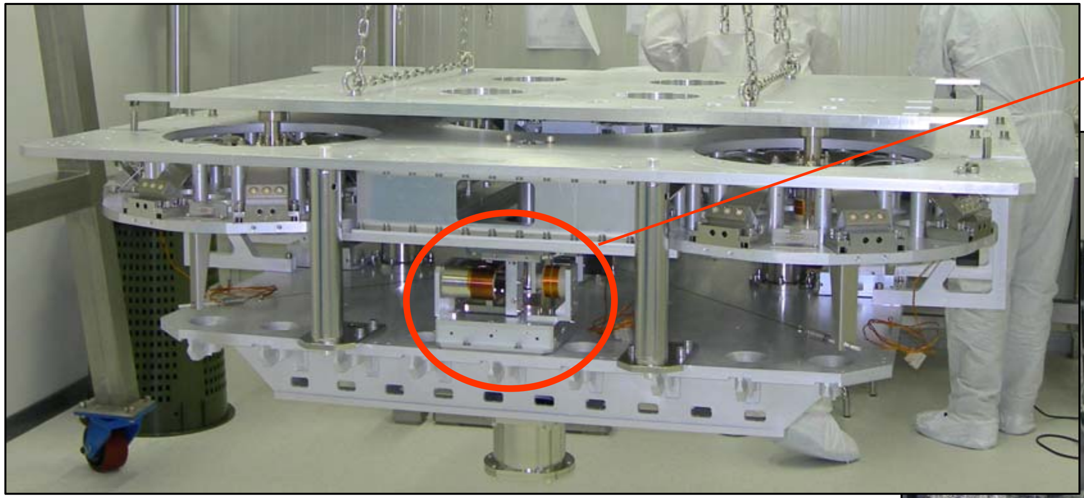


100 dB with CW

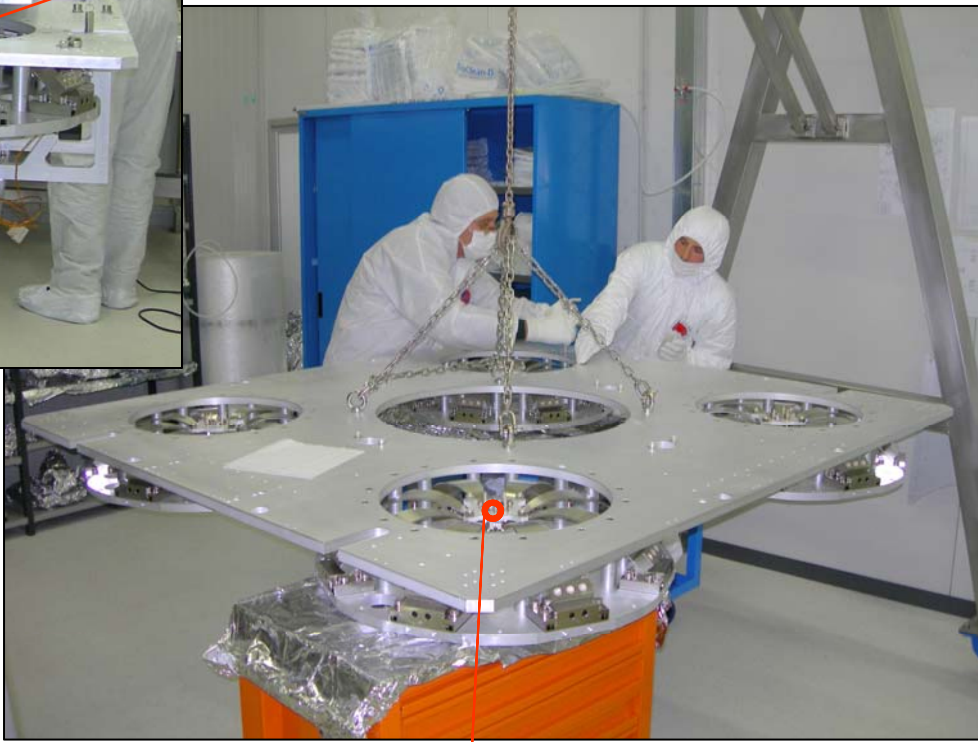
HAM-SAS



HAM-SAS construction



Horizontal Sensor and Actuator

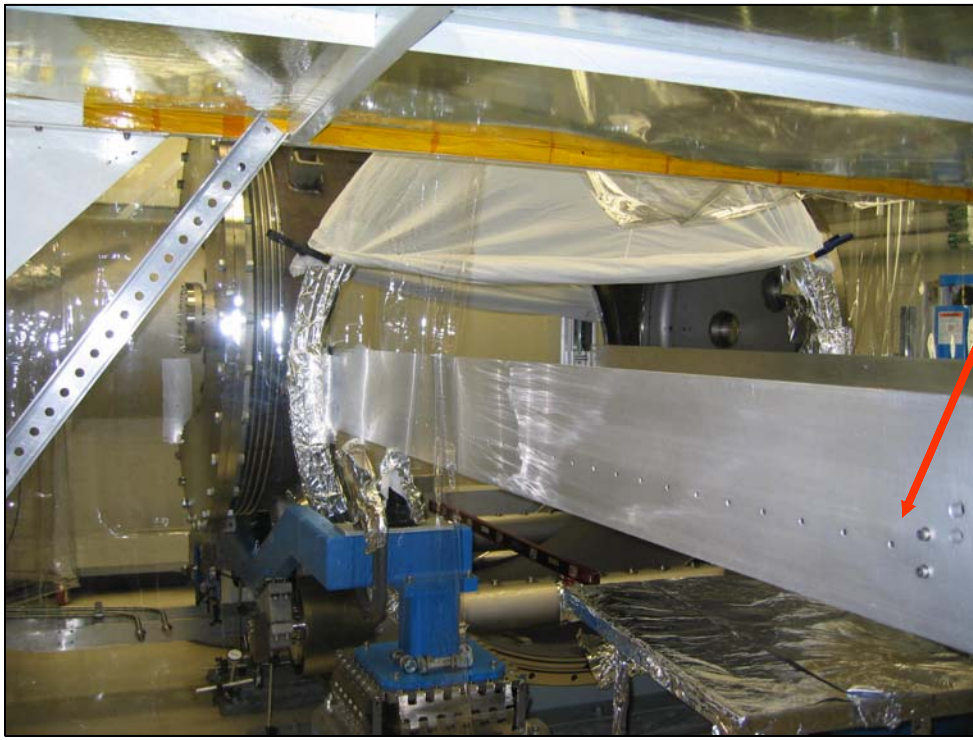


Vertical Sensor and Actuator

The G&M SAS team

The SAS prototype was built, cleaned, assembled and pre-tuned at Galli& Morelli

LASTI HAM Chamber



insertion sliders

- Ease of installation
  - Designed and built UHV installation machinery
  - Allow installation of populated HAM bench

Sensors/Actuators

- Standard instrumentation
- 8 LVDTs
  - 4 horizontal: position spring box <–> ground
  - 4 vertical: position optics table <–> spring box
- 8 voice coil actuators
- Redundancy of 1 each 3 d.o.f. for reliability

- Test instrumentation
- 6 L4C witness geophones on the optical bench

- 3 Guralp seismometers on ground

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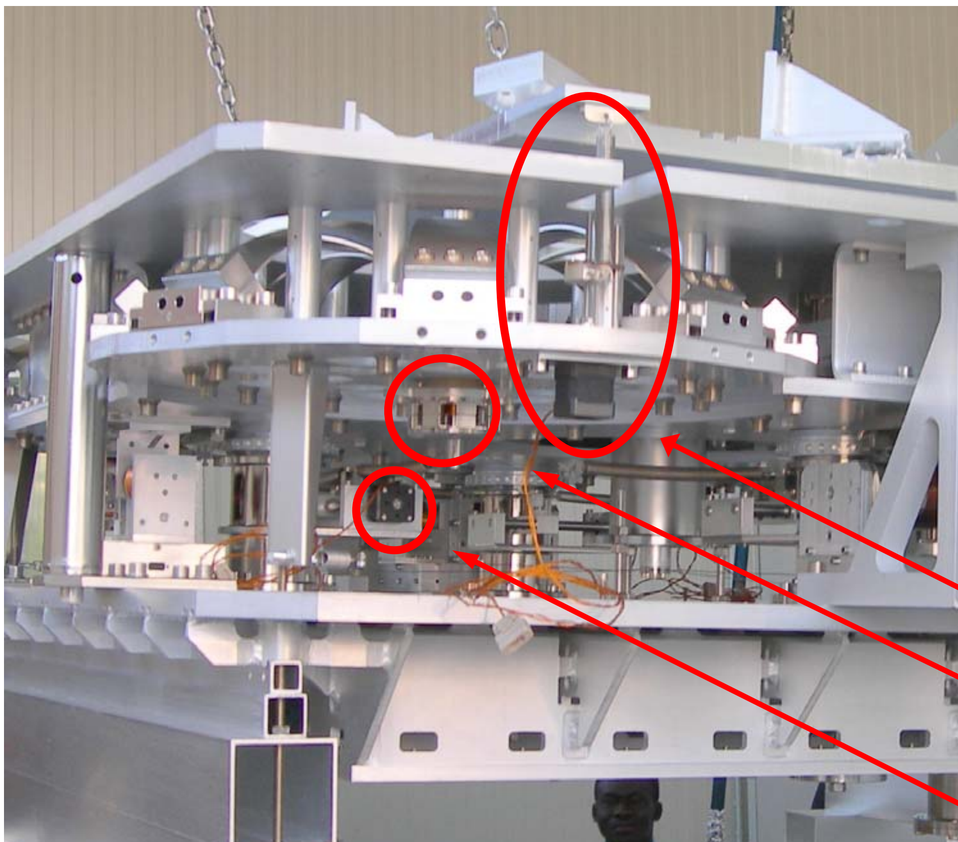
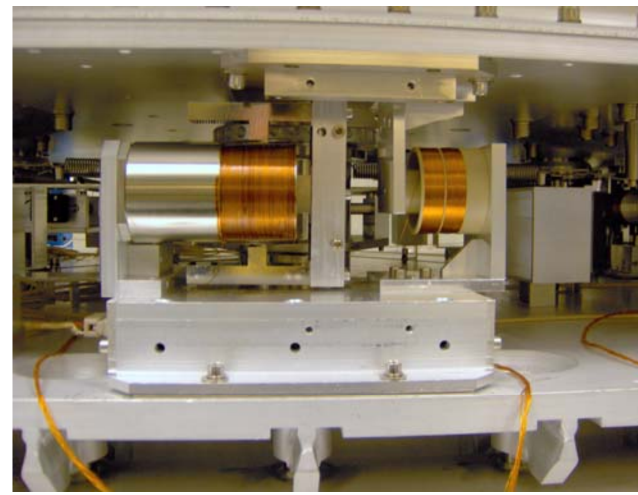
Seism Busters

Actuators

- 8 coil actuators coaxial with the LVDTs
- 8 stepper motors set the equilibrium position of the optics table



Horizontal actuator and LVDT



Vertical stepper motor

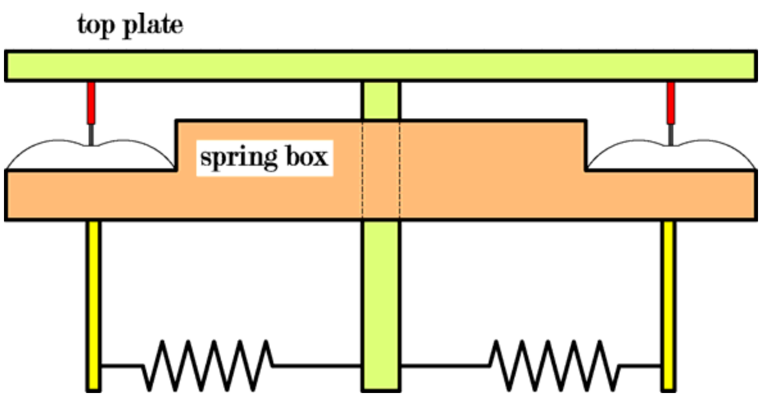
Vertical actuator

Horizontal stepper motor

Angular Stabilization

- Center of Mass in HAM is above the tilt rotation axis
- Very low stiffness of the tilt modes makes the optics table angularly unstable

⇨ add stiffness exclusively to the angular modes (Rx and Ry)



$$k_{tilt}^{(z)} = 4\left(1 - \frac{l_0}{x_0}\right)k$$

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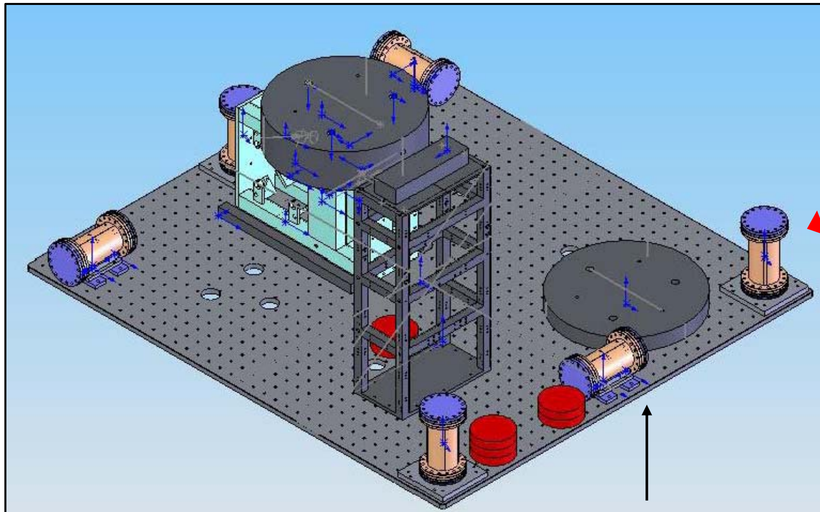
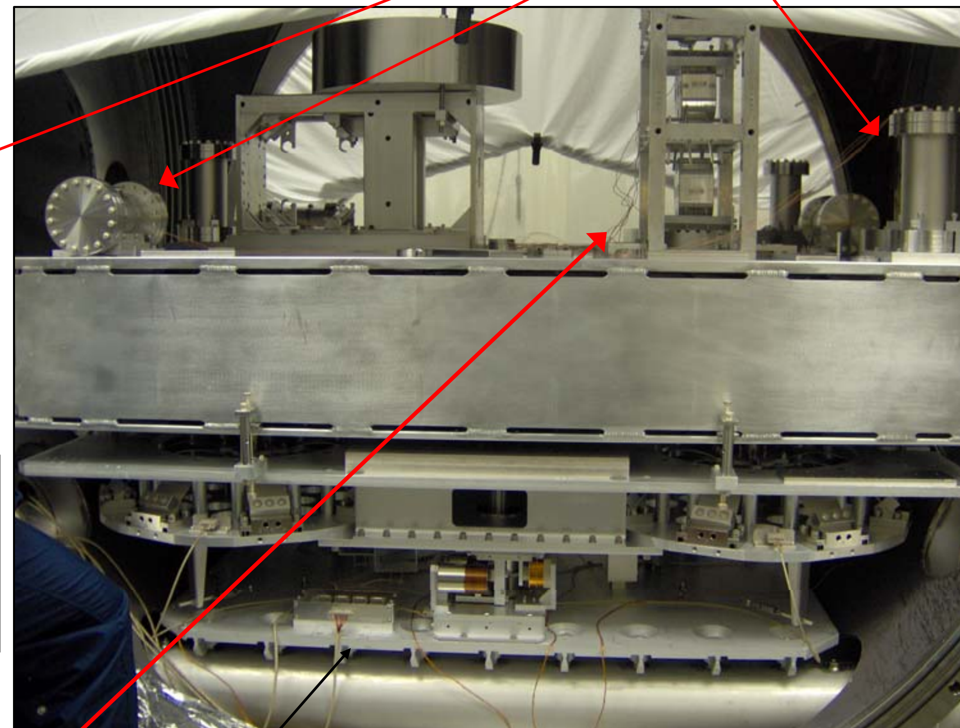
HAM Optics Bench tests

geophones





optics bench Configuration

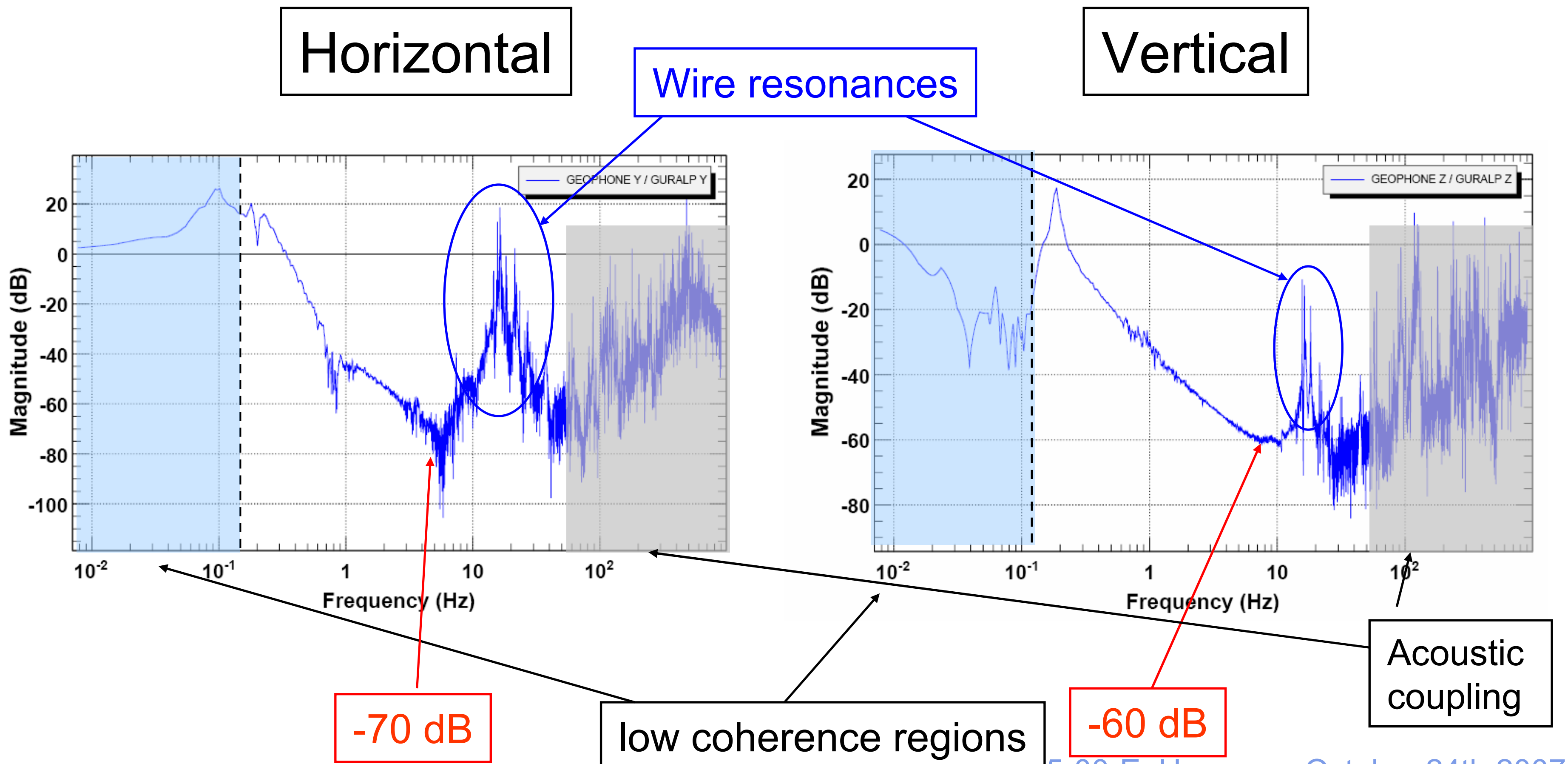
System Tested with higher Center of Mass than In worst possible case

triple pendulum

HAM-SAS supporting the optics table

Transmissibilities

Geophones/Seismometers (in air)



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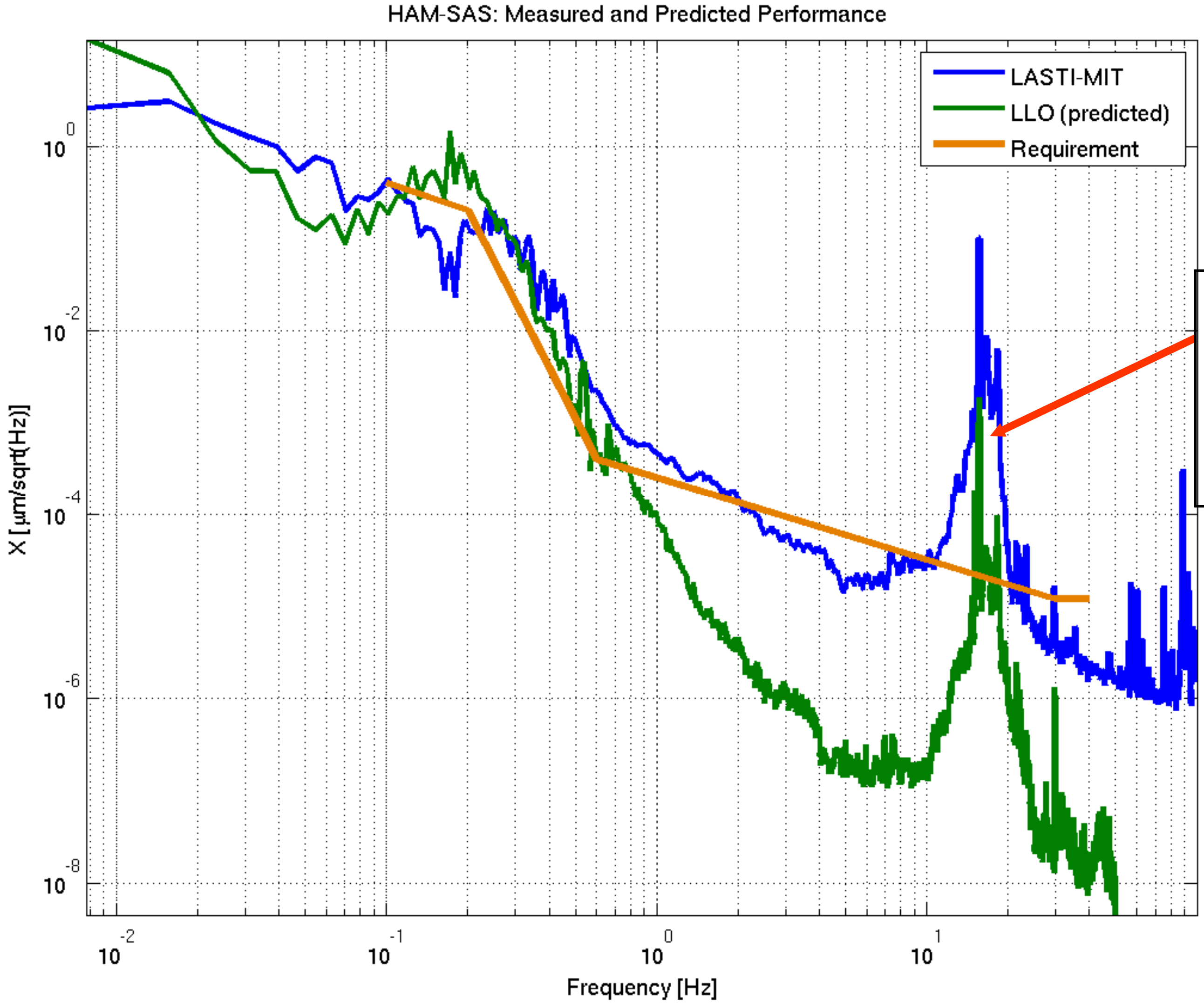
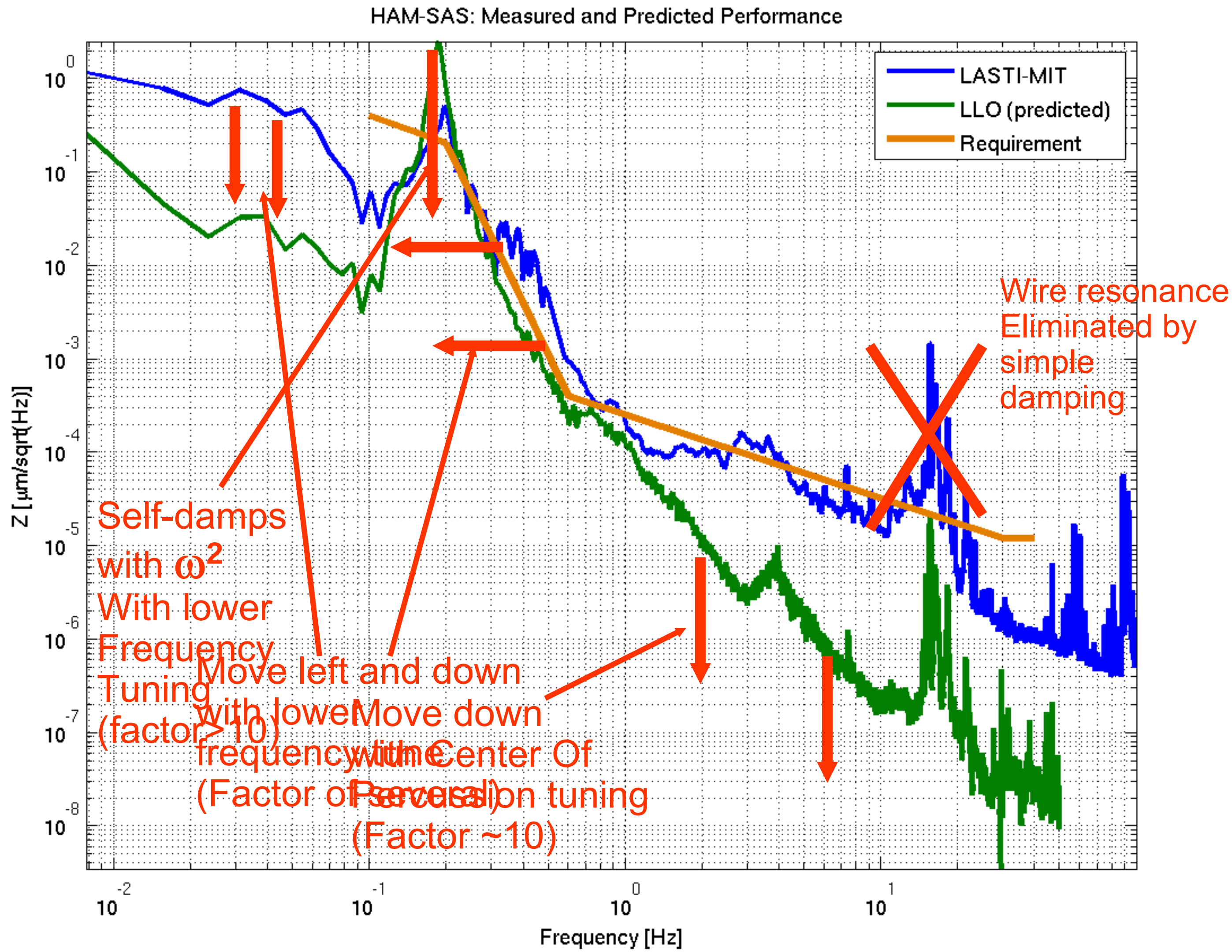
Horizontal performance

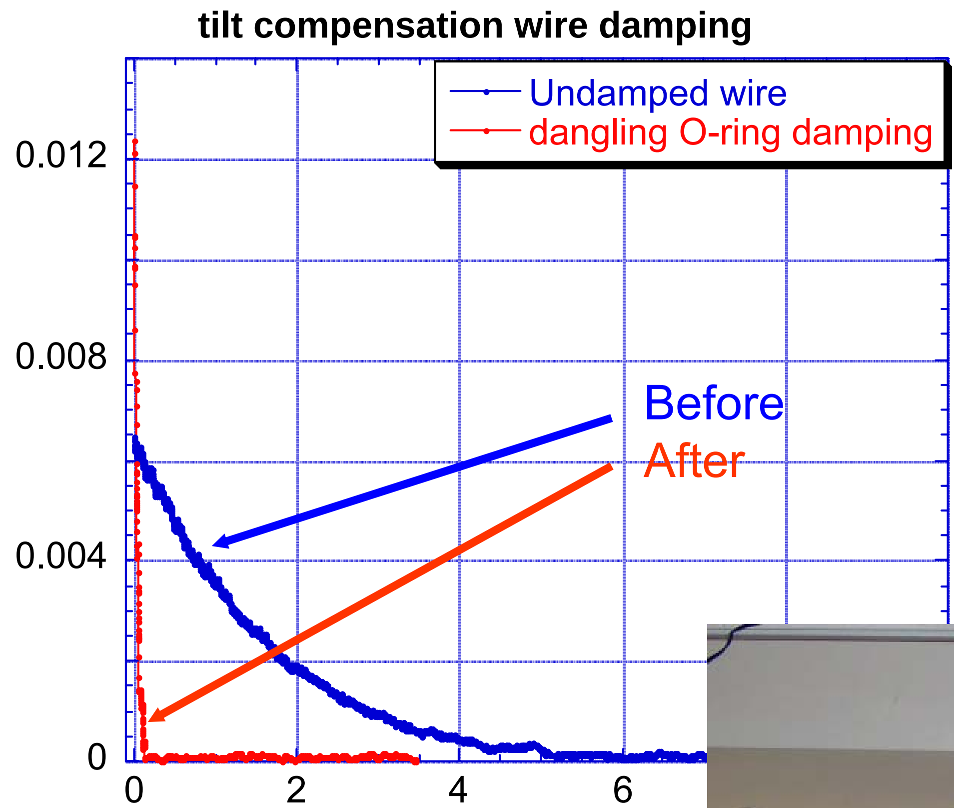


Undamped Tilt correction springs wire resonances

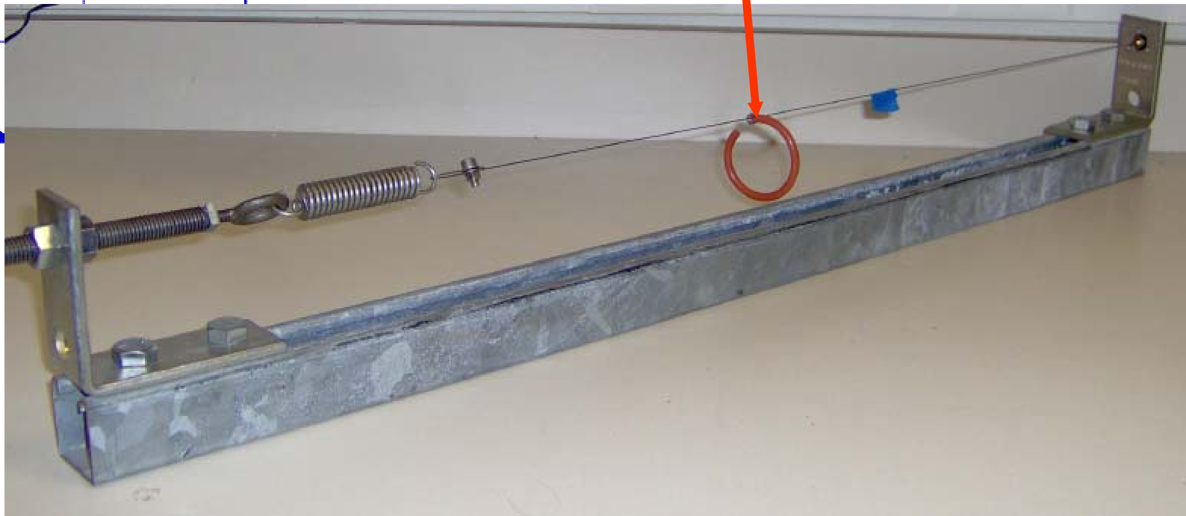
Vertical performance



Wire Resonance damping



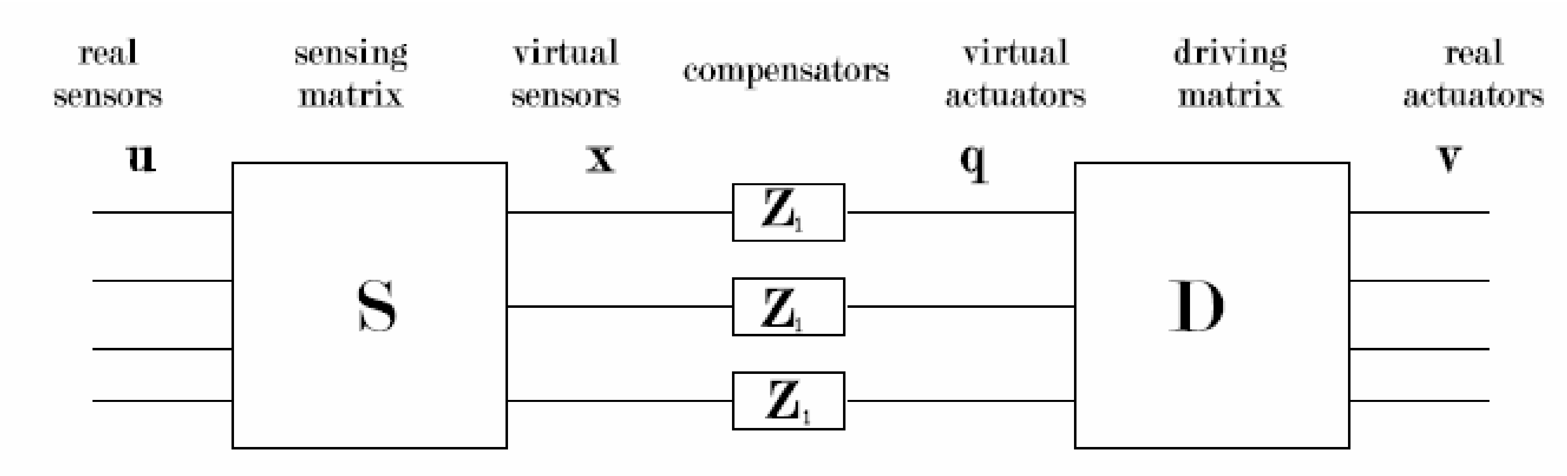
- Simple O-ring damper completely solved the problem in separate test



Sensing and Driving Diagonalization

H= transfer function matrix;
u=sensors; v= actuators

$$\mathbf{u} = \mathbf{H}\,\mathbf{v}$$



$$\mathbf{x} = \mathbf{S}\mathbf{u}$$

$$\mathbf{v} = \mathbf{D}\mathbf{q}$$

$$\mathbf{x} = \widetilde{\mathbf{H}}\mathbf{q}$$

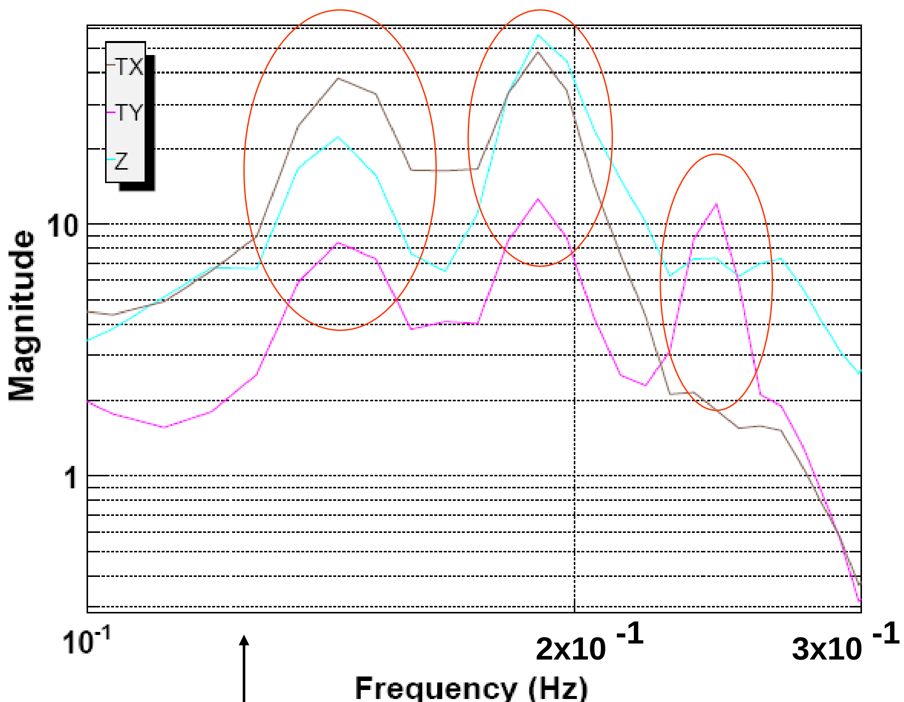
$\widetilde{\mathbf{H}}$ = diagonal transfer function matrix

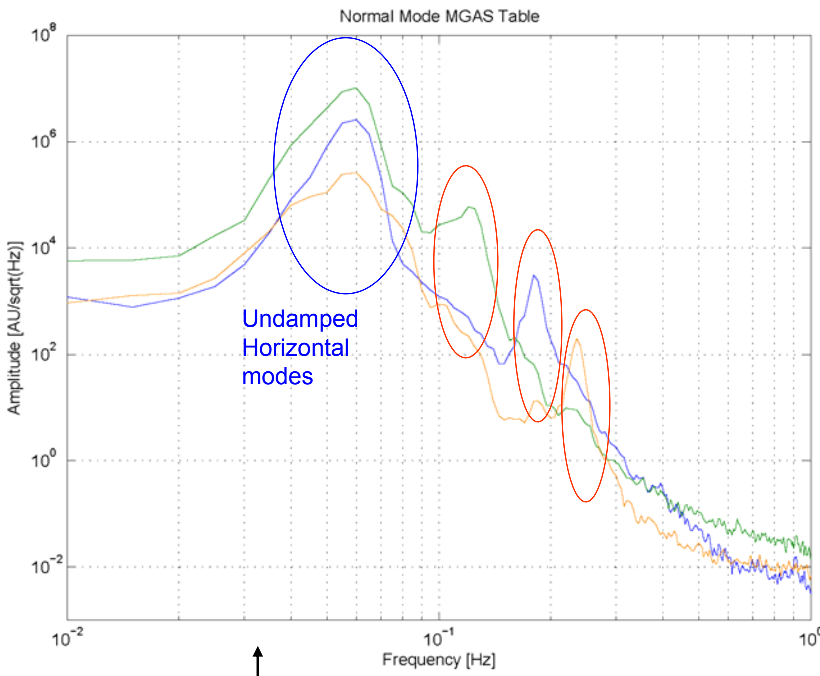
Virtual Sensor diagonalization

Vertical Power Spectra

Upstream the Sensing Matrix

Downstream the Sensing Matrix



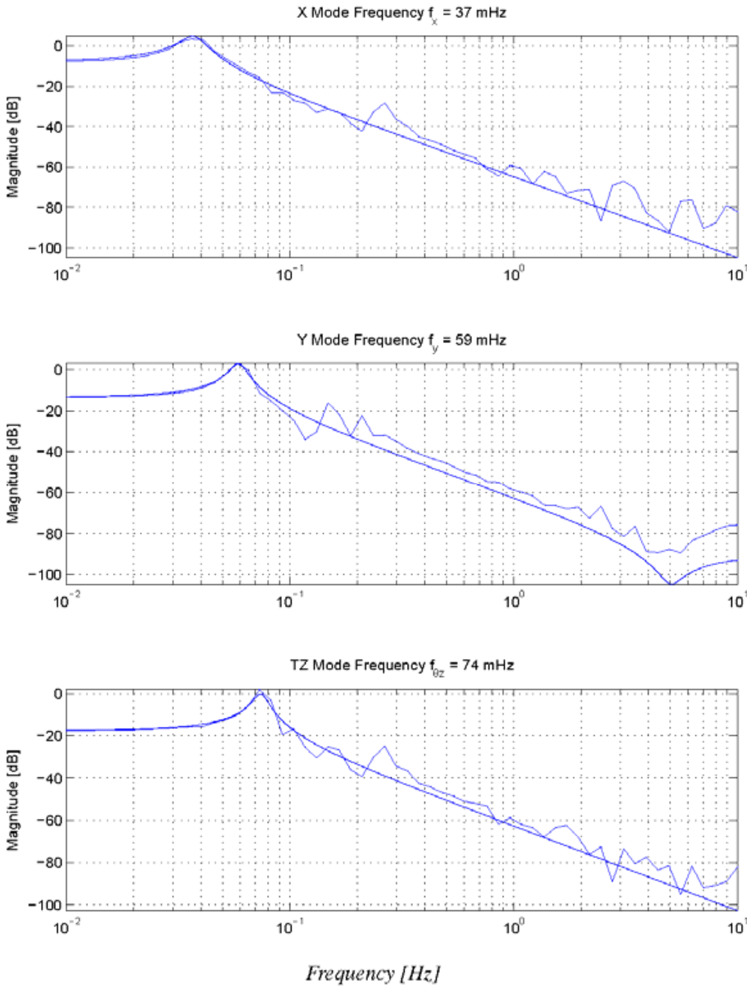


Virtual Geometrical Sensors

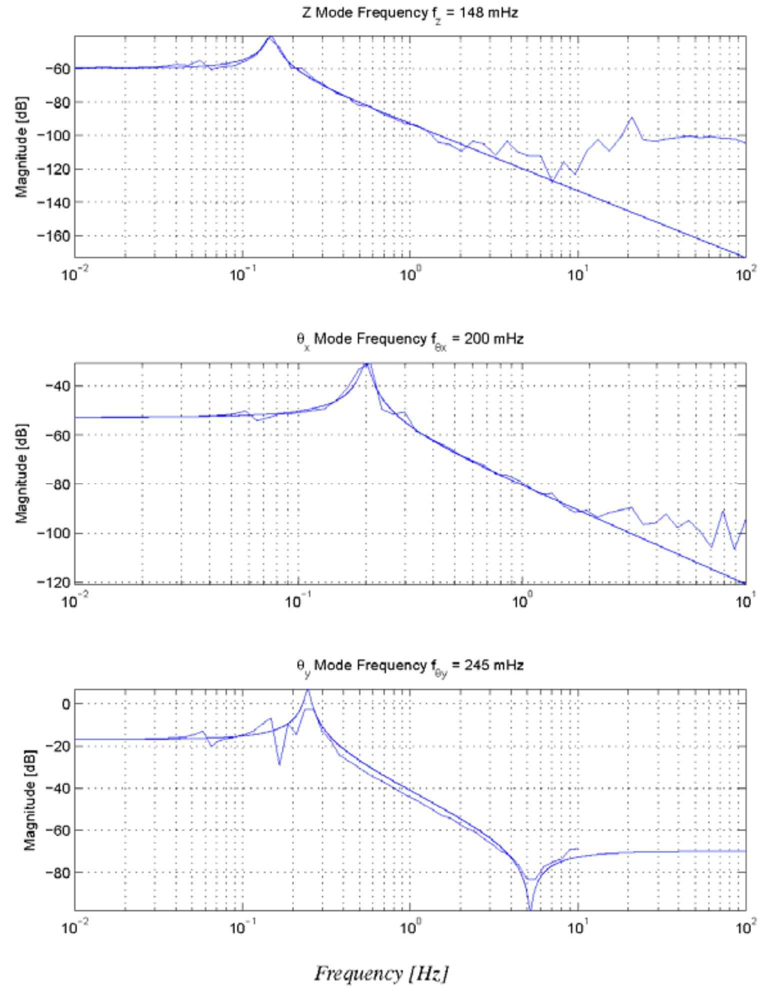
Virtual Modal Sensors

Physical plant Modal Transfer Functions

Horizontal DOFs

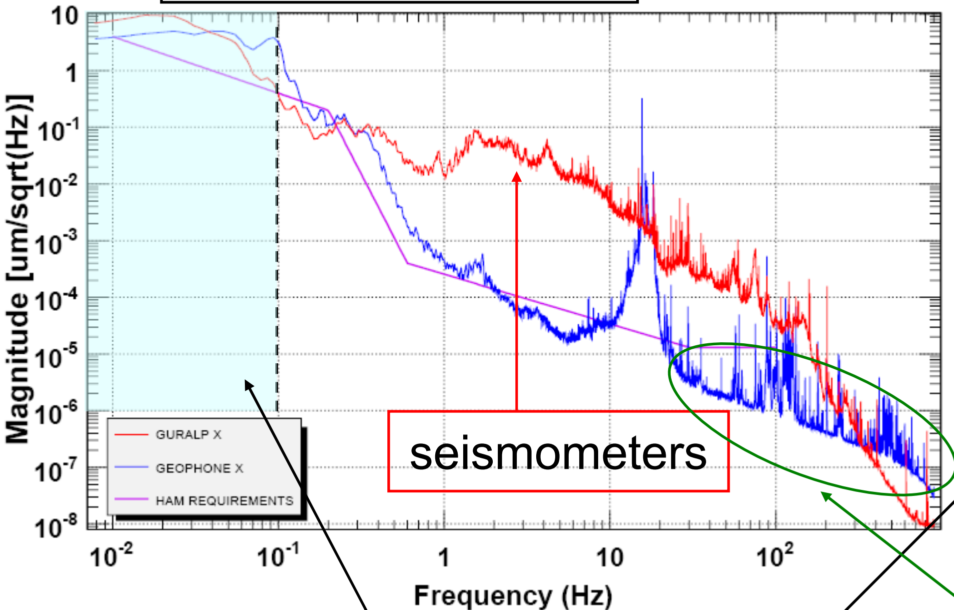


Vertical DOFs

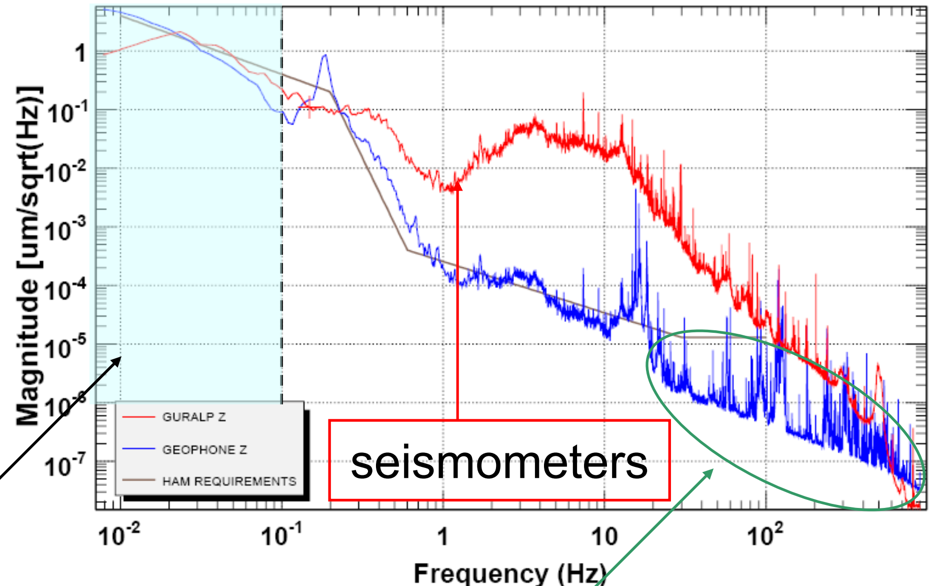


Performance at LASTI with LVDT control only

Horizontal Spectrum

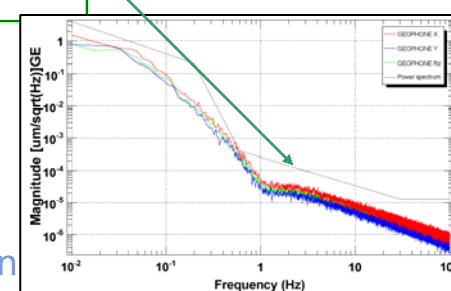


Vertical Spectrum



ultra low frequency region:
unreliable sensors

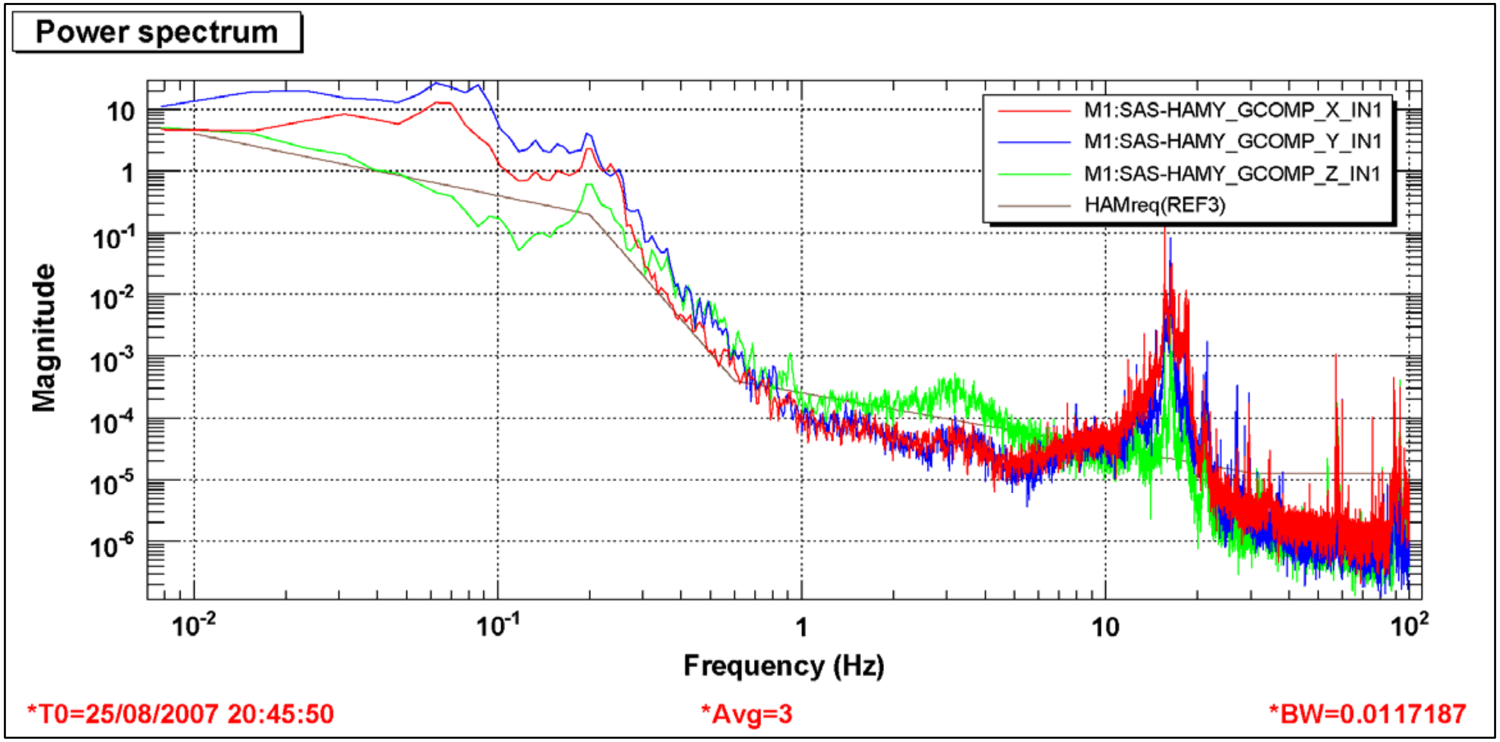
geophones noise floor



Spectra with the Position Control and the Damping Control Implemented

Performance with 6 DOFs Active Control

Onboard geophones feedback



- Thanks to the good plant design active attenuation is straightforward, despite the bad positioning of the geophones
- The geophone sensitivity limits the performance gain

Use of active controls

- Concerns were expressed that a free floating table freely recoil when the suspended optics it supports are actuated upon
- if feeding forward to the table actuators of an appropriate fraction of the force applied to the mirrors does not solve the problem
- the tested feedback scheme (previous figure) would fully and satisfactorily address the problem
- UHV compatible accelerometers of proven performance and reliability exist (Virgo and subsequent developments)

Accidents along the way..

- Severed actuator cabling
  - Continued operation until repair was possible
- SAS-optical bench interface plate accidentally warped
  - Vertical LVDT croocked
    - Sufficient clearance to operate with minor diagonalization complications
- Actuator Coil driver failure (oscillating rail to rail at full power)
  - For a week observed strange (x10 worse) performance degradation
  - No overheating, no UHV degradation, no significant table shaking
    - A very important consequence of the choice of soft flexures is the very low actuator power requirements, just enough to balance the leakage seismic noise power
    - => intrinsic safety of plant

Not implemented

- Resonance dampers
  - To cancel the 20 Hz spurious resonance
- Mechanical low frequency tuning
  - To improve the LF attenuation
- COP correction (both GAS & IP)
  - To gain an order of magnitude in attenuation at high frequency
- Tilt correction optimization
- Fine mechanical alignment

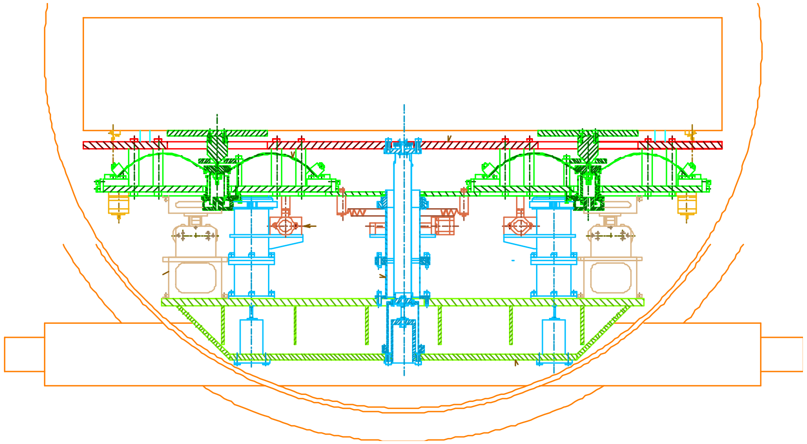
Conclusions

- Proven LIGO compatibility with:
  - Facility
  - UHV
  - CDS Control Systems
- Redundancy, Single Point Failure Tolerance, High Reliability
- Easy Controllability
- Long term Stability
- Earthquake protection over 10 mm excursion
- Seismic Attenuation Requirements achievable with implementation of missing components

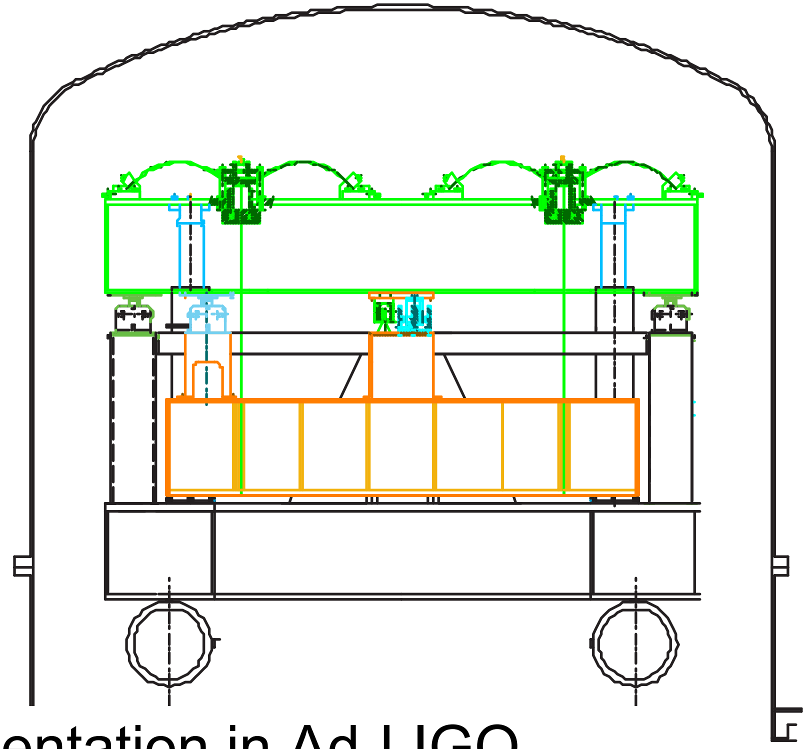
- Tilt Seismic Noise Limited because of principle of equivalence
- but may be able to take advantage of the separation of the horizontal and tilt d.o.f.

Development status

- HAM prototype
  - Succesfully tested



BSC design



- If needed, ready for rapid implementation in Ad-LIGO
- With required performance and enhanced reliability