The HAM-SAS Seismic Isolation System for the Advanced LIGO Interferometers

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LIGO-G070904-00-Z

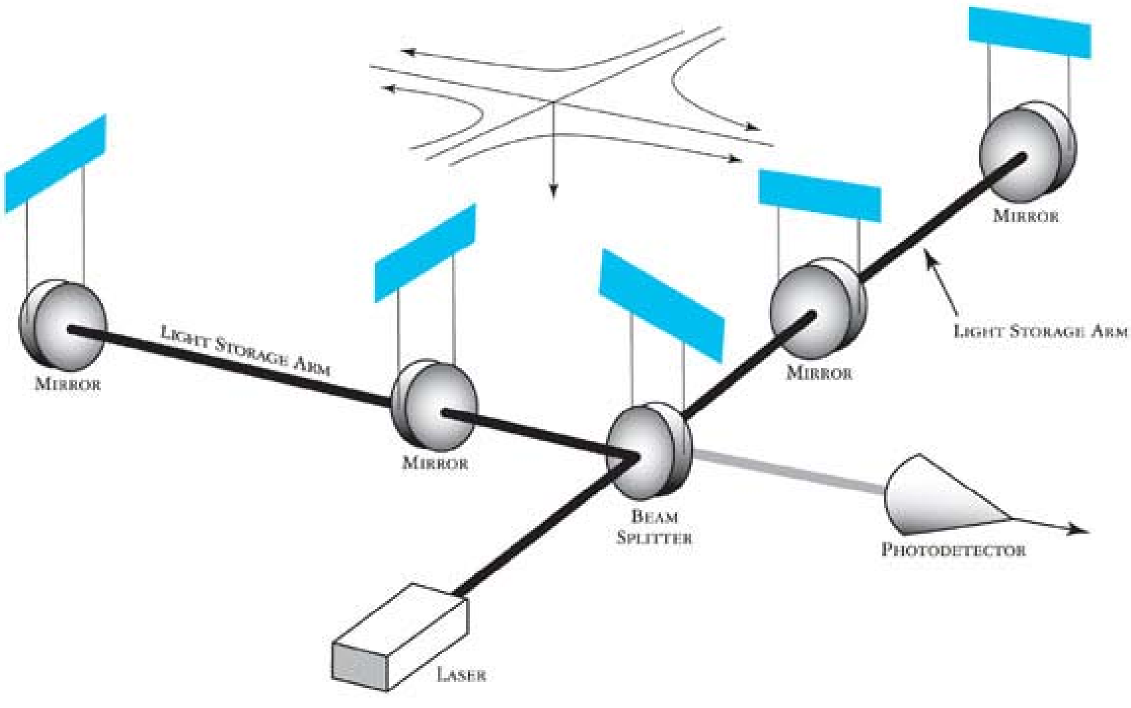
Summary

- Seismic Noise in LIGO GW detectors
- SAS “Passive” Mechanical Filters
- HAM-SAS
- Platform Control
- System Performances
- Conclusions

Gravitational Wave Interferometric Detectors

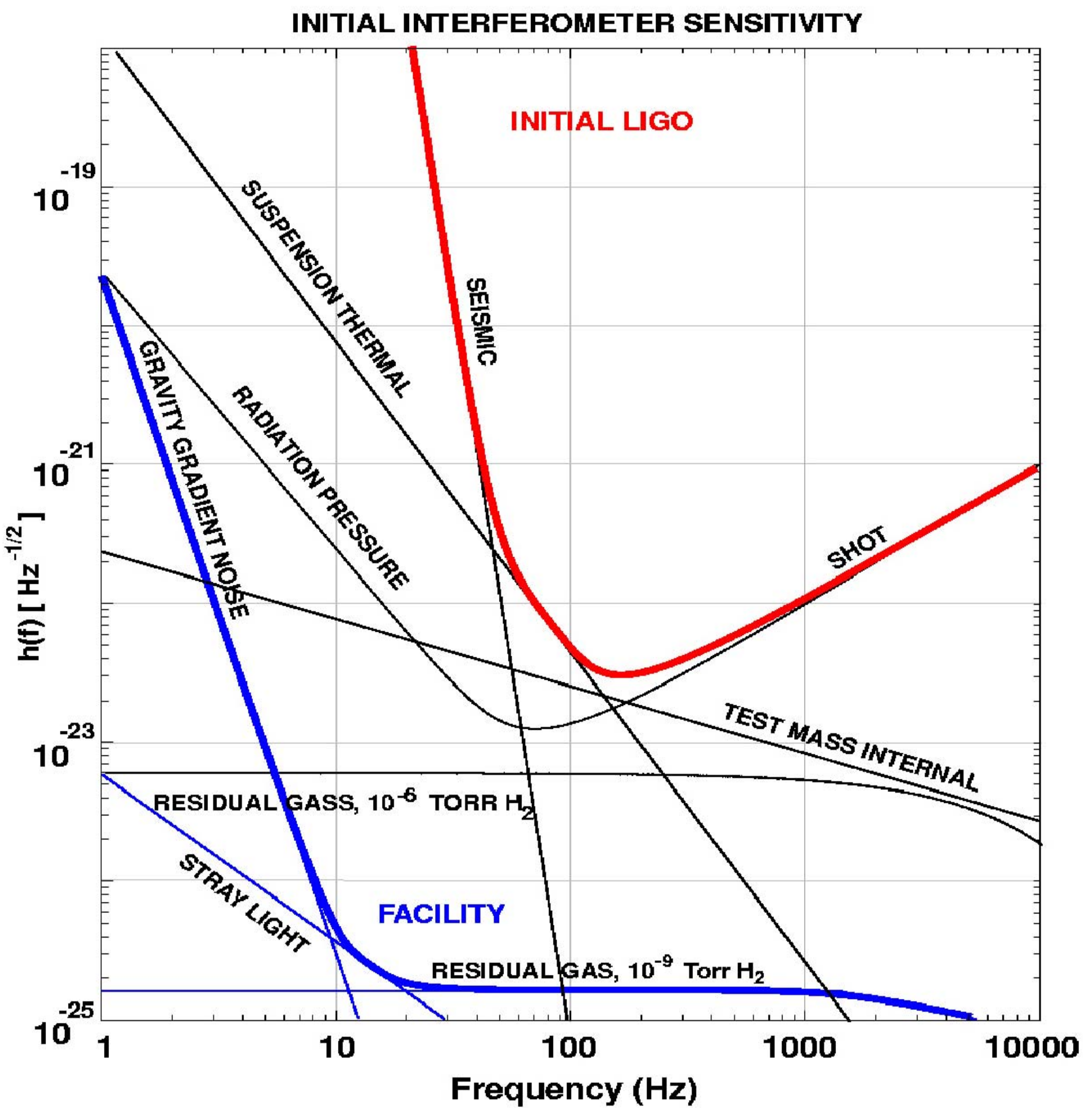
Michelson Interferometer

$$\Delta L = h\Delta L = 10^{-19} - 10^{-17}\, m$$



(length change optimistic estimate caused by a source located at inter-galactic or cosmological distance on a a 4-Km interferometer)

Noise Sources



strength

$$h = \frac{\Delta L}{L}$$

Seismic noise dominates at low frequencies

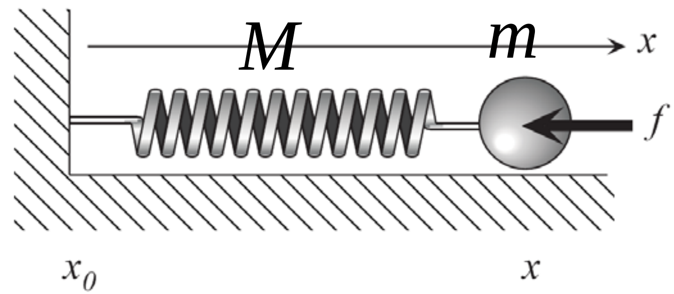
(<40 Hz)

LIGO

Passive Mechanical Filters

Massive Spring:

$$m\ddot{x} + M\ddot{x}_0 = -k(x - x_0)$$



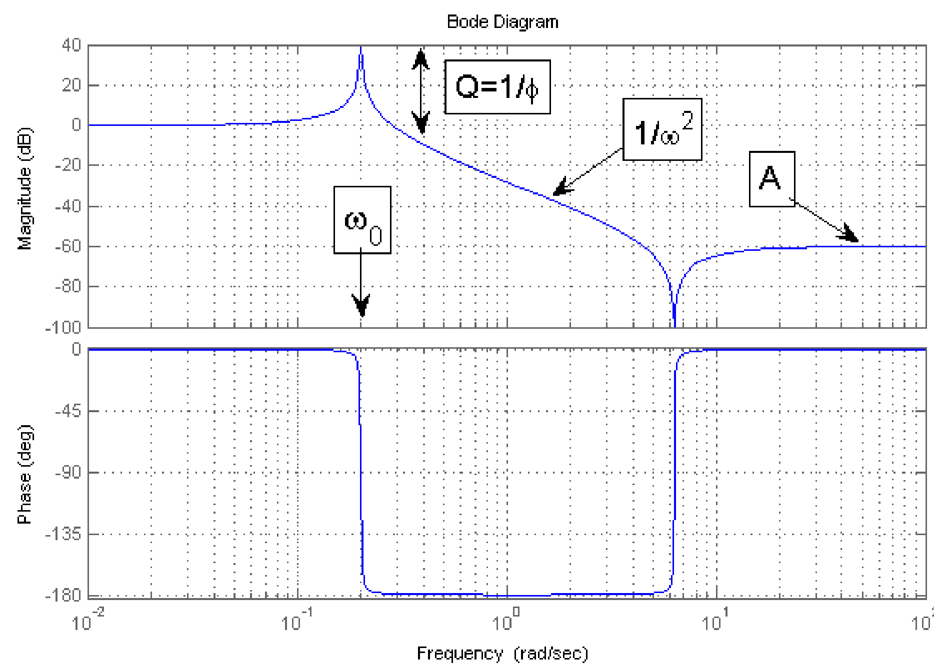
Transfer Function:

$$\frac{\hat{x}(\omega)}{\hat{x}_0(\omega)} = \frac{\omega_0^2 + A\omega^2}{\omega_0^2 - \omega^2}$$

$$\omega_0^2 = \frac{k}{m} = \frac{\tilde{k}(1 + i\phi)}{m}$$

$$\tilde{k} = \Re[k]$$

$$A = M / m$$

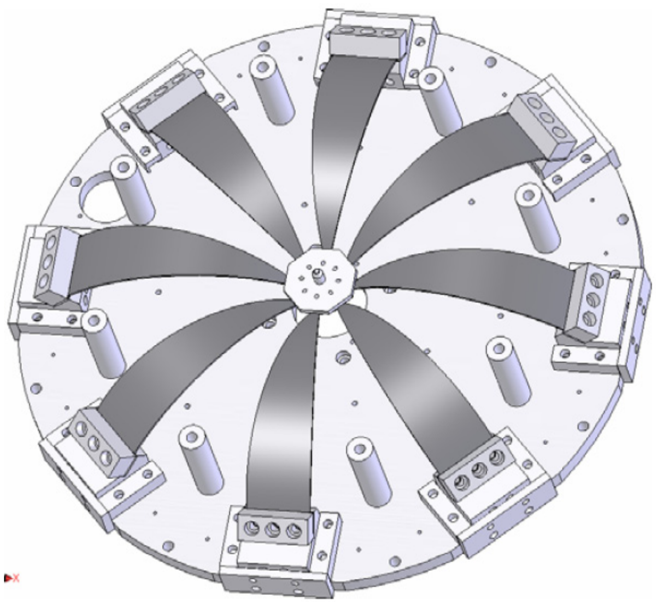


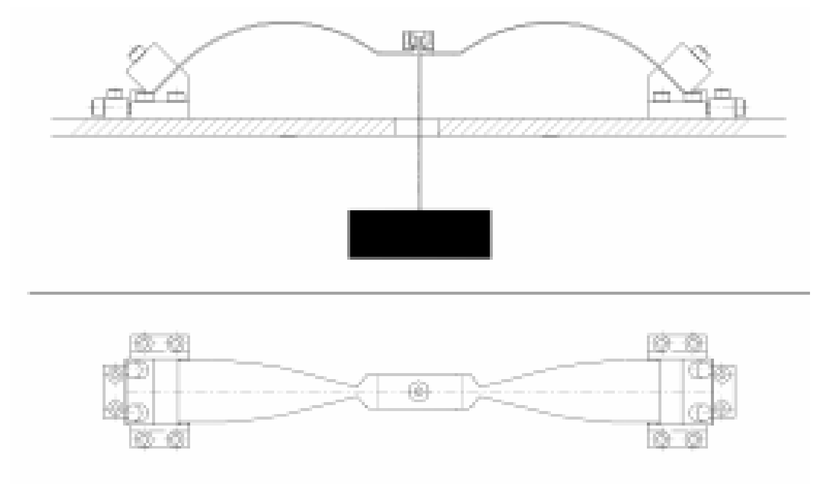
Ideal Passive Mechanical Filter

- low resonant frequency
  - ⇨ early attenuation roll-off
  - ⇨ small control force at the equilibrium point
  - ⇨ low Q because $Q \propto \omega_0^2$
- minimal Center of Percussion Effect
  - ⇨ high frequency attenuation improvement

SAS Passive Mechanical Filters

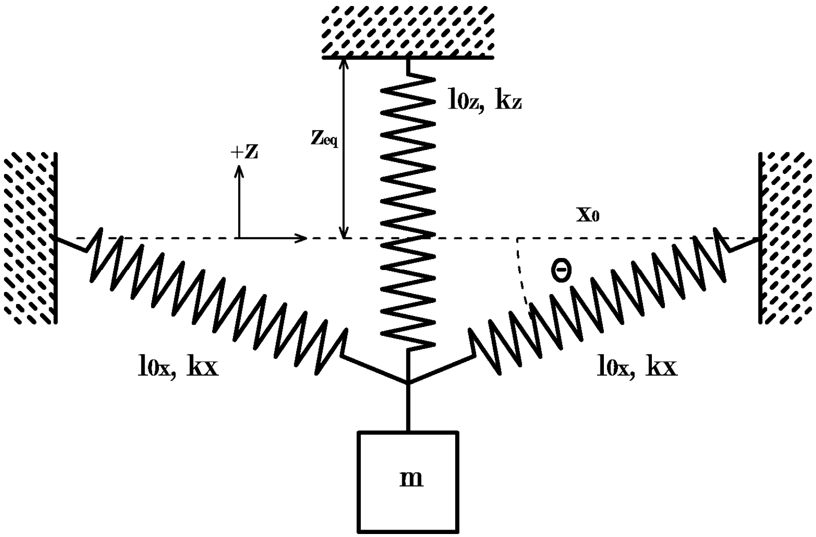
Vertical Isolation: Geometric Anti-Spring Filter (GAS)

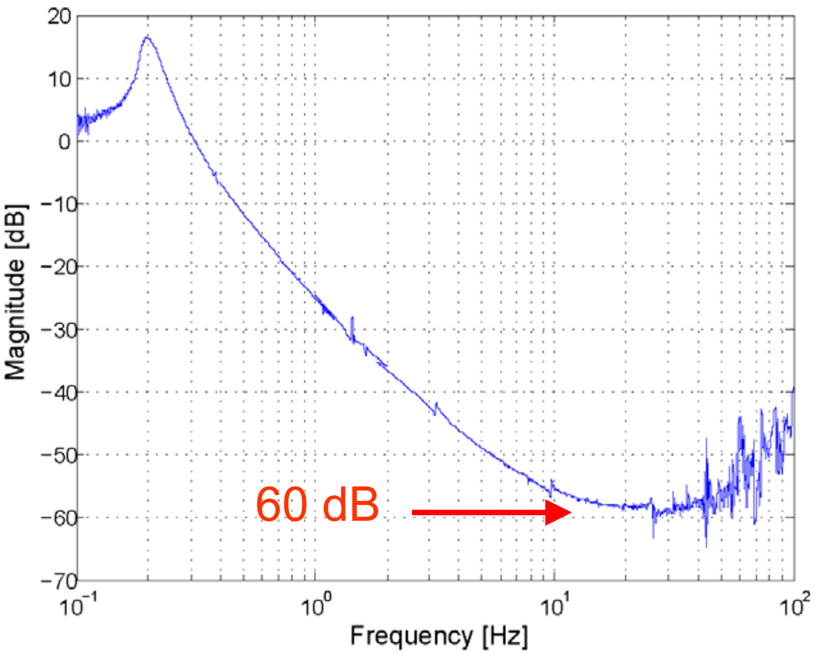




GAS working principle

Transmissibility



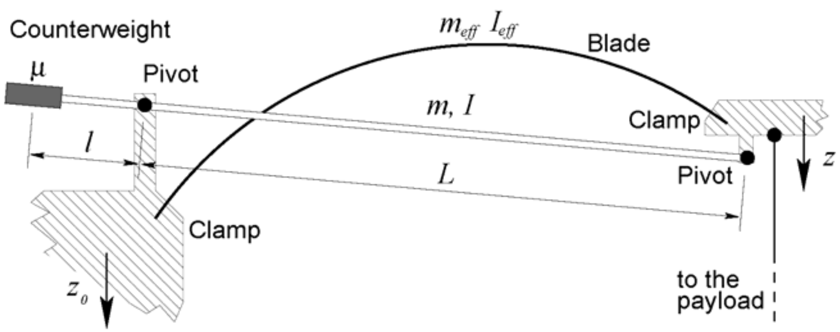


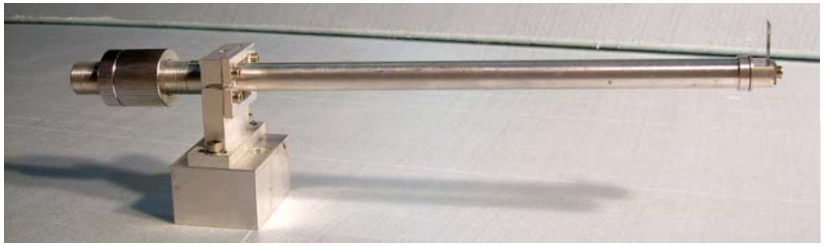
$$k_{eff} = k_z + k_x - \frac{k_x l_{0x}}{x_0}$$

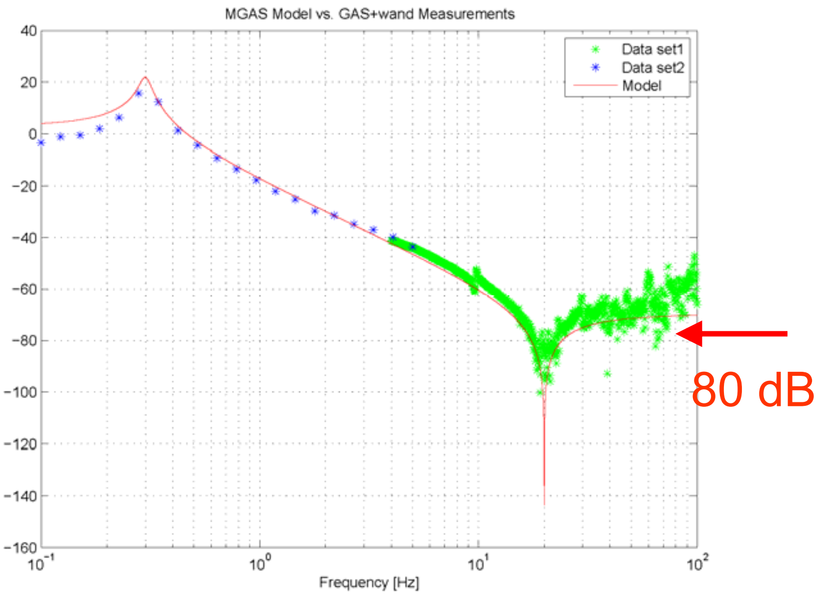
$$H_z(\omega) = \frac{\omega_0^2(1 + i\phi) + \beta\omega^2}{\omega_0^2(1 + i\phi) + \omega^2}$$

SAS Passive Mechanical Filters

Center of Percussion Compensation for the GAS Filter



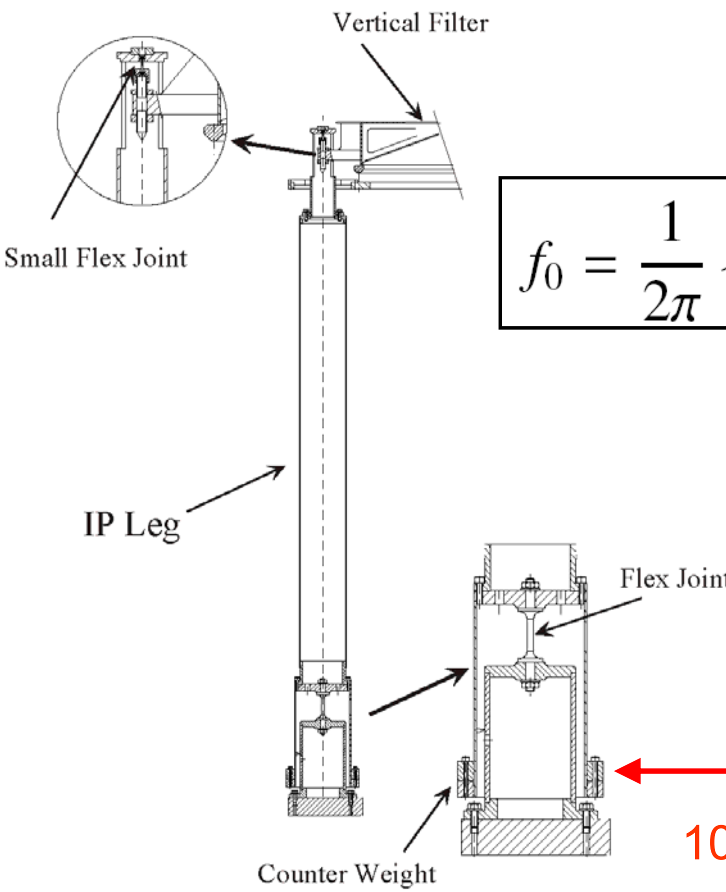




[A. Stochino, et al., Nucl. Instr. and Meth. A (2007), in press: doi:10.1016/j.nima.2007.06.029]

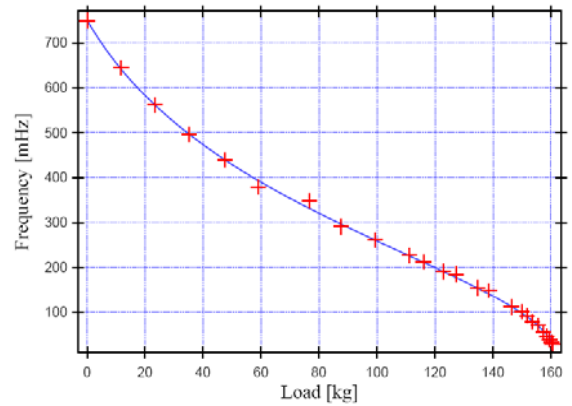
Seismic Attenuation System (SAS) Passive Filters

Horizontal Isolation: Inverted Pendulum



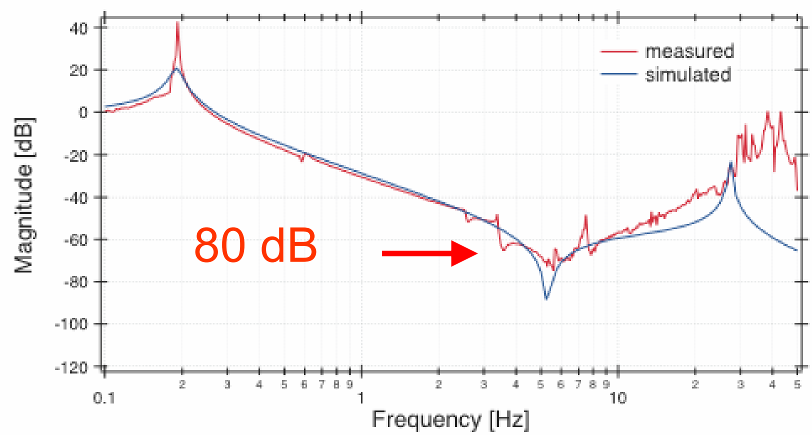
100 dB

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{M} - \frac{g}{l}}$$

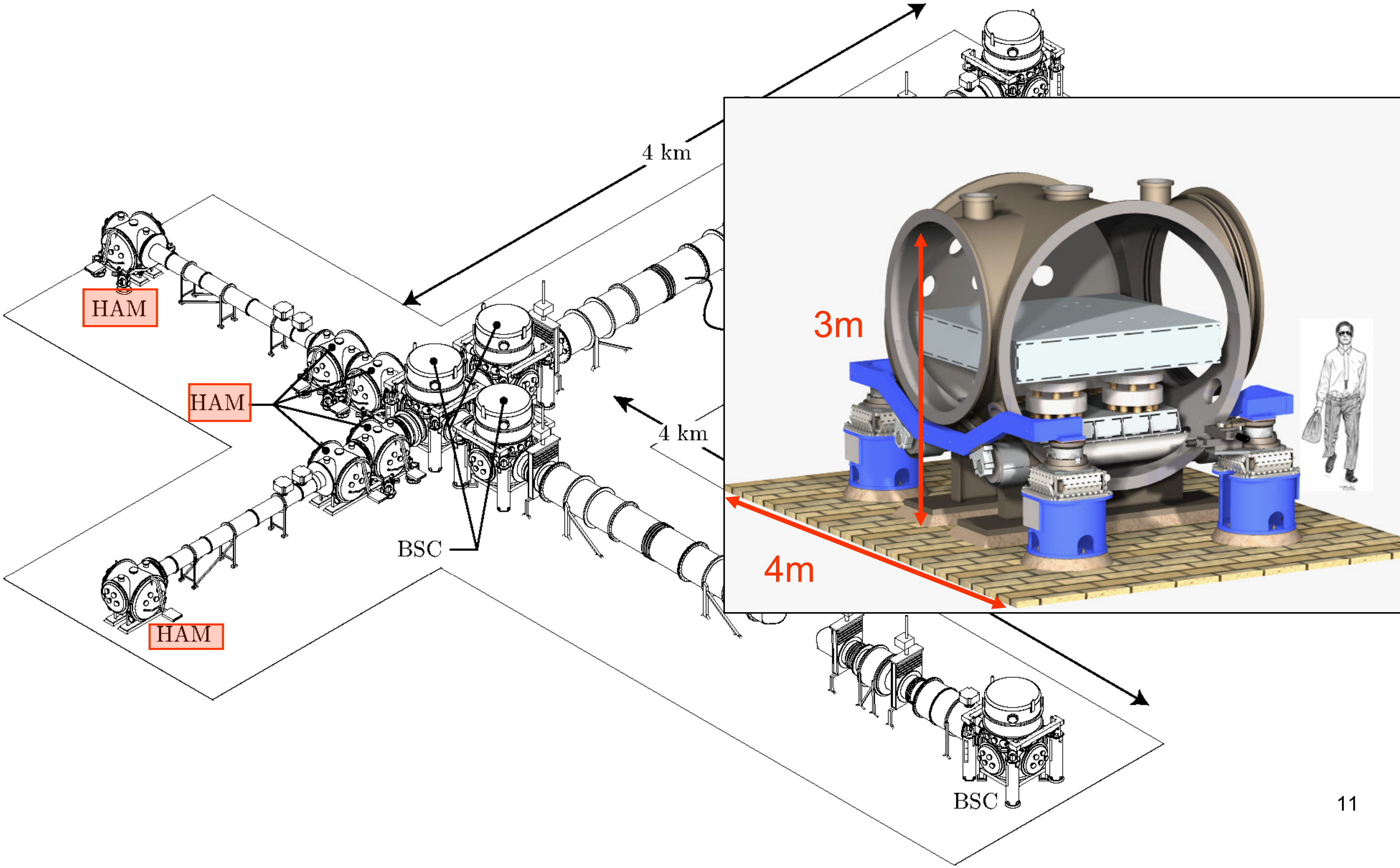


Frequency vs Load

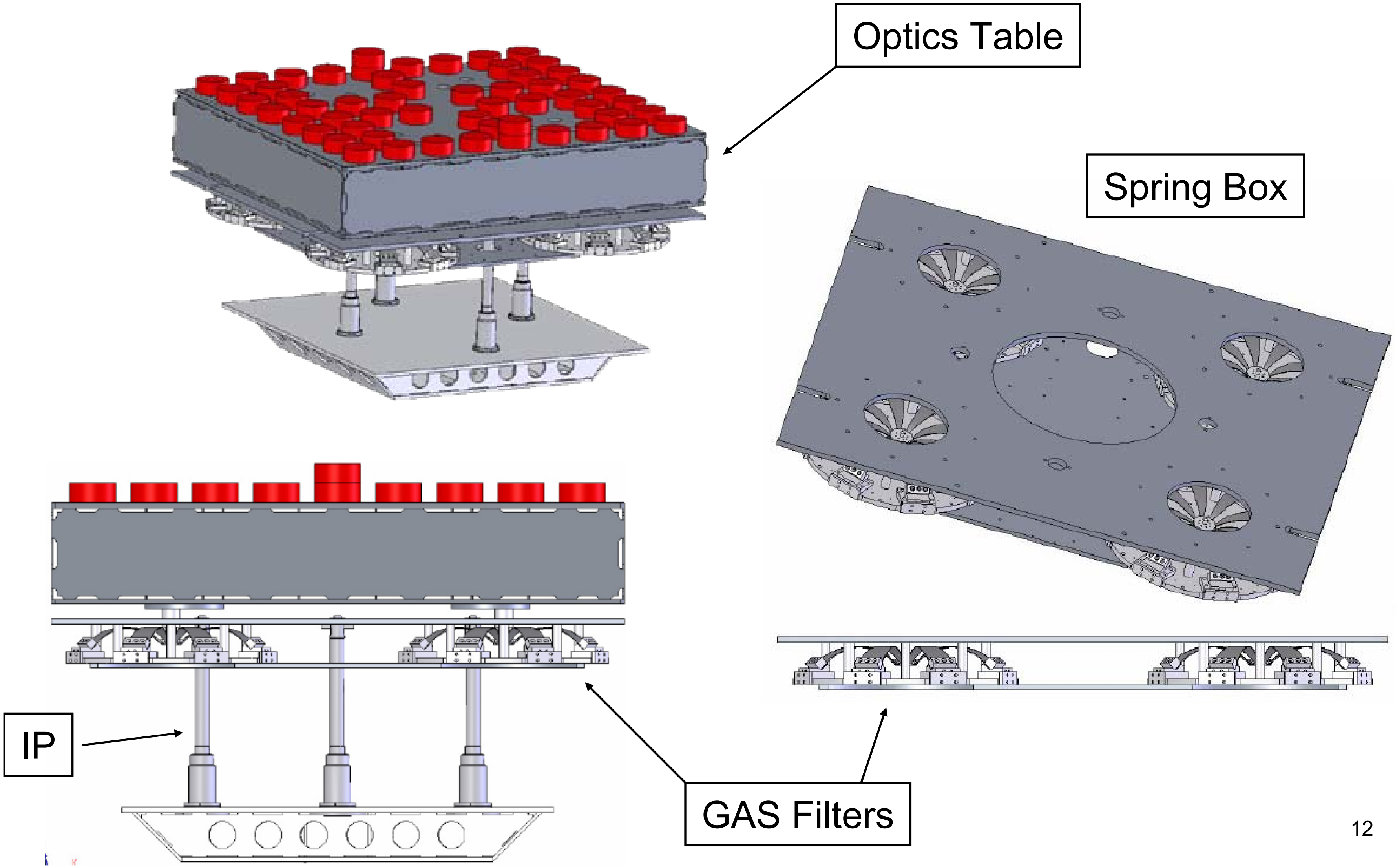
transmissibility



LIGO Horizontal Axis Module (HAM) Chambers

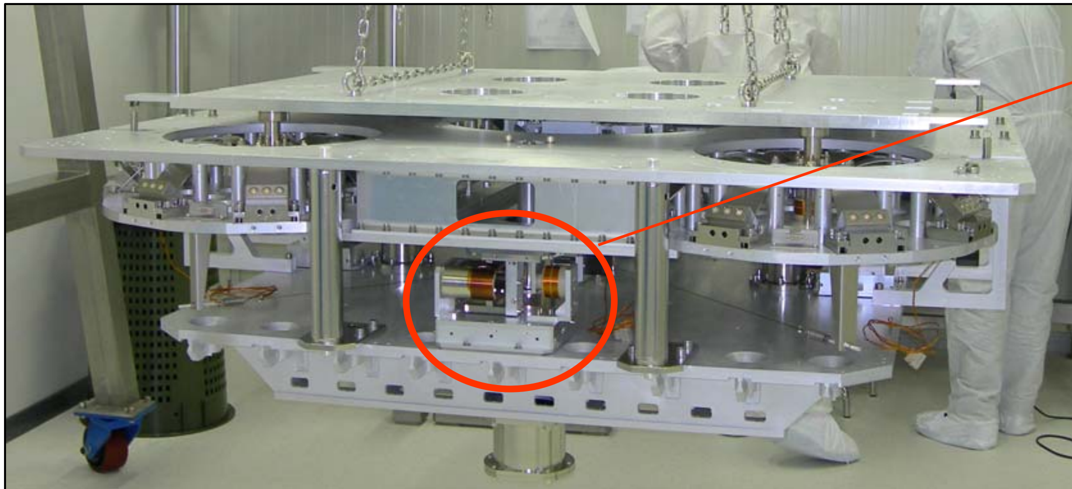


HAM-SAS

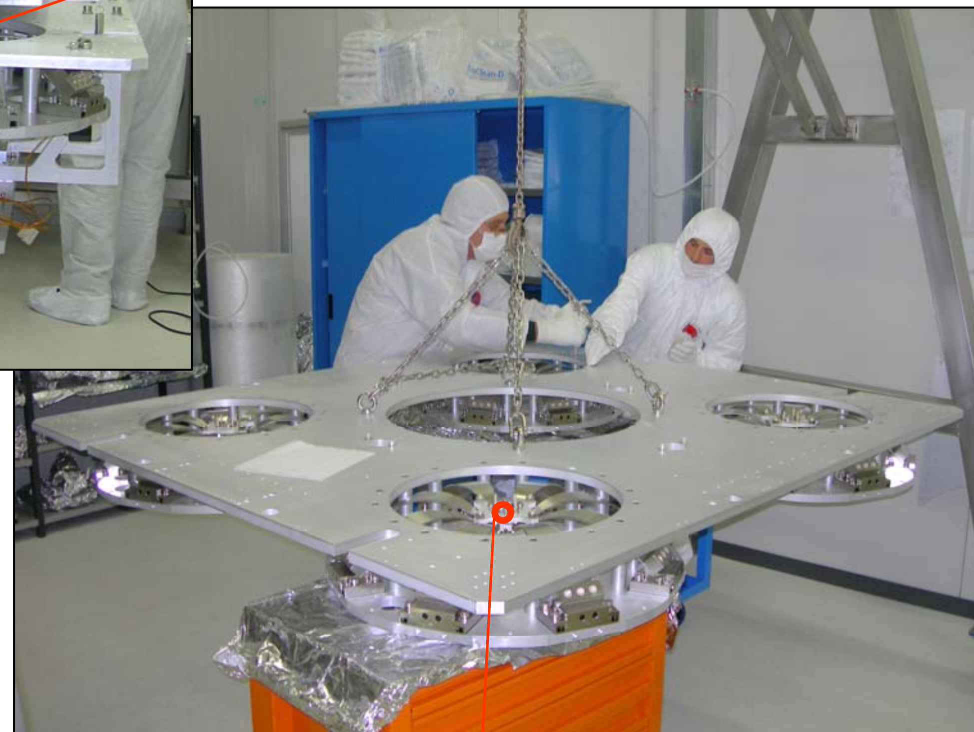


LIGO

HAM-SAS construction



Horizontal Sensor and Actuator



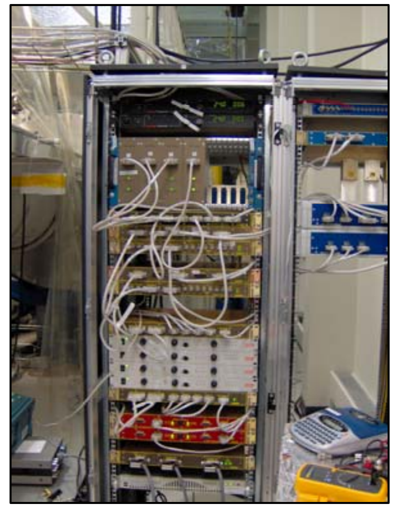
Vertical Sensor and Actuator

LIGO

HAM-SAS

LIGO

MIT LASTI HAM Chamber



- installation
- mechanical setup
- electronics setup
- sensors setup
- controls software
- commissioning...

HAM chamber

electronics

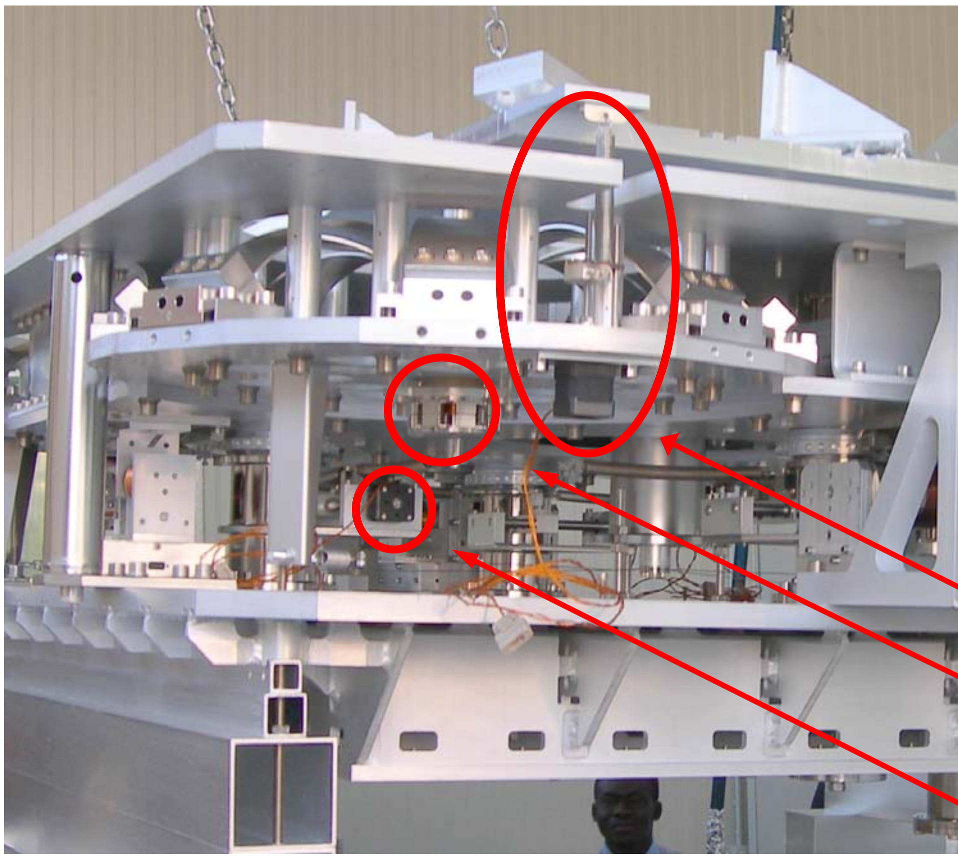
insertion system

Sensors

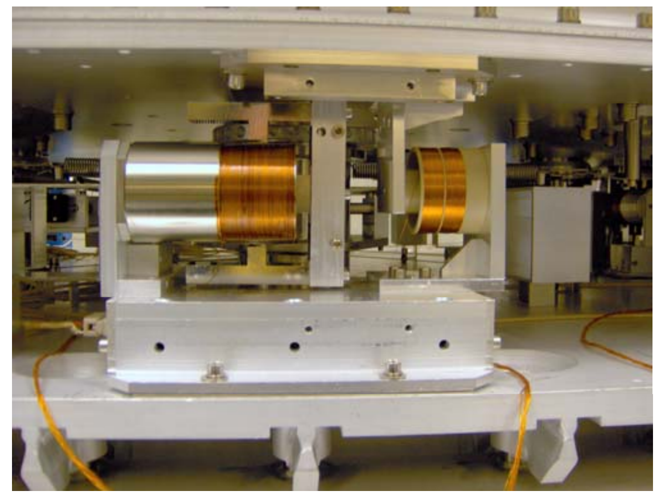
- 8 LVDTs
  - 4 horizontal: position spring box – ground
  - 4 vertical: posiion optics table – spring box
- 6 L4C witness onboard geophones
  - Inertial sensors of velocity for the DOFs of the optics table
- 3 Guralp onground seismometers
  - Monitor the ground seismic reference

Actuators

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



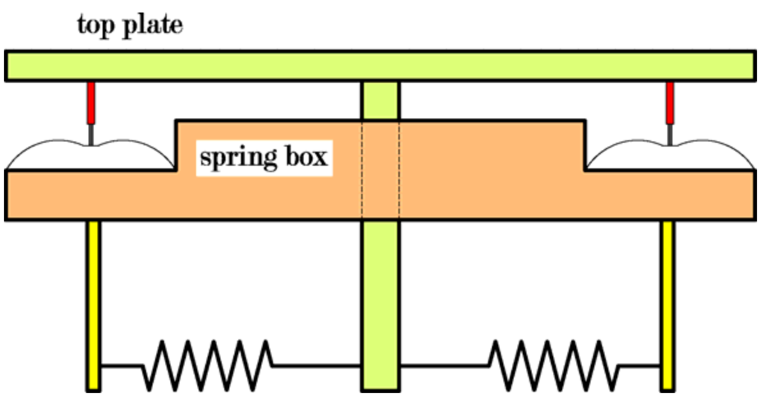
Horizontal actuator and LVDT



Angular Stabilization

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

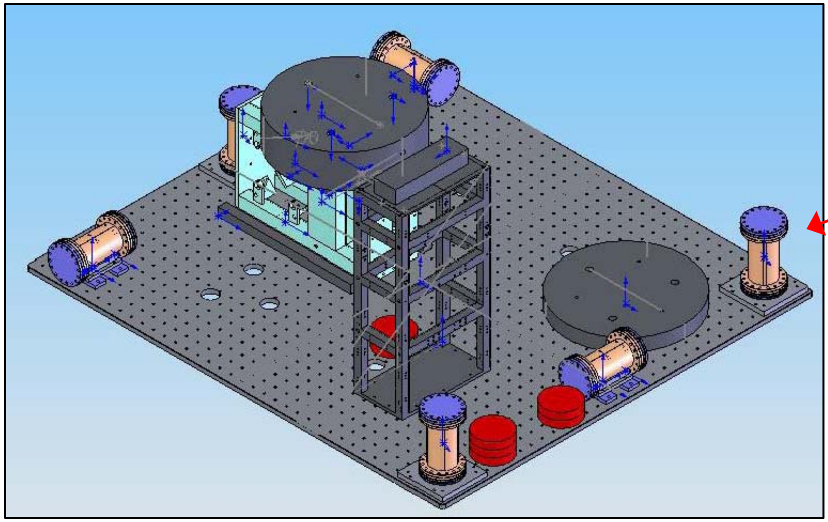
⇨ *Solution*: to add stiffness exclusively to the angular modes (Rx and Ry)

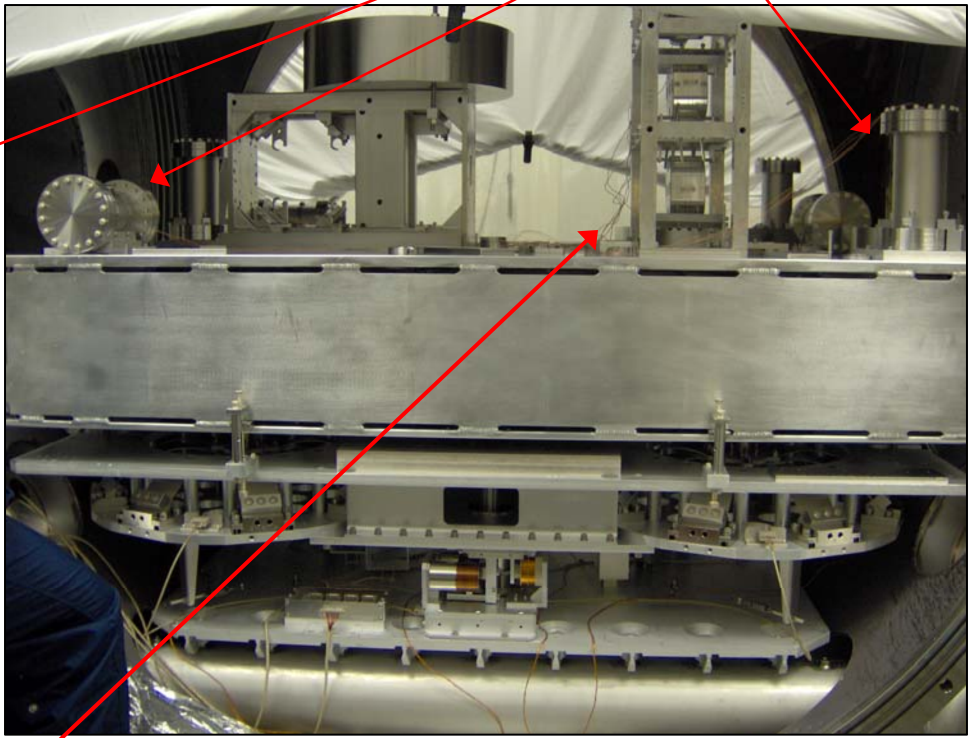


$$k_{tilt}^{(z)} = 4\left(1 - \frac{l_0}{x_0}\right)k$$

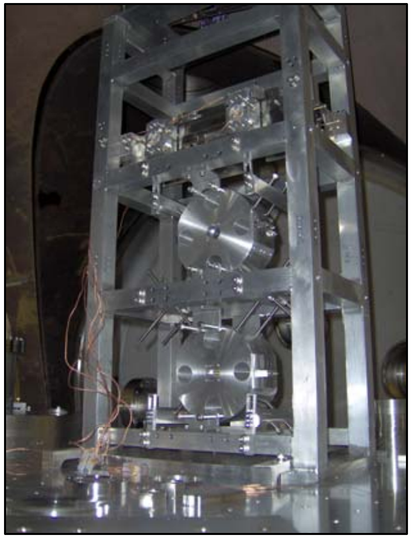
HAM Optics Bench

geophones





optics bench

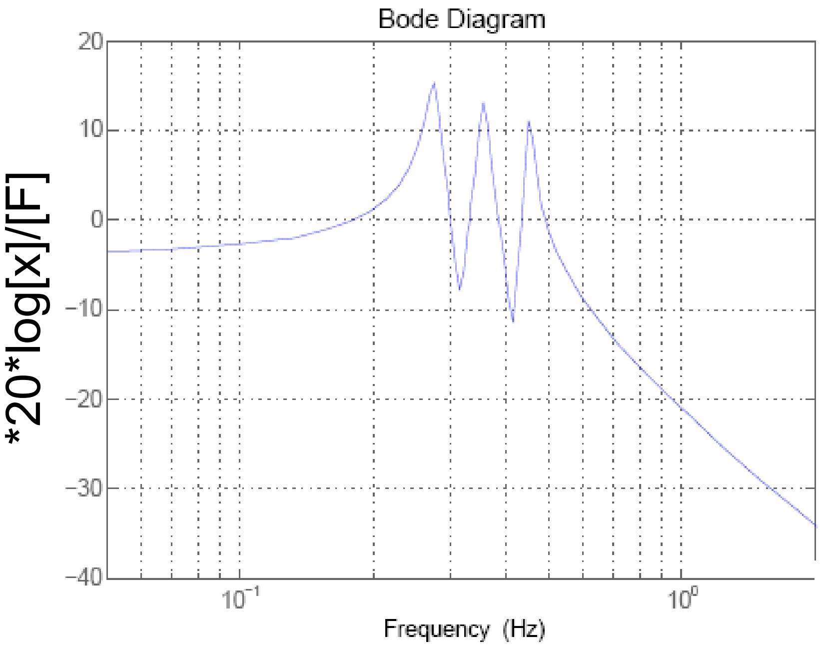


triple pendulum

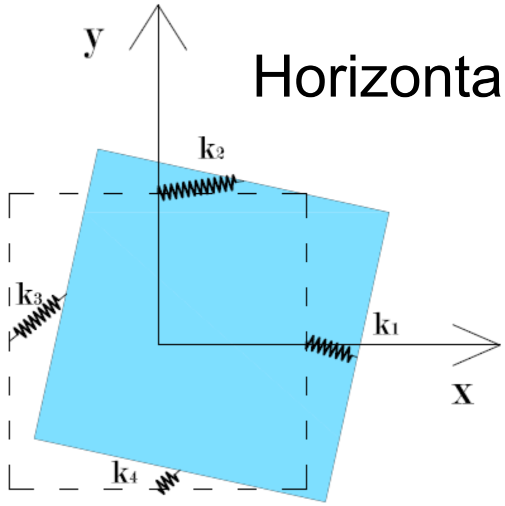
HAM-SAS supporting the optics table

Normal Modes

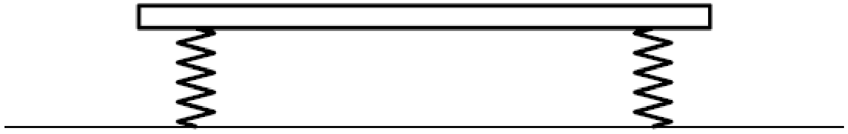
- Horizontal and Vertical Degrees of Freedom uncoupled
- 2 independent stiffness matrices



Horizontal DOFs model



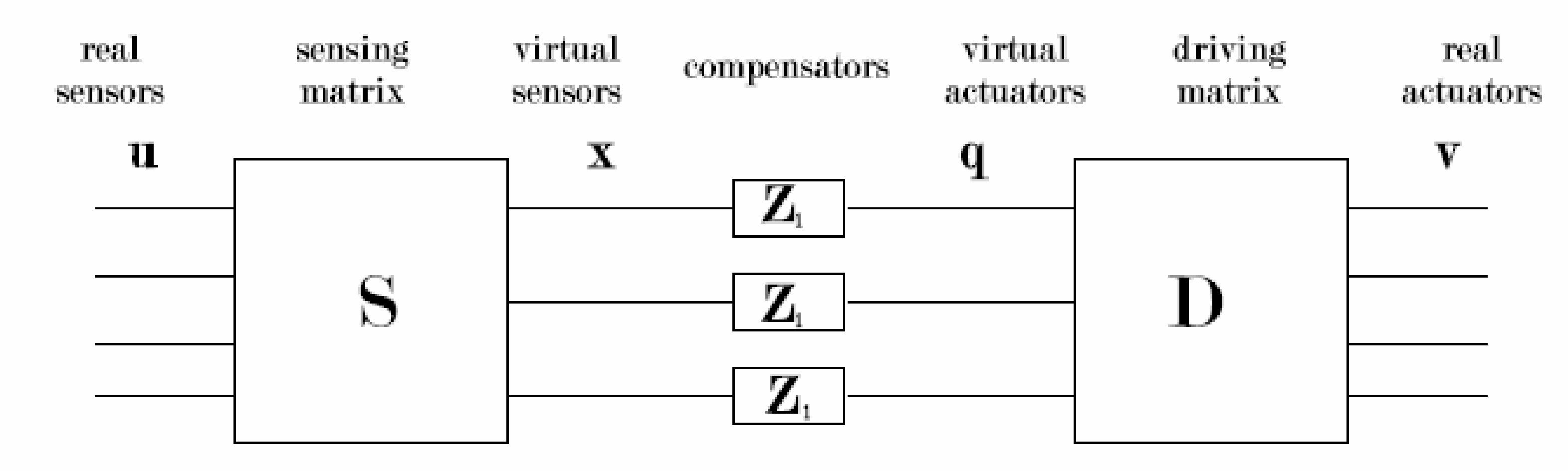
Vertical DOFs model



Sensing and Driving Diagonalization

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

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



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

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

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

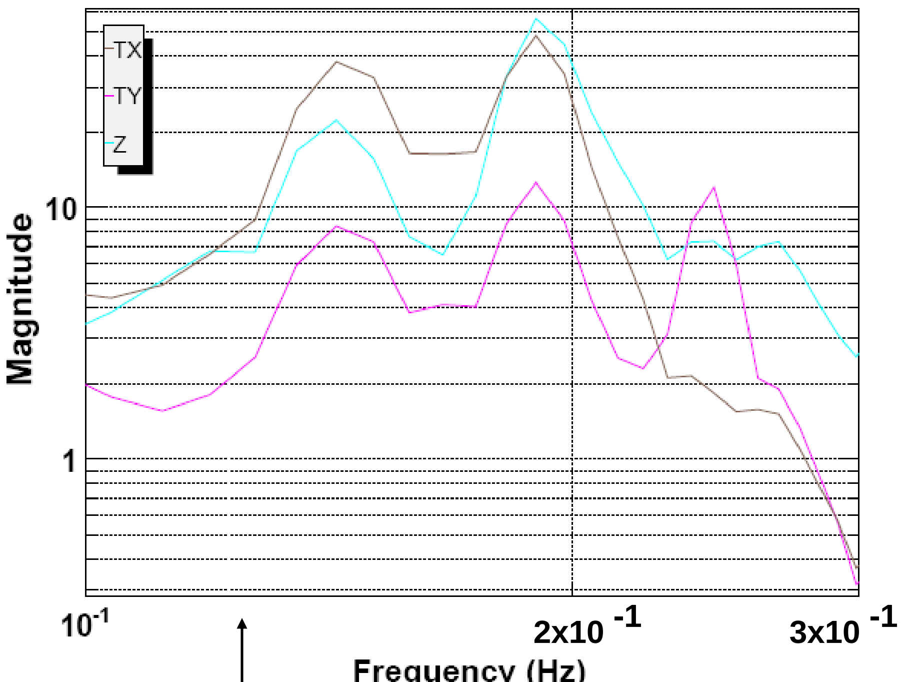
$\widetilde{\mathbf{H}}$ = diagonal transfer function matrix

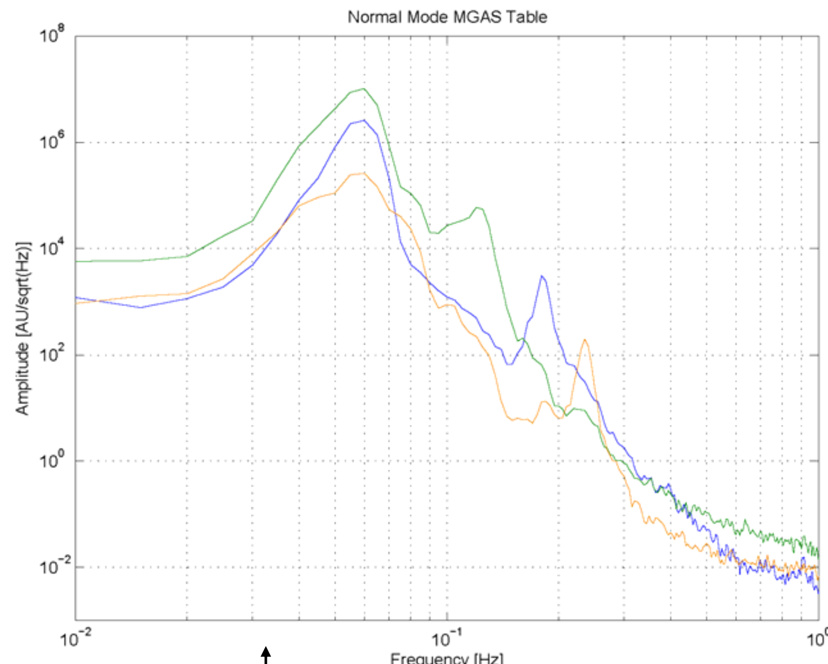
Virtual Sensors

Vertical Power Spectra

Upstream the Sensing Matrix

Downstream the Sensing Matrix



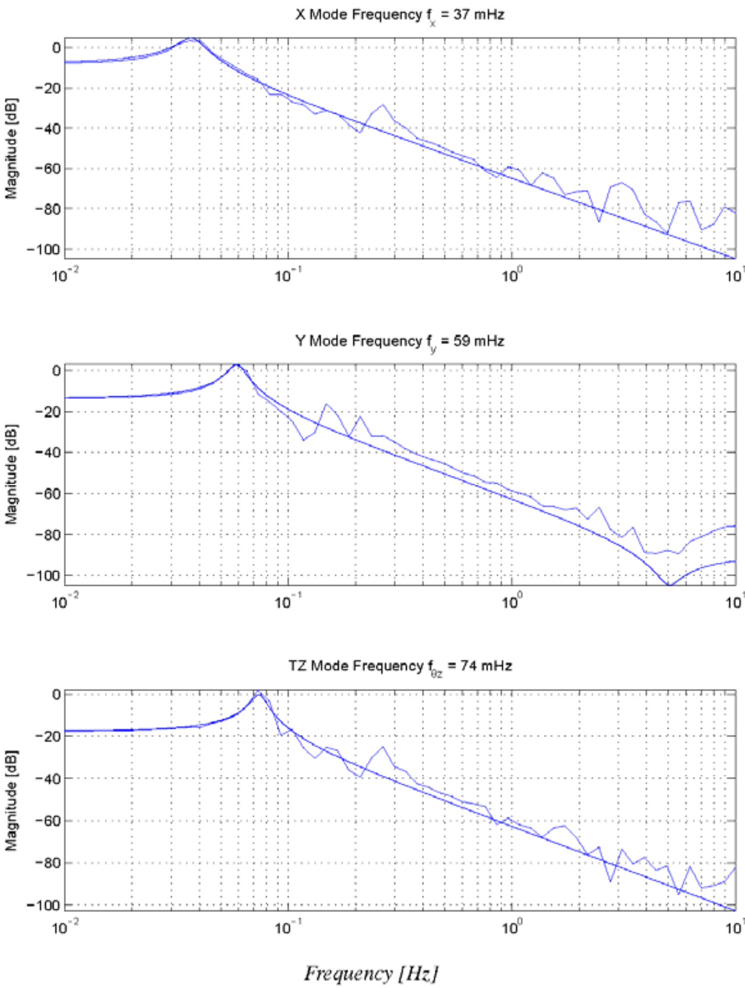


Virtual Geometrical Sensors

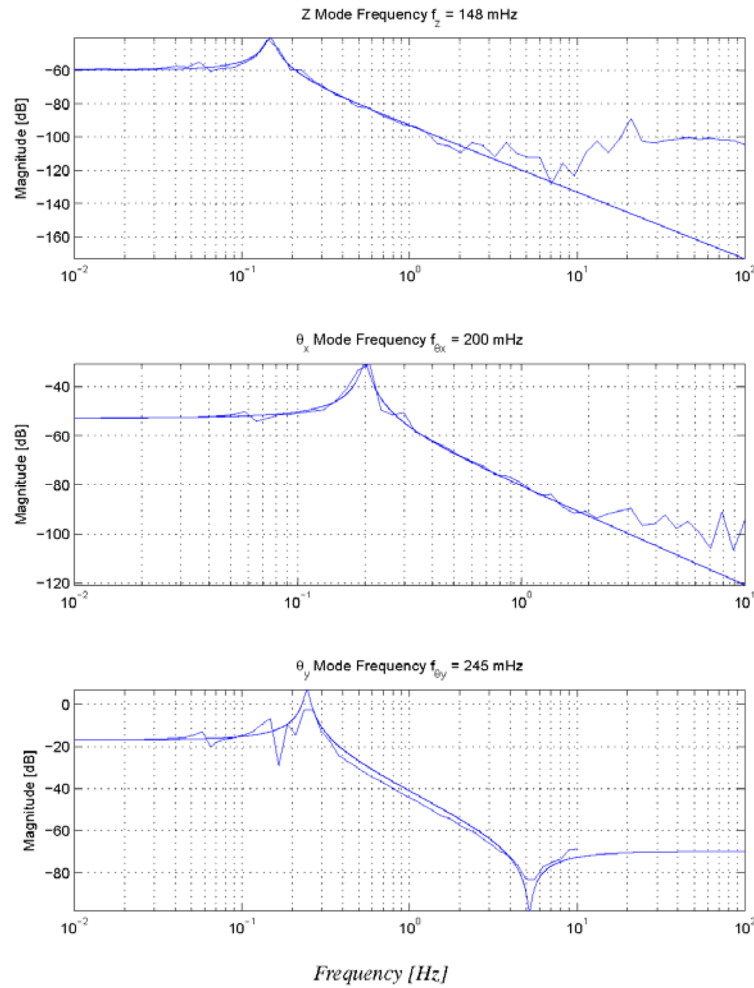
Virtual Modal Sensors

Modal Transfer Functions

Horizontal DOFs



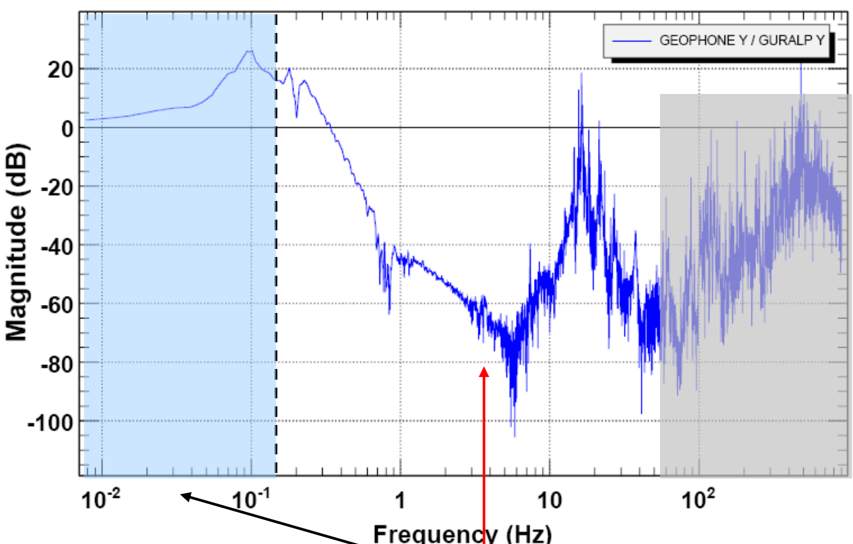
Vertical DOFs



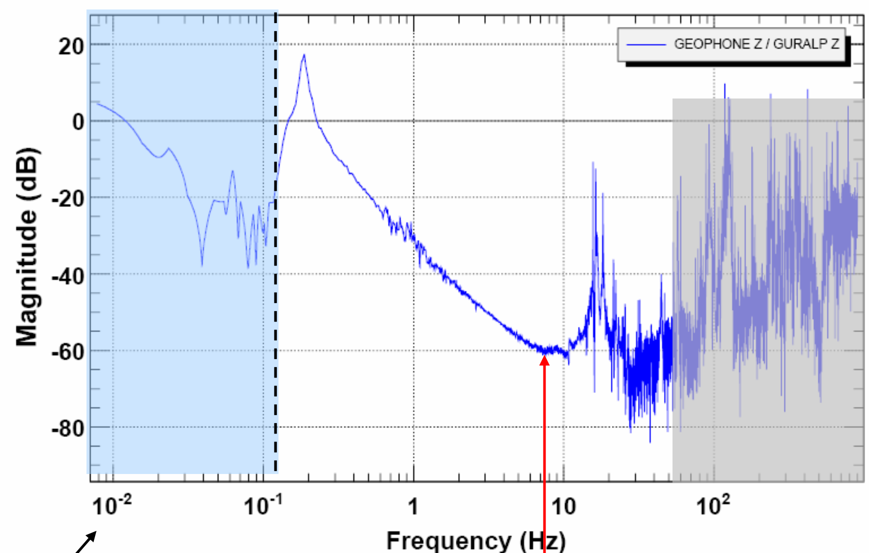
Transmissibilities

Geophones/Seismometers

Horizontal



Vertical



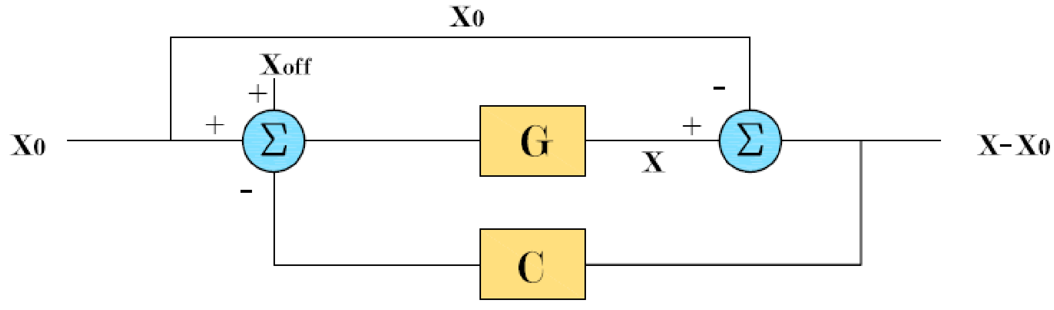
-70 dB

low coherence regions

-60 dB

HAM-SAS control strategy

input noise



LVDT sensors

$$TF_{cl}(s) = \frac{G(s)}{1+G(s)C(s)}$$

GC = open loop transfer function

unitary gain frequency

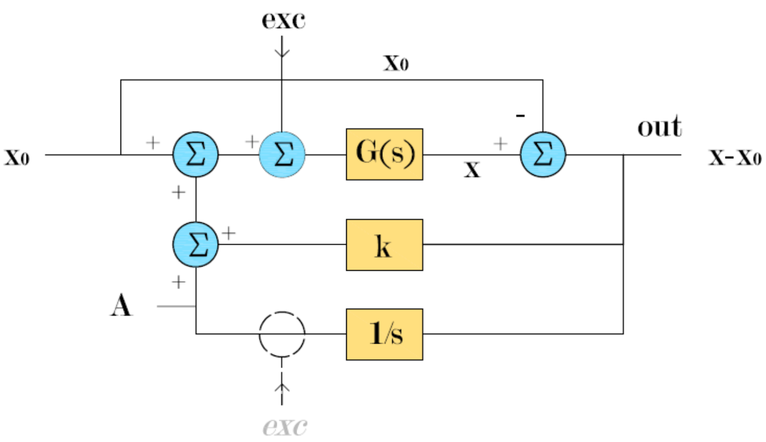
$$|GC(f_{ug})| = 1$$

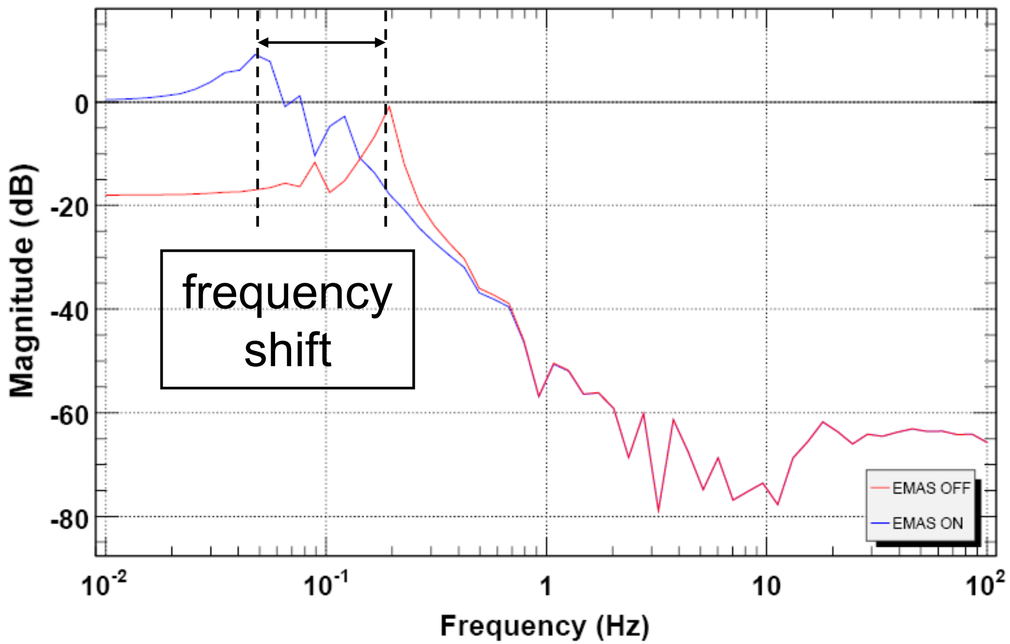
Minimal controls

- Position Control (DC)
  C(s)=a/s
- Velocity Control (Damping)
  C(s)=a*s
- Stiffness Control (EMAS)
  C(s)=-k

Stiffness Control (Electromagnetic Anti-Spring)

Control loop

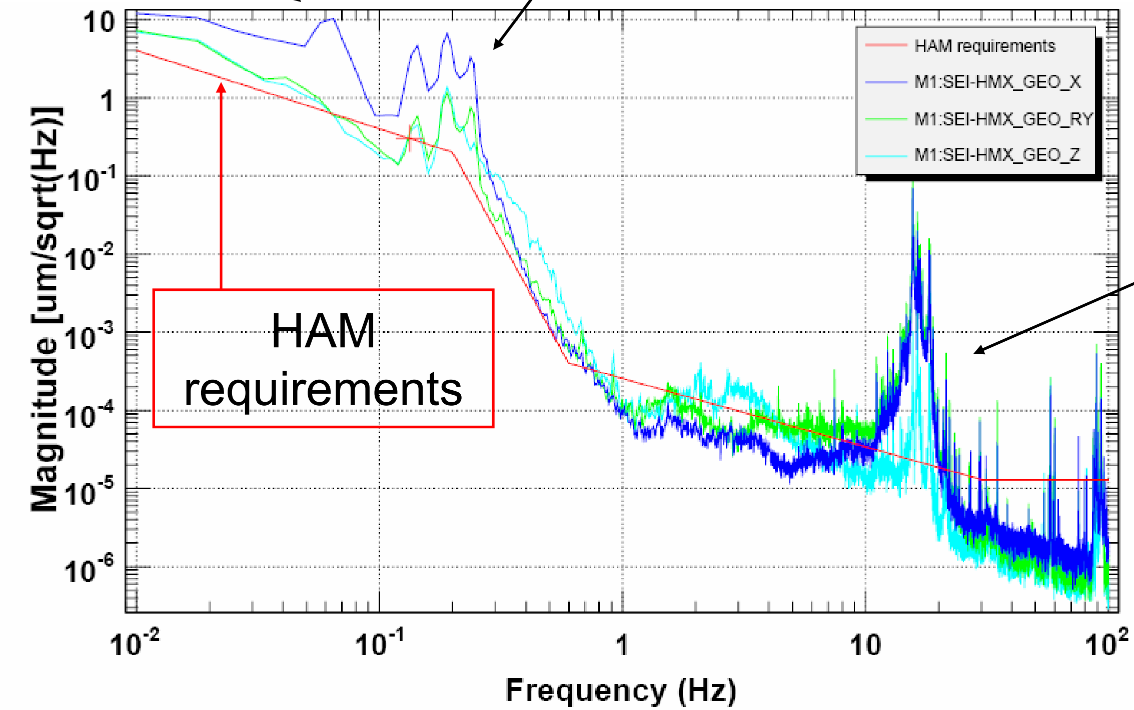




Passive Performance

Horizontal resonances

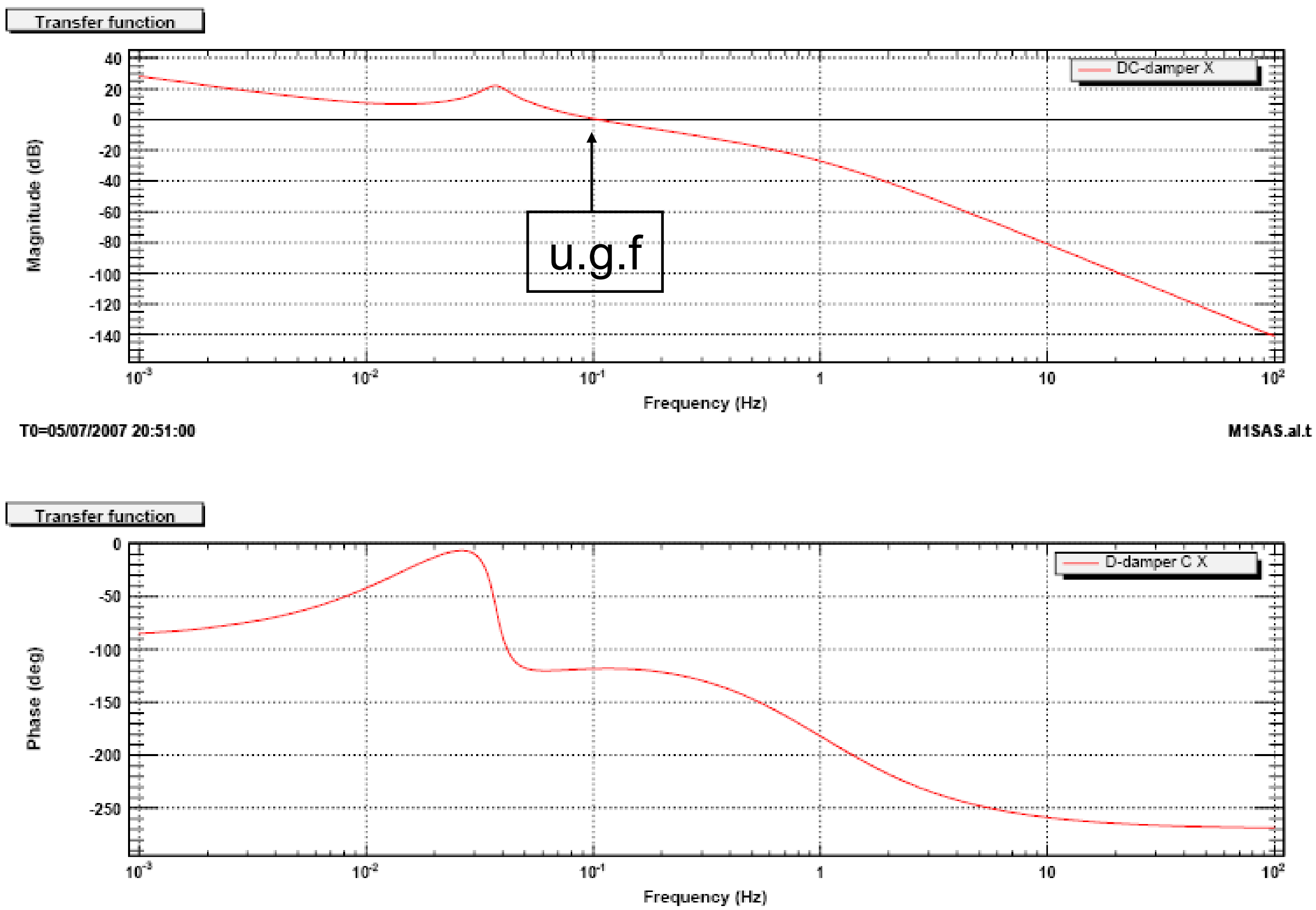
Vertical resonances



HAM requirements

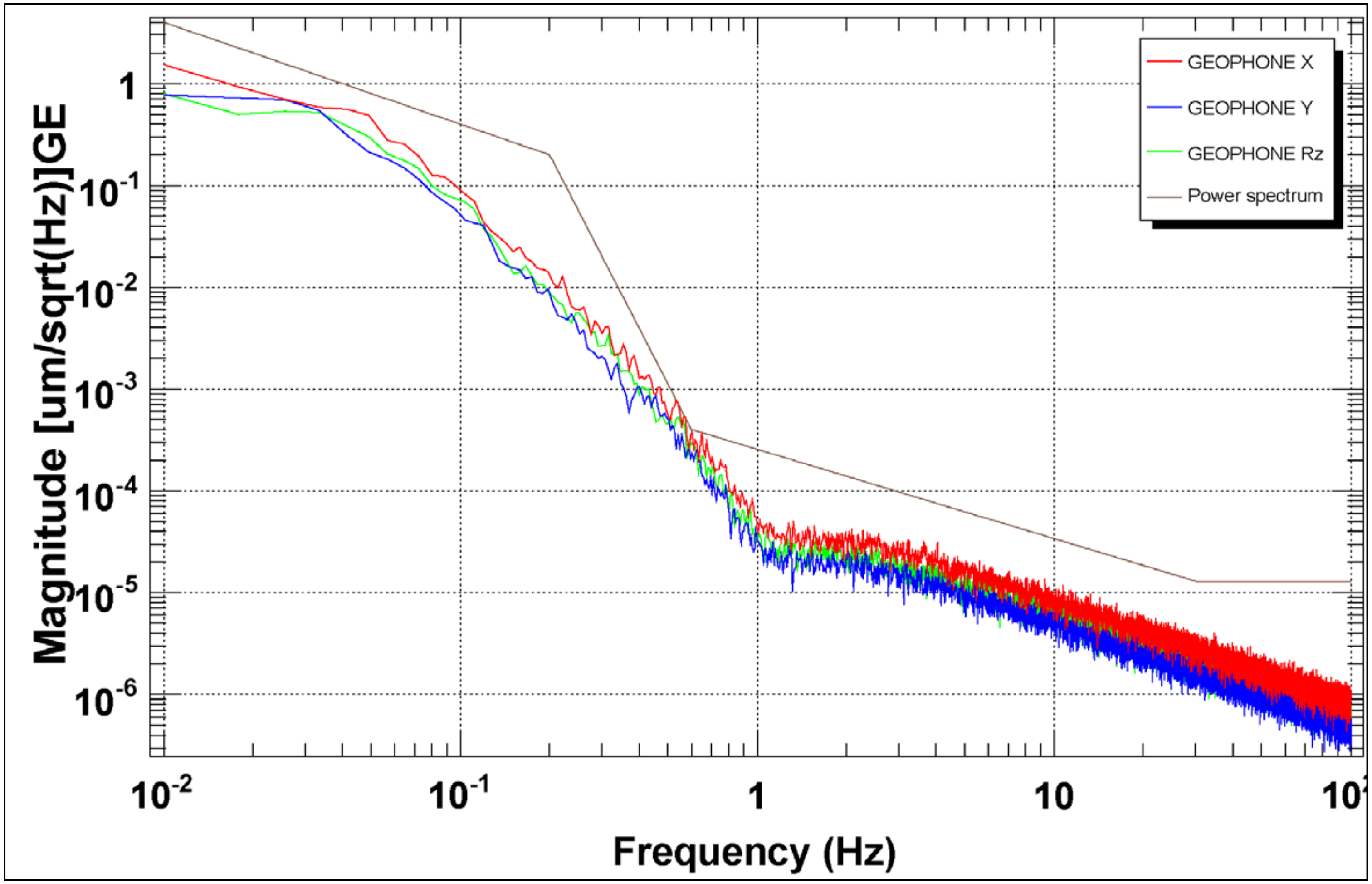
Tilt correction springs resonances

DC-Damping Control

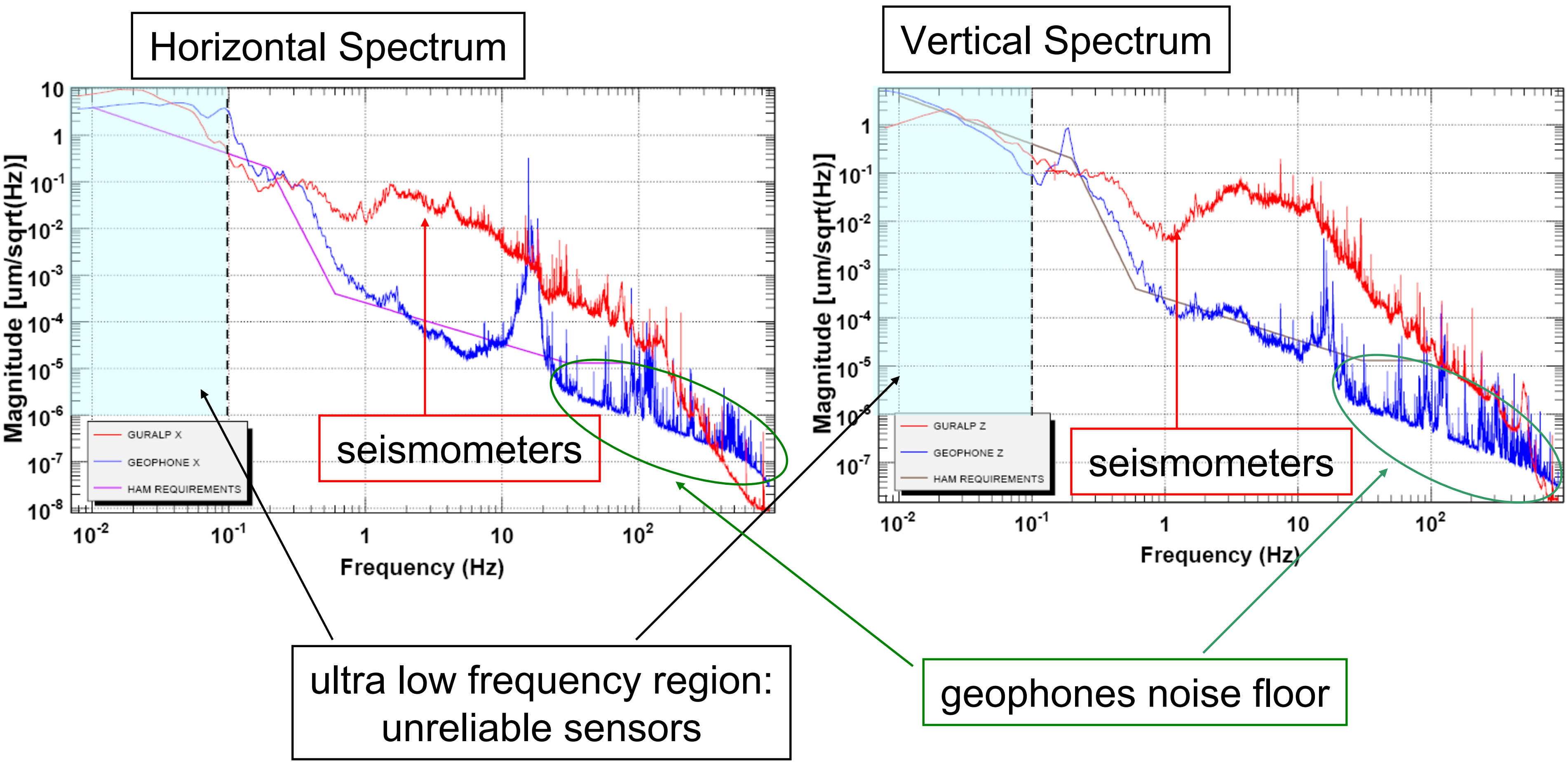


Open loop transfer function

Geophones floor noise



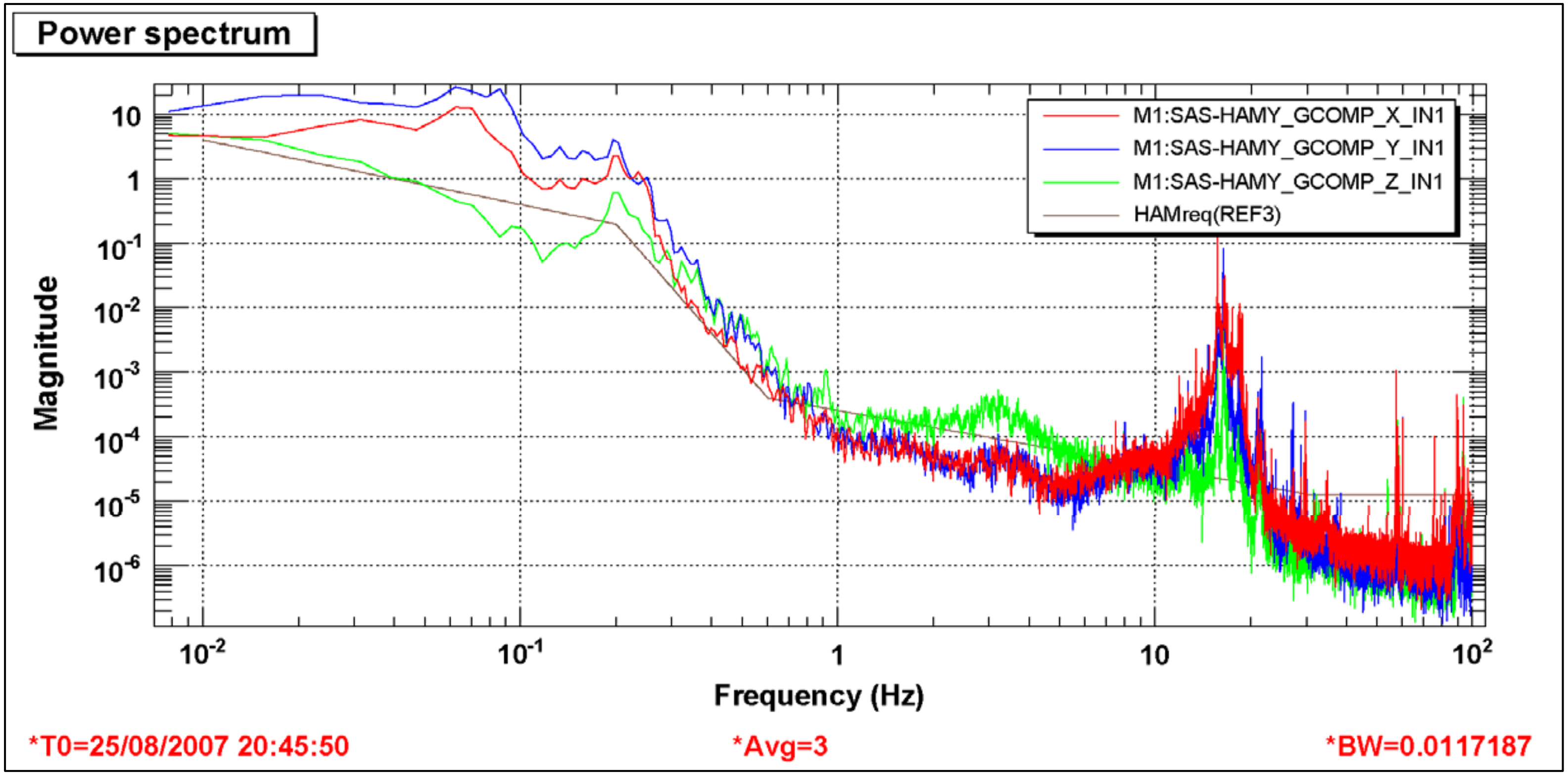
Performance with LVDT control



Spectra with the Position Control and the Damping Control Implemented

6 DOFs Active Control

Onboard geophones feedback



Accidents along the way..

- Tilt instability
- Coil driver failure
- Temperature roller coaster at LASTI
  ("*If you don't like the weather in New England, just wait a few minutes*", Mark Twain)

Possible improvements

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

Conclusions

- LIGO compatibility
  - Facility
  - UHV
  - CDS Control Systems
- Reliability and Redundancy
- Controllability
- Stability
- Seismic Attenuation Requirements Satisfaction
- Tilt Seismic Noise Limited

LIGO

Aknowledgments

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