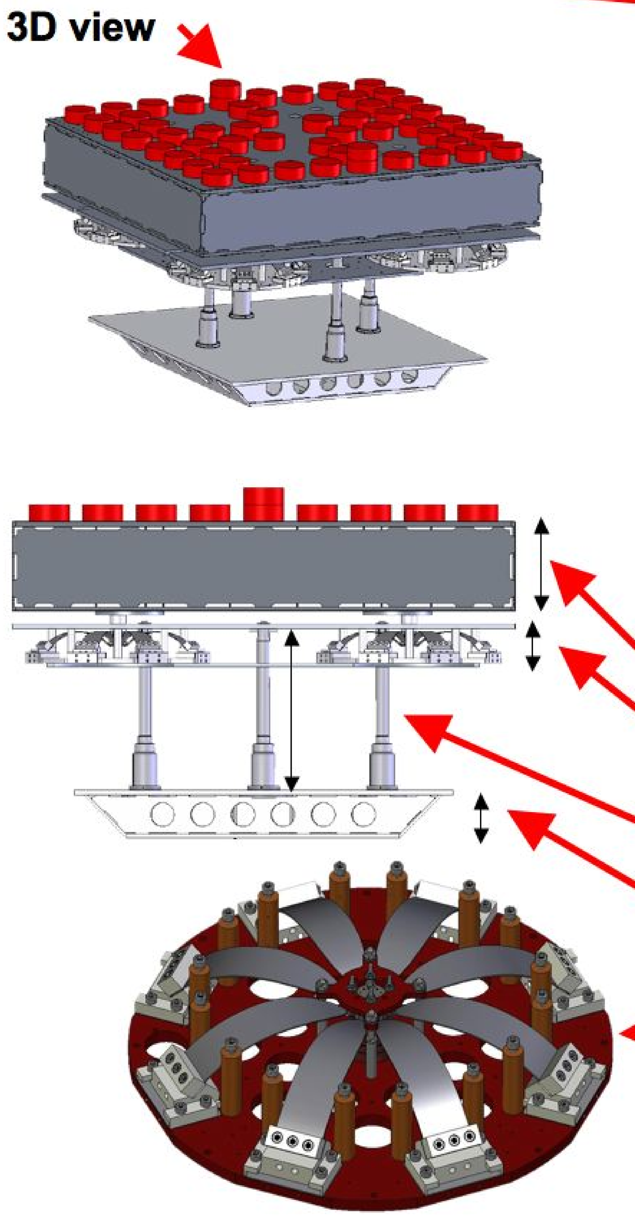
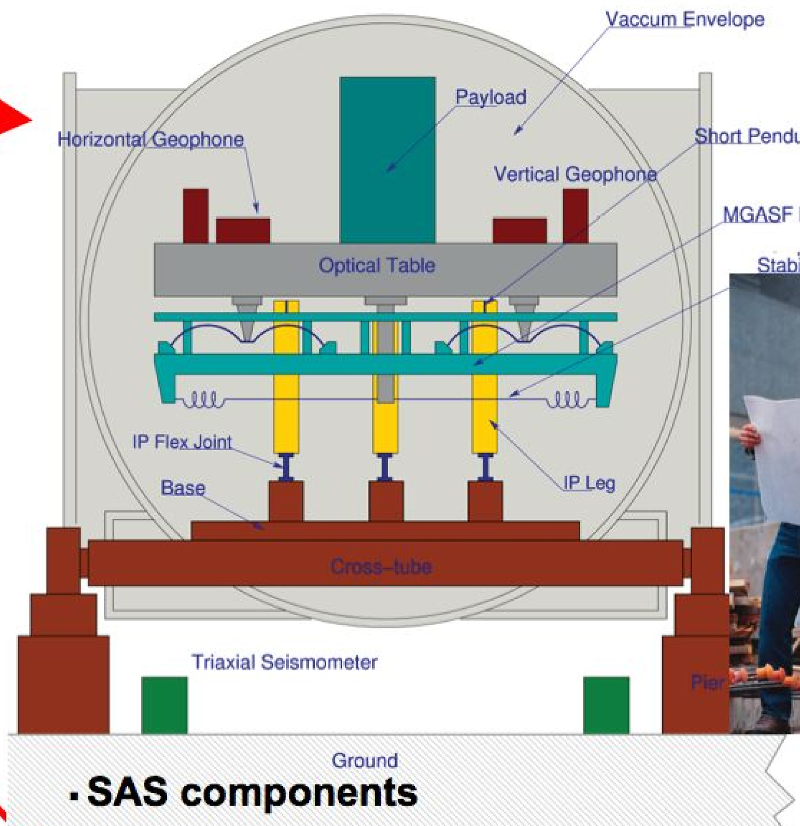
The SAS primary Seismic Attenuation System for Advanced LIGO's optical benches

Benjamin Abbott[1], Yoichi Aso[3], Valerio Boschi[1,4], Dennis Coyne[1], **Riccardo DeSalvo**[1], Alex Ivanov[1], Szabolcs Márka[3], David Ottaway[2], Virginio Sannibale[1], and Alberto Stochino[2,4].
[1] LIGO California Institute of Technology, Pasadena, CA, USA.[2] LIGO, Massachusetts Institute of Technology, Cambridge, MA, USA[3] Columbia University, New York, NY, USA. [4] Università di Pisa, Italy.

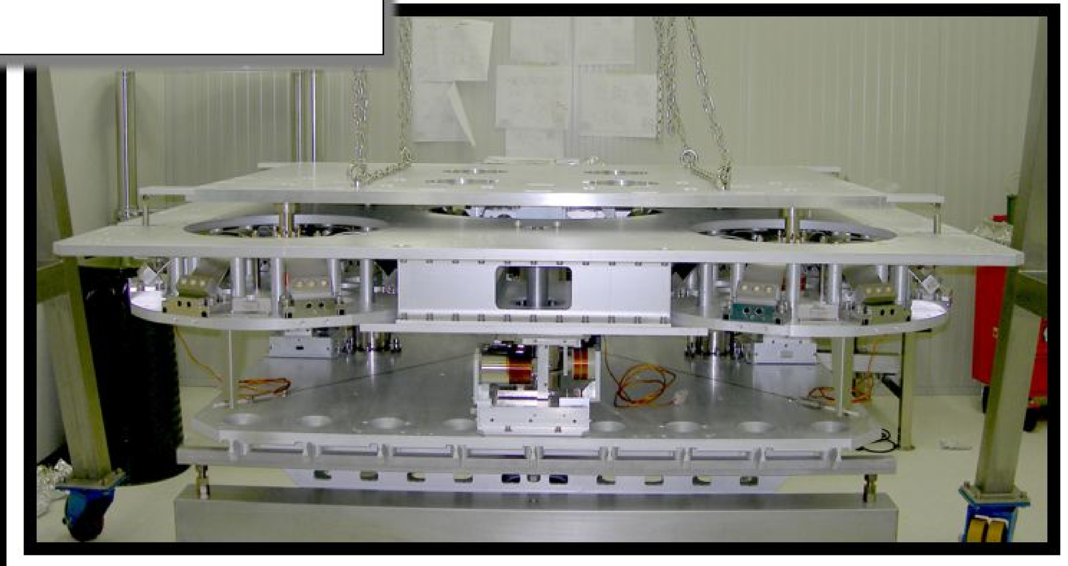
- **SAS for the HAM vacuum chambers**
  - **fit in vacuum chamber**
  - **3D view**

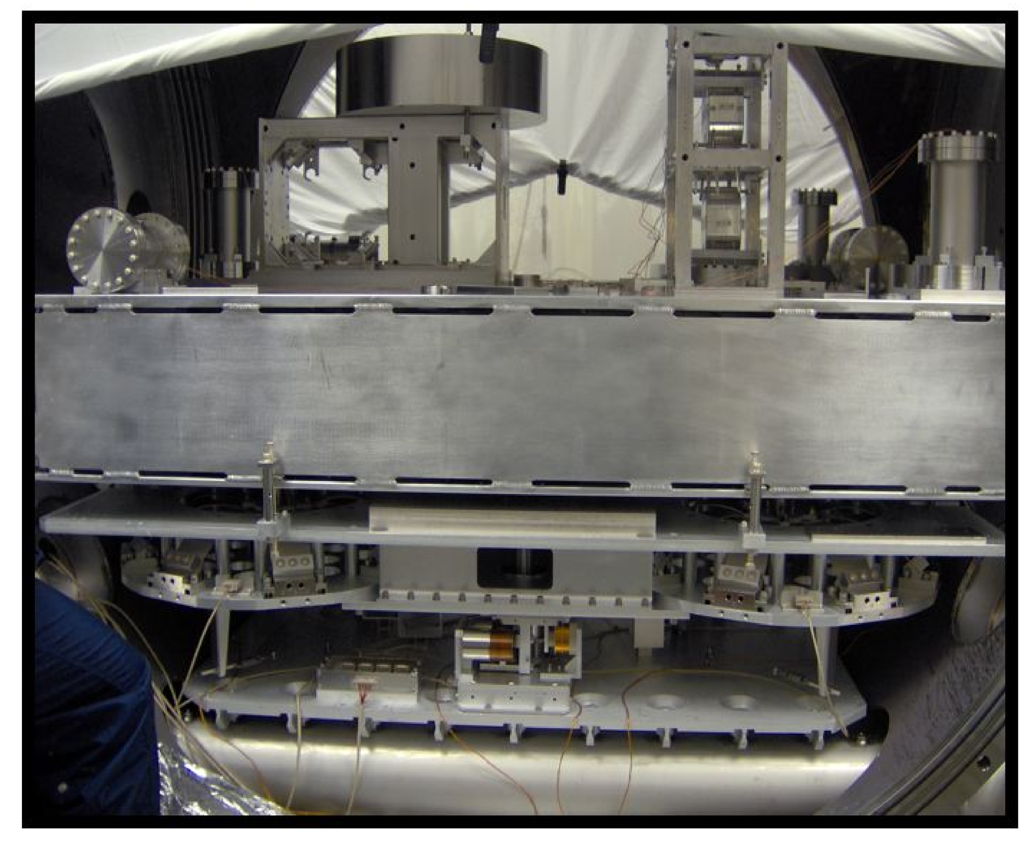




- **SAS components**
  - **Optical Table and Payload**
  - **Spring Box platform :**
  - **4 Inverted Pendula Legs horizontal attenuation**
  - **Base Platform**
  - **One of 4 MGAS Springs vertical attenuation**

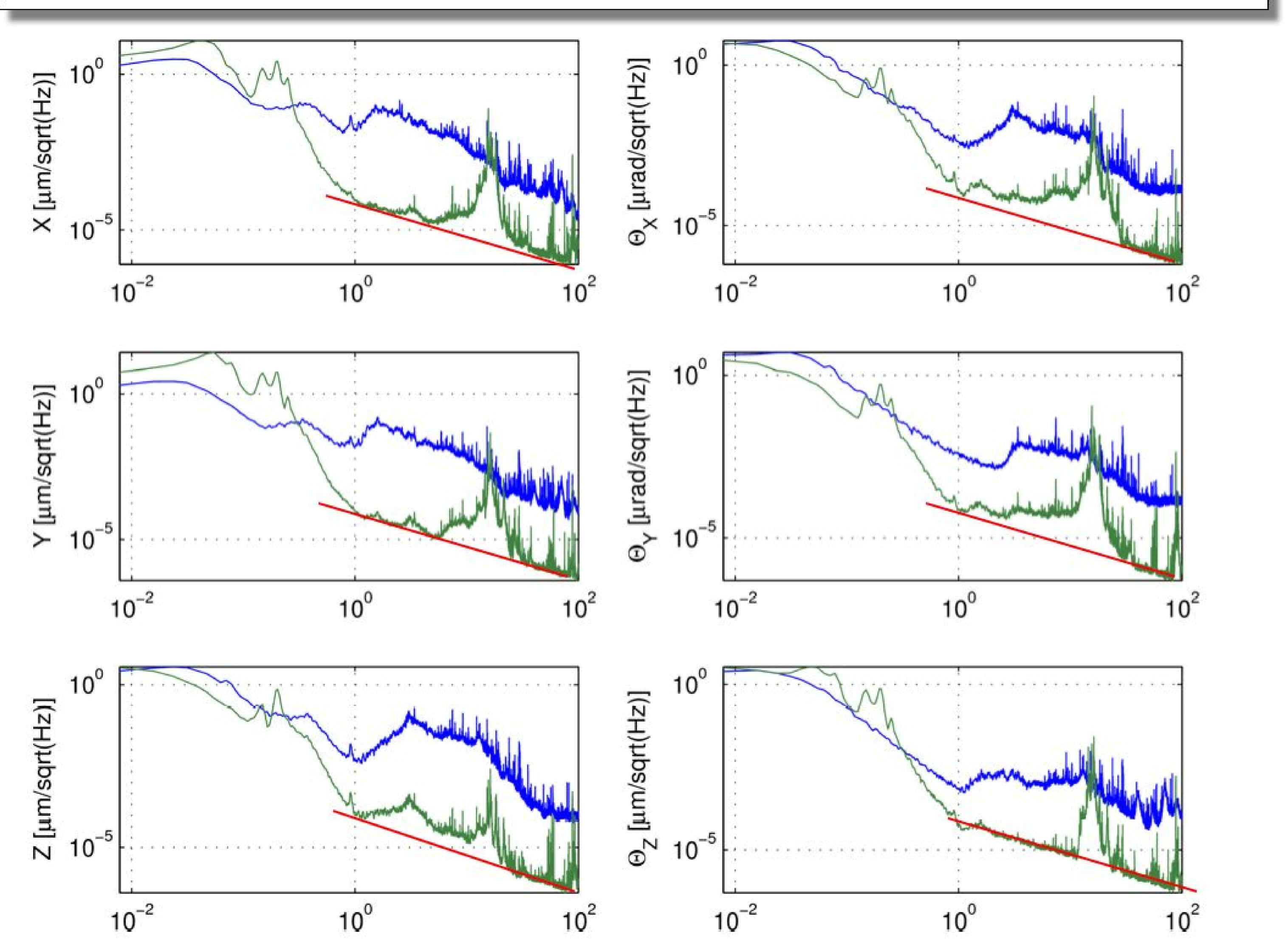
SAS System: Assembly & Installation





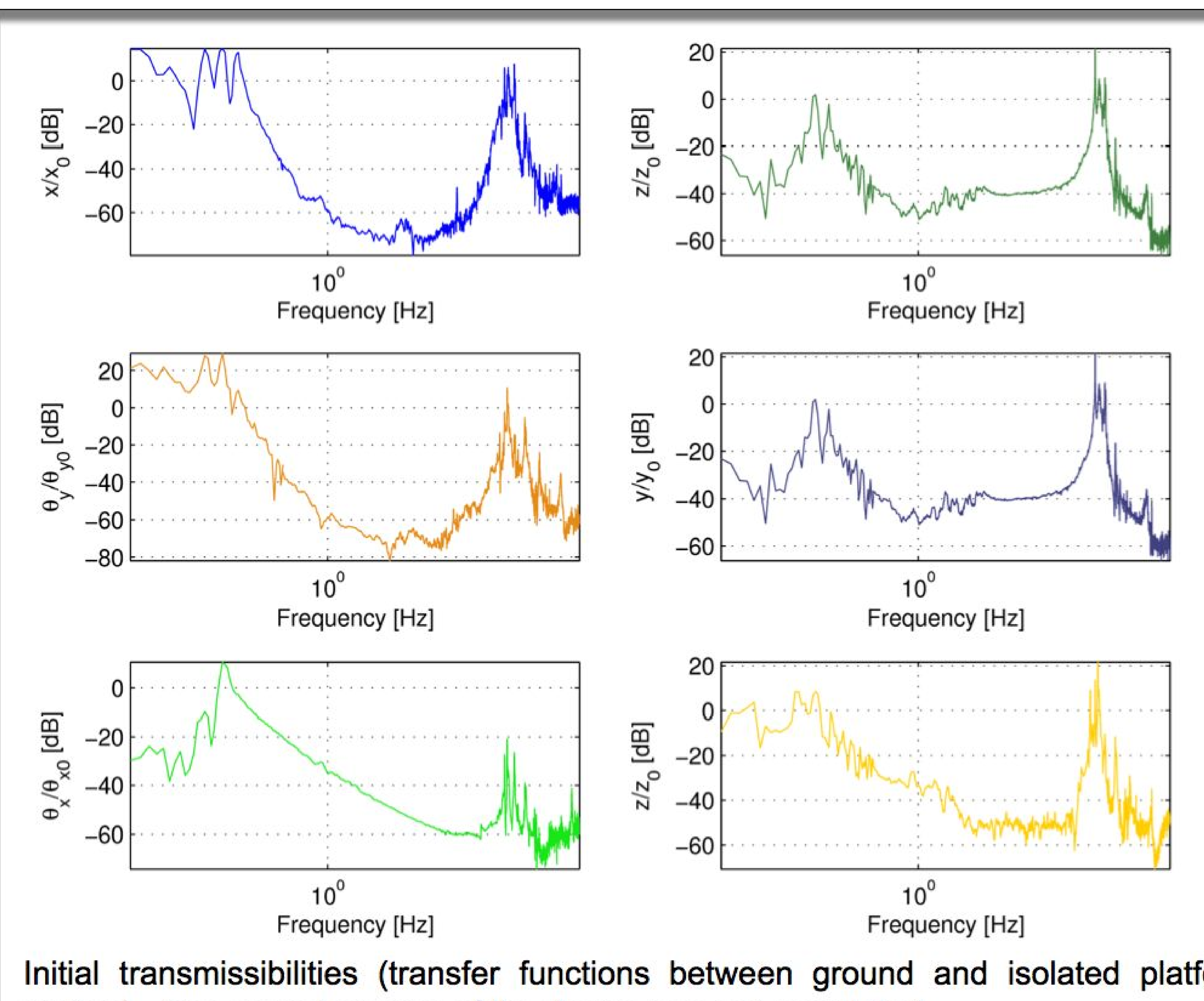
- Above: Four Assembled MGAS filters,
- Top-right: Inverted Pendulums Table with "Spring Box" ,
- Bottom right: Final assembly in the LIGO Horizontal Access Module (HAM chamber) in the LASTI facility at the MIT.

Passive Attenuation Performance: Seismic Noise PSDs



Seismic noise power spectral densities of all 6 DOFs obtained at the LIGO LASTI MIT Facility (blue-ground, green-optical table, red-geophone noise). Attenuation in the frequency range from 15Hz to 40Hz is spoiled by the spurious and still undamped pitch and roll resonances of the stabilizing device. Resonance below the Hz are the also undamped rigid body modes of SAS. The offset payload introduce coupling among the DOFs.

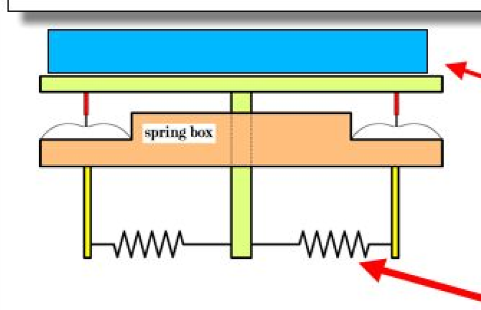
Passive Attenuation: Translational and Rotational Transmissibilities



Initial transmissibilities (transfer functions between ground and isolated platform motion). The commissioning of the device was not completed.

- Attenuation of the Horizontal DOFs reaches 70dB without IP counterweight.
- Attenuation of the Vertical DOFs reaches 60dB without magic wands.
- The attenuation performance can be improved by an additional order of magnitude in all 6 d.o.f. by implementing and tuning the existing Center Of Percussion effect compensators.
- The attenuation performance can be further extended to lower frequency (x2 in horizontal, x5-10 in vertical) by simple tuning GAS springs and IP.
- Damping of the low frequency resonances naturally ensues from the LF tune and reduce r.m.s. motion.
- The resonance between 15Hz to 40Hz can be eliminated by implementing wire dampers on the Pitch/Roll stabilizing springs.

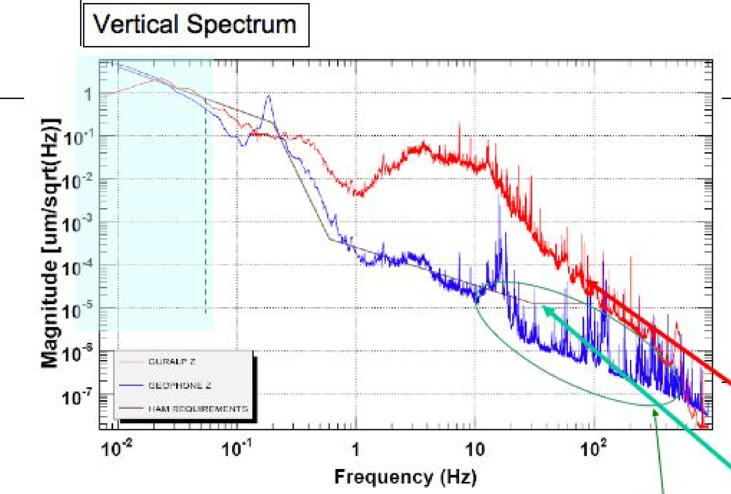
Pitch/Roll Stabilizing Device: Spurious 10Hz-50Hz Resonances

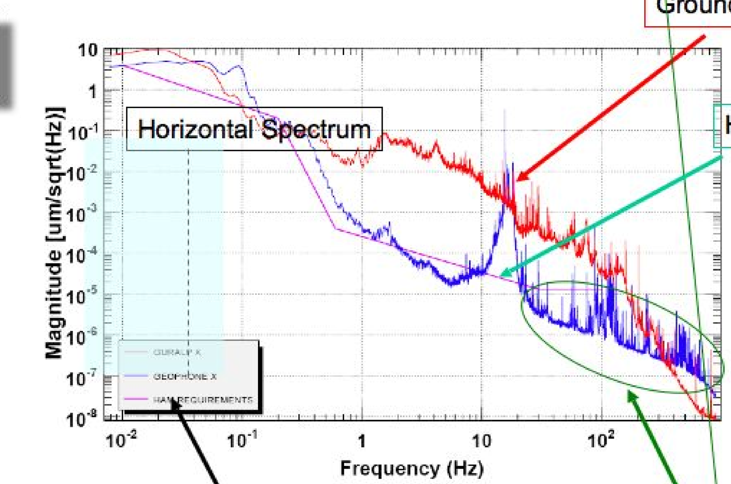


The optical table is above the seismic isolators

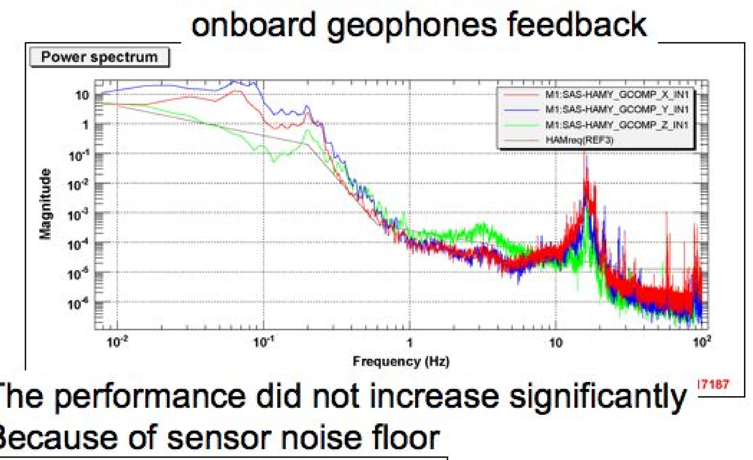
Pitch stabilization springs necessary

LVDT Control Performance:

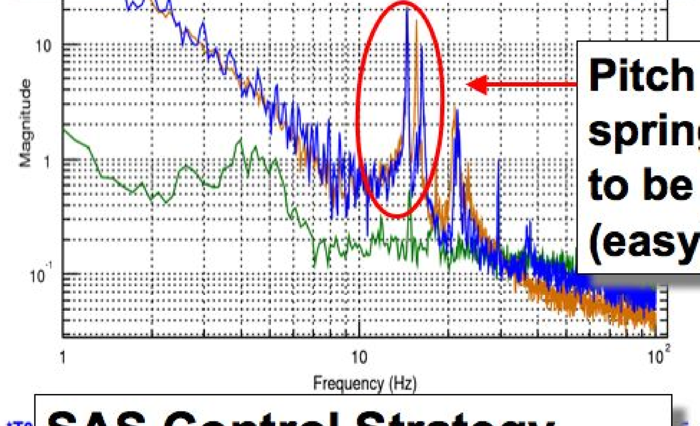




6 d.o.f.active controls with onboard geophones feedback



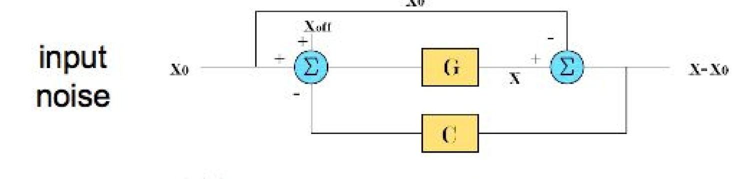
The performance did not increase significantly Because of sensor noise floor



Pitch stabilization springs resonances to be damped (easy)

SAS Control Strategy

Mechanically tune all the rigid body modes to lowest possible mechanical resonant frequency
Apply Electromagnetic Anti Springs "EMAS" to further reduce resonant frequency
Lowering the resonance frequency reduces the Quality factors ($Q\sim f^2$) and makes damping unnecessary
- Apply minimal controls: a very low frequency position control (relative to ground) to minimize of the RMS Seismic Noise.



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

GC = open loop transfer function

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

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

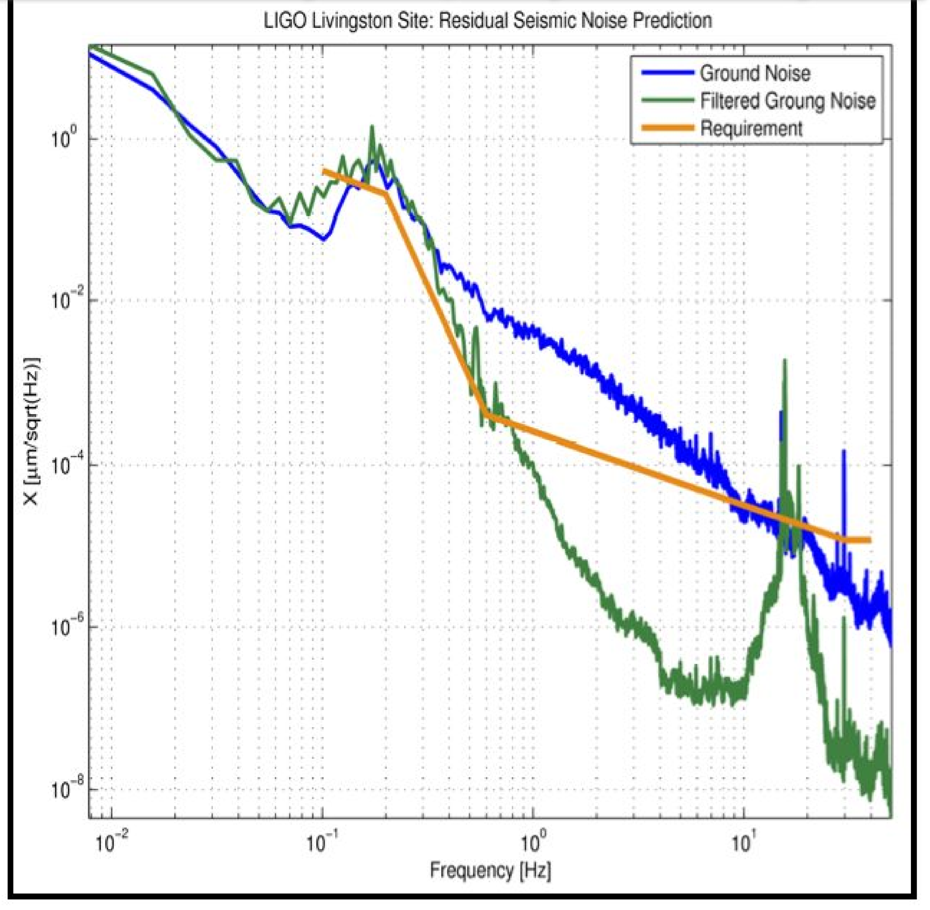
CONCLUSIONS

SAS Performance close to ad-LIGO requirements.

Can be exceeded with the following modification :

- Damp the Pitch/Roll stabilizing device resonances.
- Mechanical tune of ALL the modes below 80mHz.
- Install the "magic wands" and the IP counterweights to lower the transmissibility saturation 20dB extra attenuation expected.
- Better tuning of the existing DC control scheme.
- Potential further improvements from accelerometer feedback

Example: Horizontal Direction Residual Seismic Noise Prediction at LIGO Livingston (noisiest site and present, un-optimized tune)



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ABSTRACT

A passive (minimally active) Seismic Attenuation System (SAS) for primary seismic attenuation of the Advanced LIGO optical benches was designed, prototyped and tested in the LIGO HAM vacuum chambers at the LASTI laboratory. The main design aim, beyond providing the required seismic attenuation using a single attenuation stage, is to guarantee reliability of operation. To do this passive attenuation was optimized, thus limiting the requirements from active attenuation feedback (mainly at low frequencies,below the Hz), and only passive sensor and actuators (without in-vacuum active components) were used. The low frequency flexures used to couple the rigid platforms of the system automatically provide nearly ideal decoupling for effective active control upgrades.

The SAS functions are divided in two parts. An intermediate platform supported by four inverted pendulum legs provides attenuation of the horizontal degrees of freedom. Four GAS filters integrated in this structure, called Spring Box, provide the isolation of the three vertical degrees of freedom. The geometry is such that the horizontal degrees of freedom and the vertical ones are separate and can be treated separately.
Each of the four GAS filter carries coaxially an LVDT position sensor and an electromagnetic actuator. Each leg of the inverted pendulums is similarly equipped. The redundancy is such that failure of one of the four LVDT or e.m. actuator cannot not cripple the system. Eight stepper motors driving parasitic springs, in parallel to the 8 e.m. actuators, provide the static positioning of the system. UHV compatible accelerometers were foreseen (but not built) to boost the system performance if necessary. An important feature is that horizontal inertial sensors mounted on the horizontal stage, upstream of the vertical one, would not suffer from tilt interference effects.

The tests at LASTI showed that the vertical and horizontal degrees of freedom are actually uncoupled and can be treated independently. It was possible to clearly identify the modes of the system and build a set of synthetic position sensors and a set of synthetic actuators, which diagonalize the transfer function of the system. We measured accurate physical plants responses for each degree of freedom and, based on these, designed specific control strategies. For the horizontal degrees of freedom we implemented simple control loops for control of the static position and the damping of the resonances. For the vertical ones, beyond these functions, the loops introduced an electromagnetic anti-spring effect and lowered the resonance frequency.

The overall result was the achievement of the HAM optical bench LIGO seismic attenuation requirements within the sensibility limits of the geophone sensors used to measure the performances. At the low frequency end, the system without LVDT position feedback showed a residual r.m.s. motion consistent with the motion of a mass on a frictionless table, subject to ground tilt noise. Feedback from a low-noise tilt meter could reduce this motion reducing the feedback from the low-pass-filtered LVDT position sensor signals.

The entire project, from the construction to the commissioning, occurred within a very tight time schedule which left scarce possibility to complete the expected mechanical setup. Some of the subsystems (among which the counterweights for the center of percussion of the pendulums and the ``magic wands'' for the GAS filters) could not be implemented and several operations of optimization (i.e. the lower tuning of the vertical GAS filters' resonant frequencies and the tilts' optimization) had no chance to be completed. Nonetheless the performances measured on the HAM-SAS prototype were in agreement with the simulations with the same configuration and the obtained results prove that, with completed mechanics, proper tuning and low frequency feed back, the system can provide the seismic attenuation required by any of the Advanced LIGO optical benches. This table, or scaled versions of, can be an useful test bench for accelerometers and seismometers.

These devices should provide an attenuation factor of about 70dB above 10Hz at the suspension point of the Advanced LIGO triple pendulum suspension. Automatic control techniques are used to position the optical table and reduce the low frequency rms motion. Here, we report the main results obtained from the full scale prototype installed at the MIT LIGO Advanced System Test Interferometer (LASTI) facility. Seismic attenuation performance, control strategies, improvements and limitations are also discussed.