Adv LIGO and retrofit seismic isolation research update

LSC Aug 19, '03. LIGO-G030429-00-D

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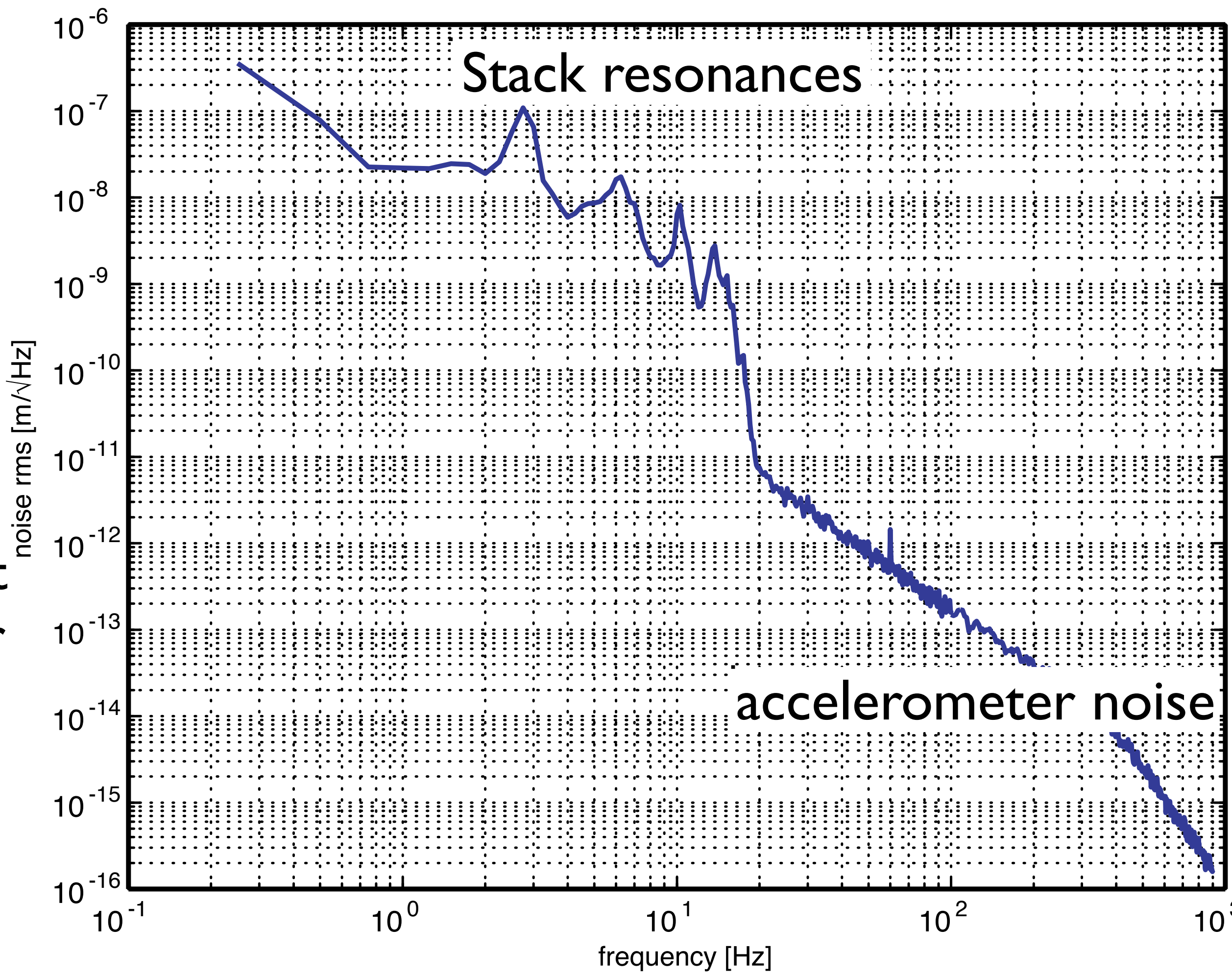
LIGO-1 Seismic isolation Stack

- 4 cascaded mass-spring layers support integral down-tube/ optics table
- novel internally-damped coil springs bring *Q's* of normal modes down to ≈10–30.

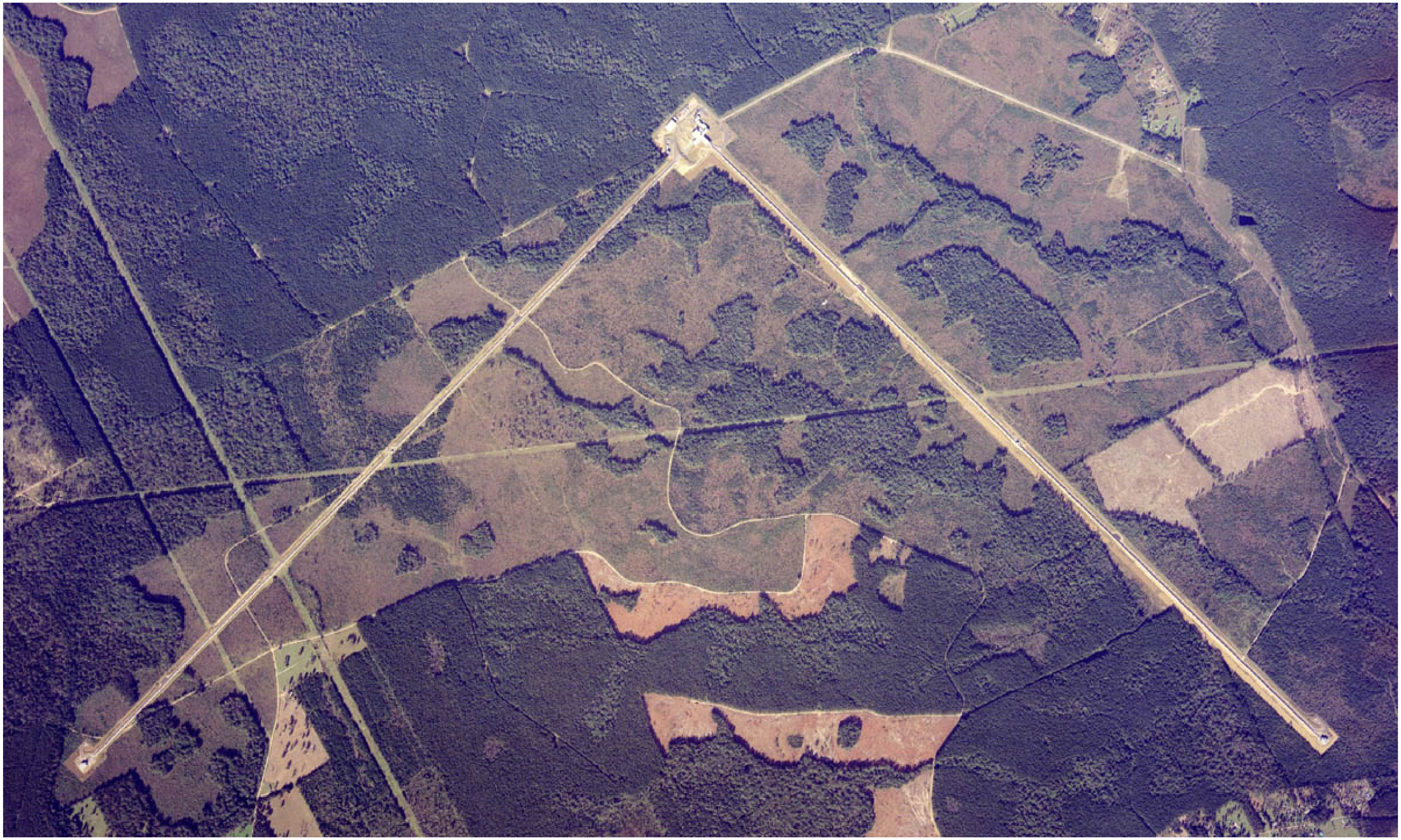
Stack performance

- Stack isolates very well at high frequencies, meeting requirements.
- But, there are several troublesome resonances in the 1–12 Hz band that affect the interferometer when excited by ground noise.



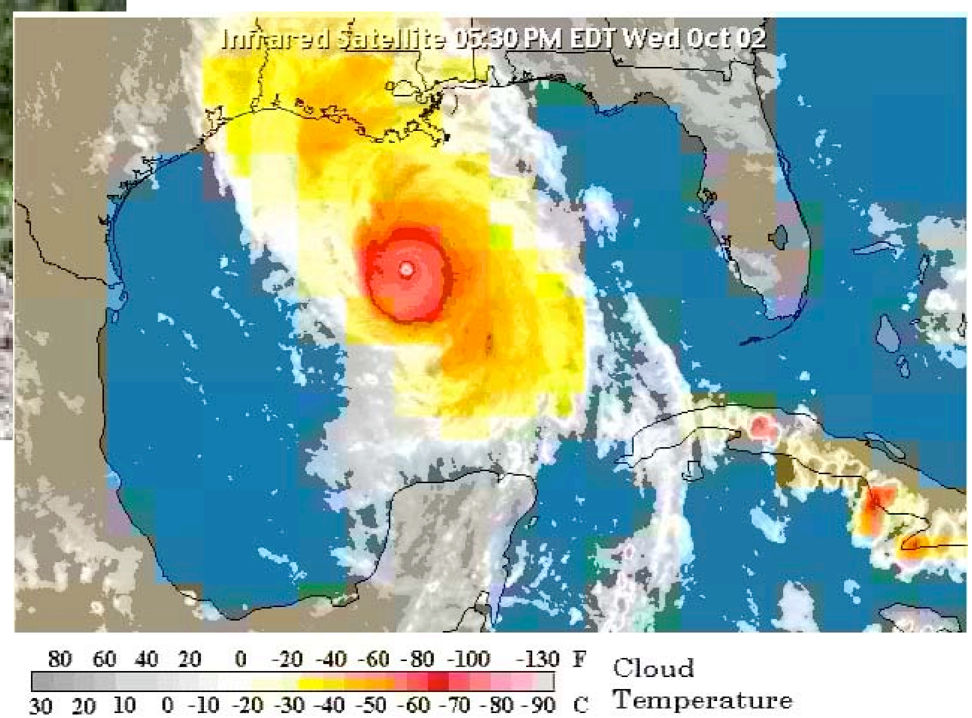
Noise seen by accelerometer on optics table (vertical)

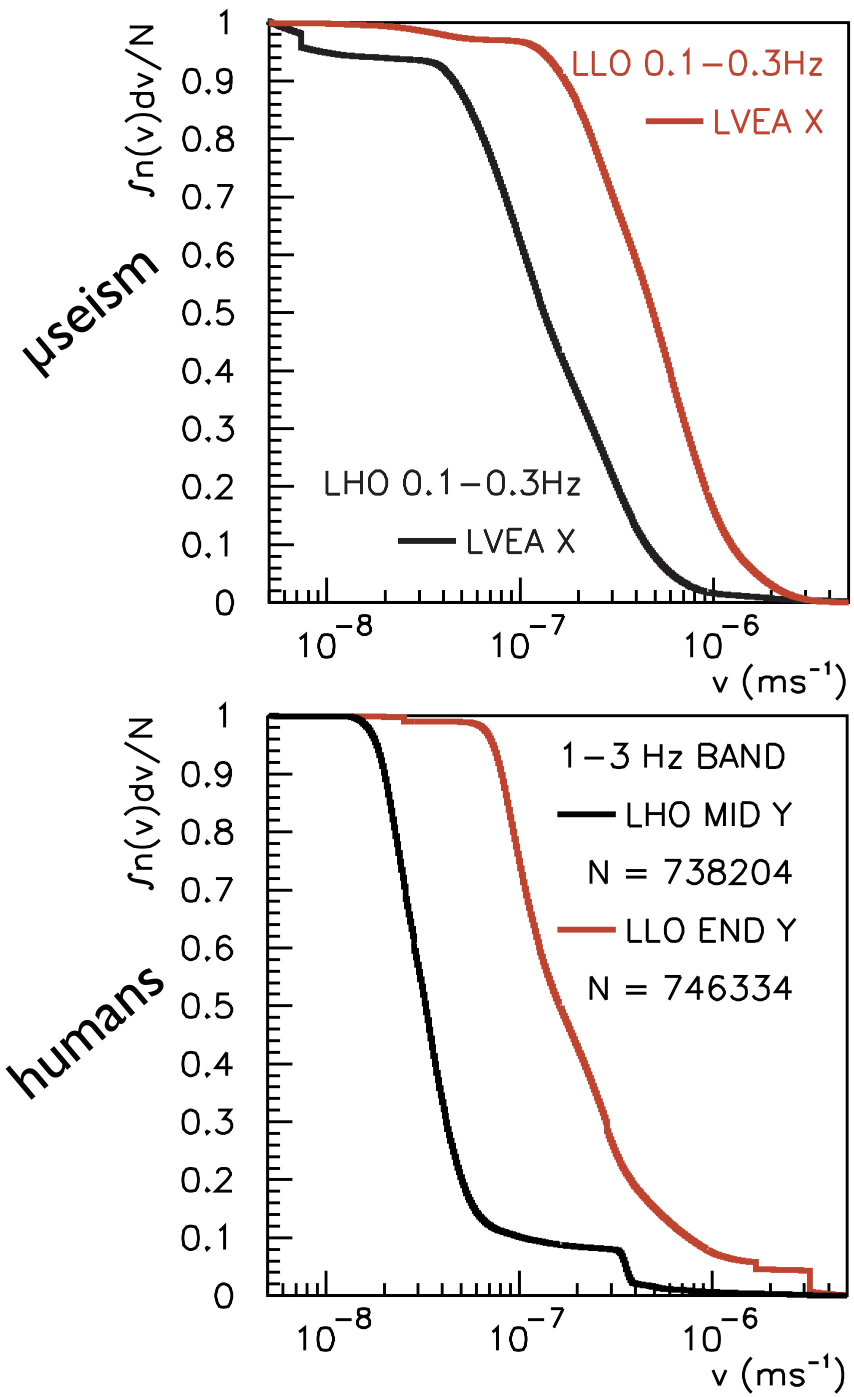
Ground noise studies.



Louisiana ground noise

- Timber harvesting adds noise in 1–3 Hz band
- Storms and waves in the Gulf of Mexico add noise in sub-Hz bands.
- Trucks, cars and trains...

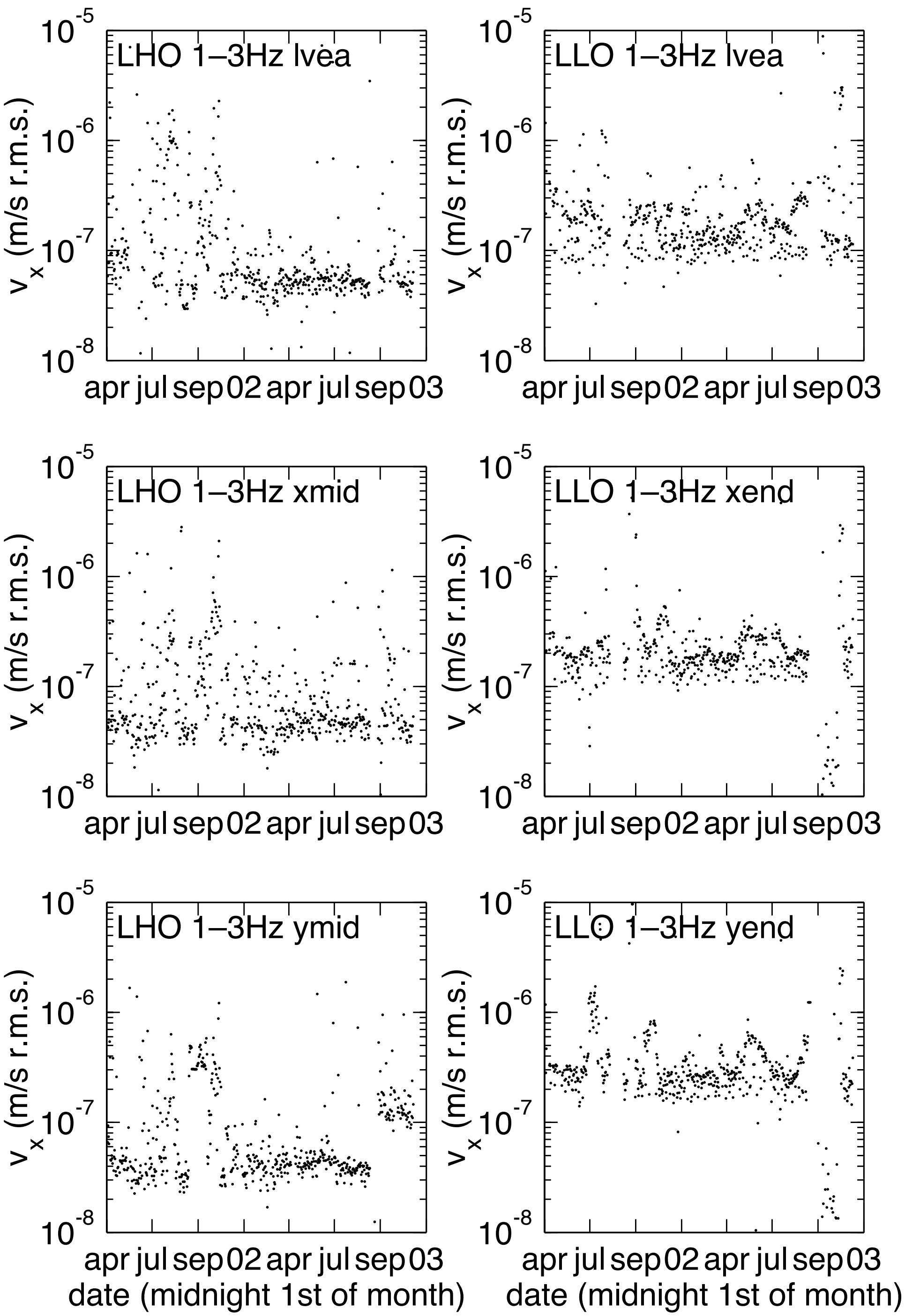




Statistics of band-limited rms velocities over 613 days

1–3 Hz 90th percentile values

site	chan	90%, μm/s	llo/ lho
LLO	lvea x	0.31	4.0
	lvea y	0.29	3.6
	ex x	0.34	4.5
	ey y	0.75	7.3
LHO	lvea x	0.078	
	lvea y	0.083	
	mx x	0.077	
	my y	0.10	



Long-term ground noise trends

- 600+ day study of band-limited RMS of seismometer signals at both sites.
- no long-term trend is evident.
- large excursions seen in high frequencies due to human activity
- large seasonal excursions seen in microseism due to large-scale weather.

Torture test: 1500 s segments during ‘interesting’ times.

- Quantities listed are for the greatest arm length peak-to-peak excursion, and for the differential rms arm length deviation.
- Displacement integrated down to 30 mHz, acceleration up to 16 Hz.

data file	Displacement	Velocity	Acceleration
Enormous µseism	**63 µm p-p**	**35 µm/s p-p**	**180 $\mu m/s^2$ p-p**
	11 µm rms	4.8 µm/s rms	17 $\mu m/s^2$ rms
Day Train	13 µm p-p	13 µm/s p-p	150 $\mu m/s^2$ p-p
	1.7 µm rms	1.6 µm/s rms	17 $\mu m/s^2$ rms
Borderline day	30 µm p-p	18 µm/s p-p	150 $\mu m/s^2$ p-p
	4.6 µm rms	2.5 µm/s rms	17 $\mu m/s^2$ rms

Active noise reduction

Feedback

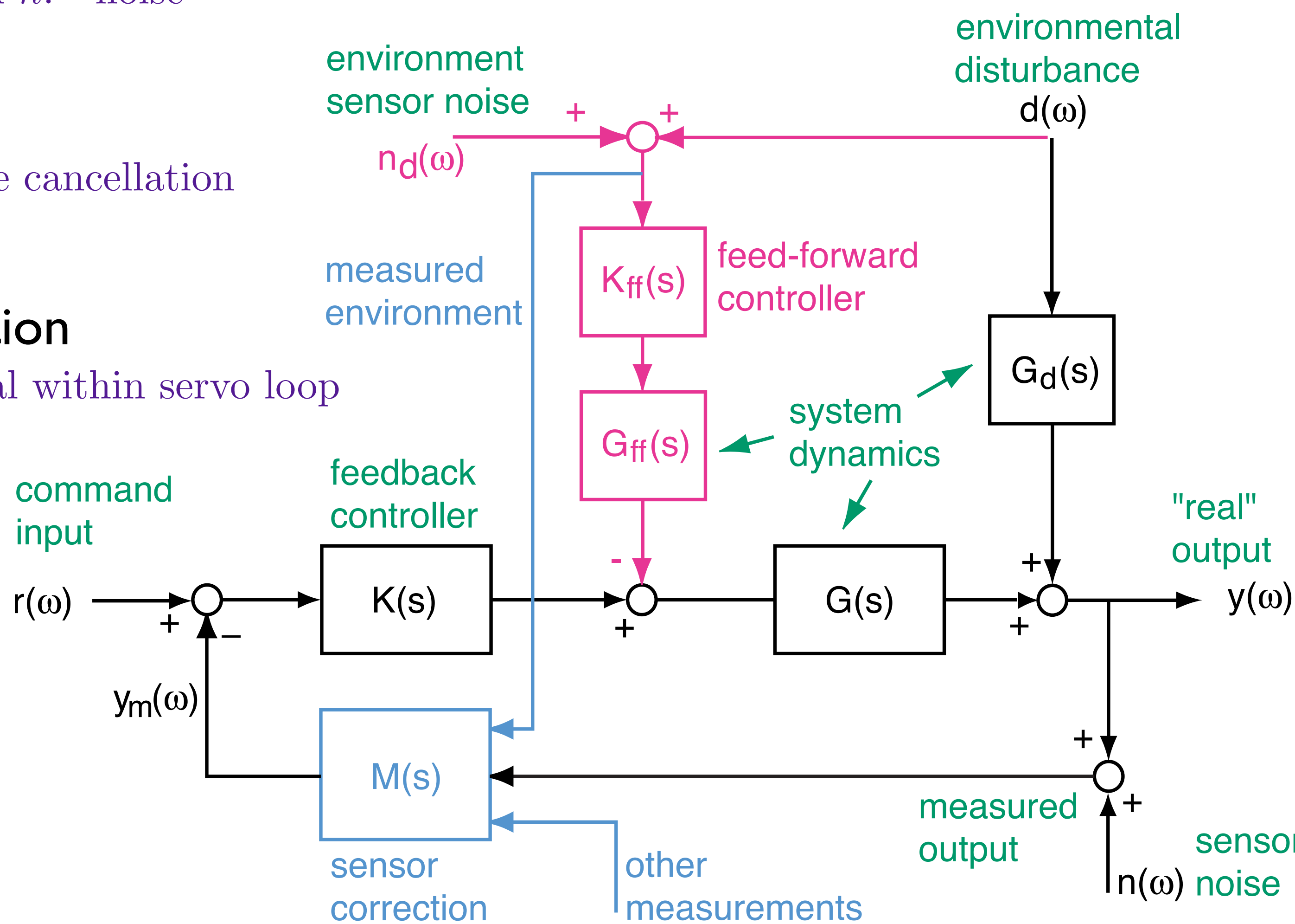
$$y = (I+GK)^{-1}GK\,r \quad \text{command tracking}$$
$$+\,(I+GK)^{-1}G_{\mathrm{d}}\,d \quad \text{disturbance suppression}$$
$$-\,(I+GK)^{-1}GK\,n. \quad \text{noise}$$

Feedforward

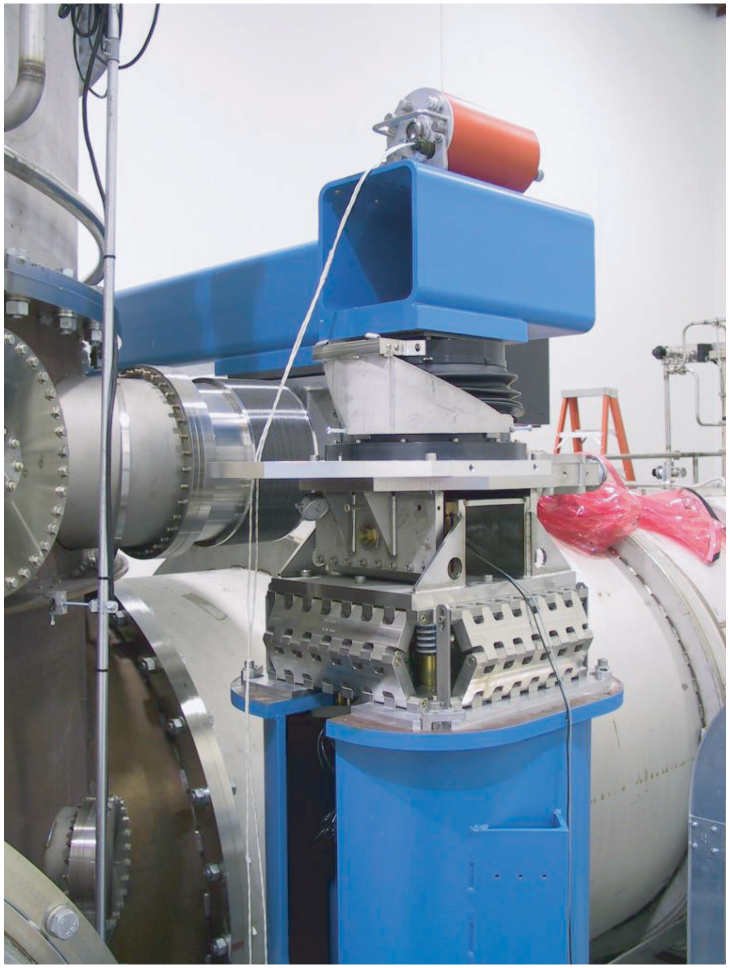
$K_{\mathrm{ff}}G_{\mathrm{ff}}G = G_{\mathrm{d}} \Rightarrow$ noise cancellation

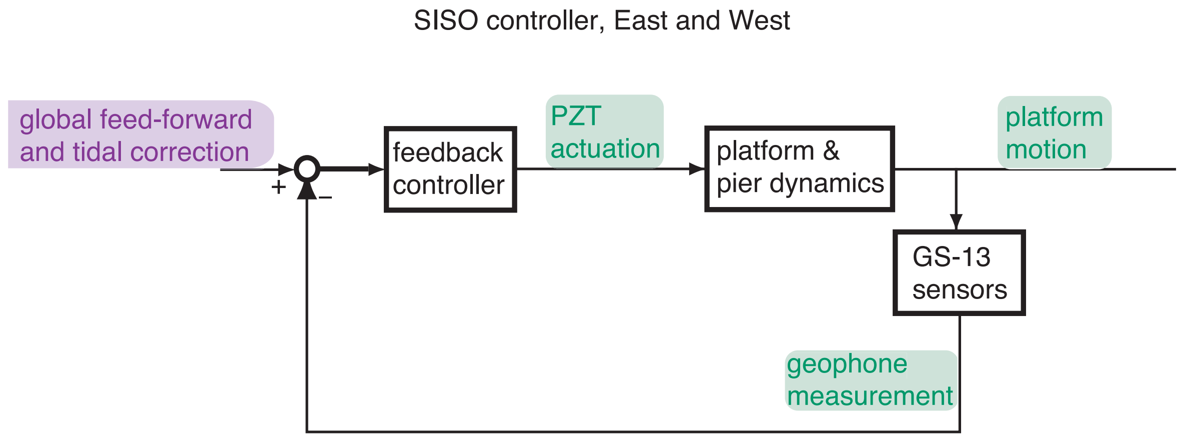
Sensor Correction

M corrects error signal within servo loop



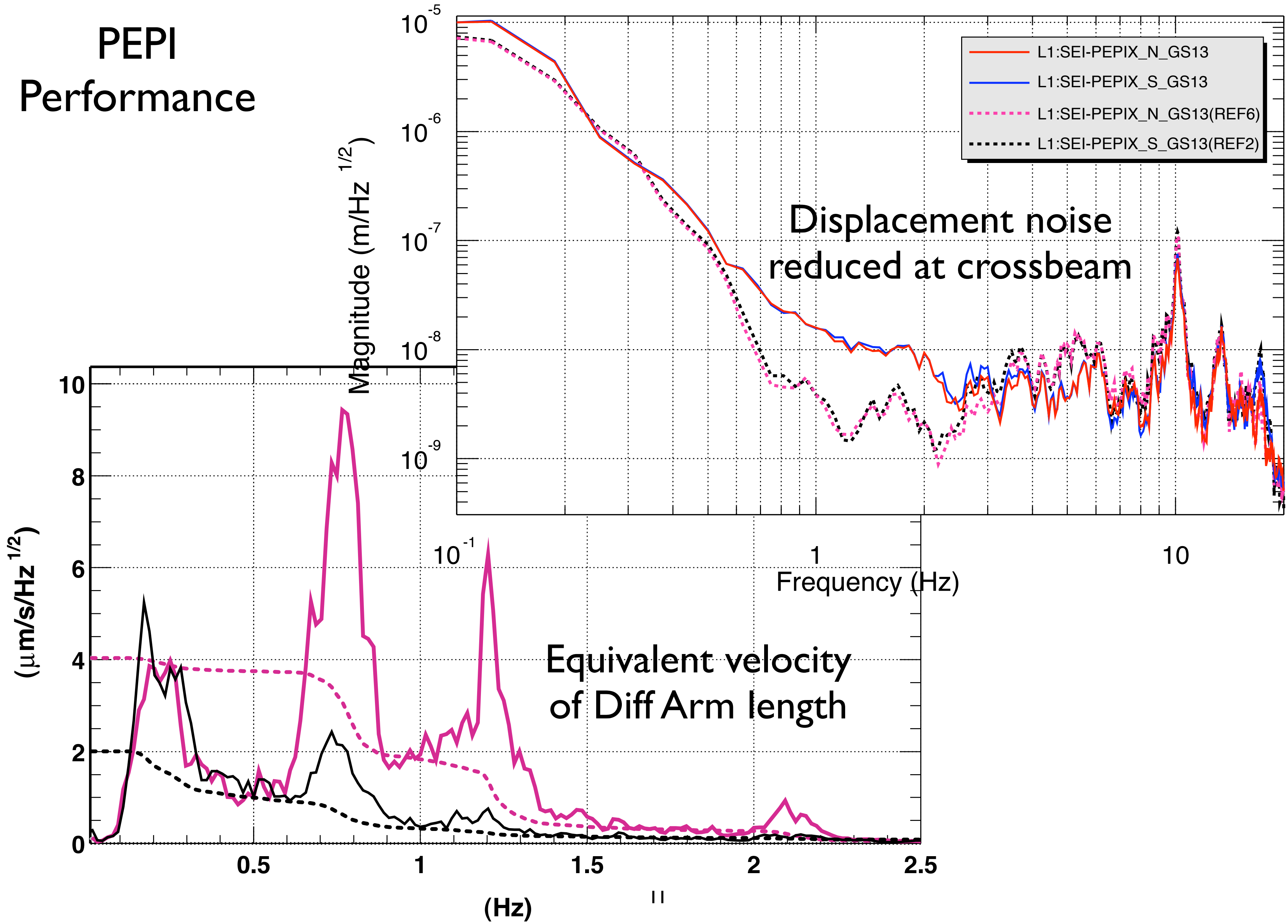
PEPI: Piezoelectric pre-isolation



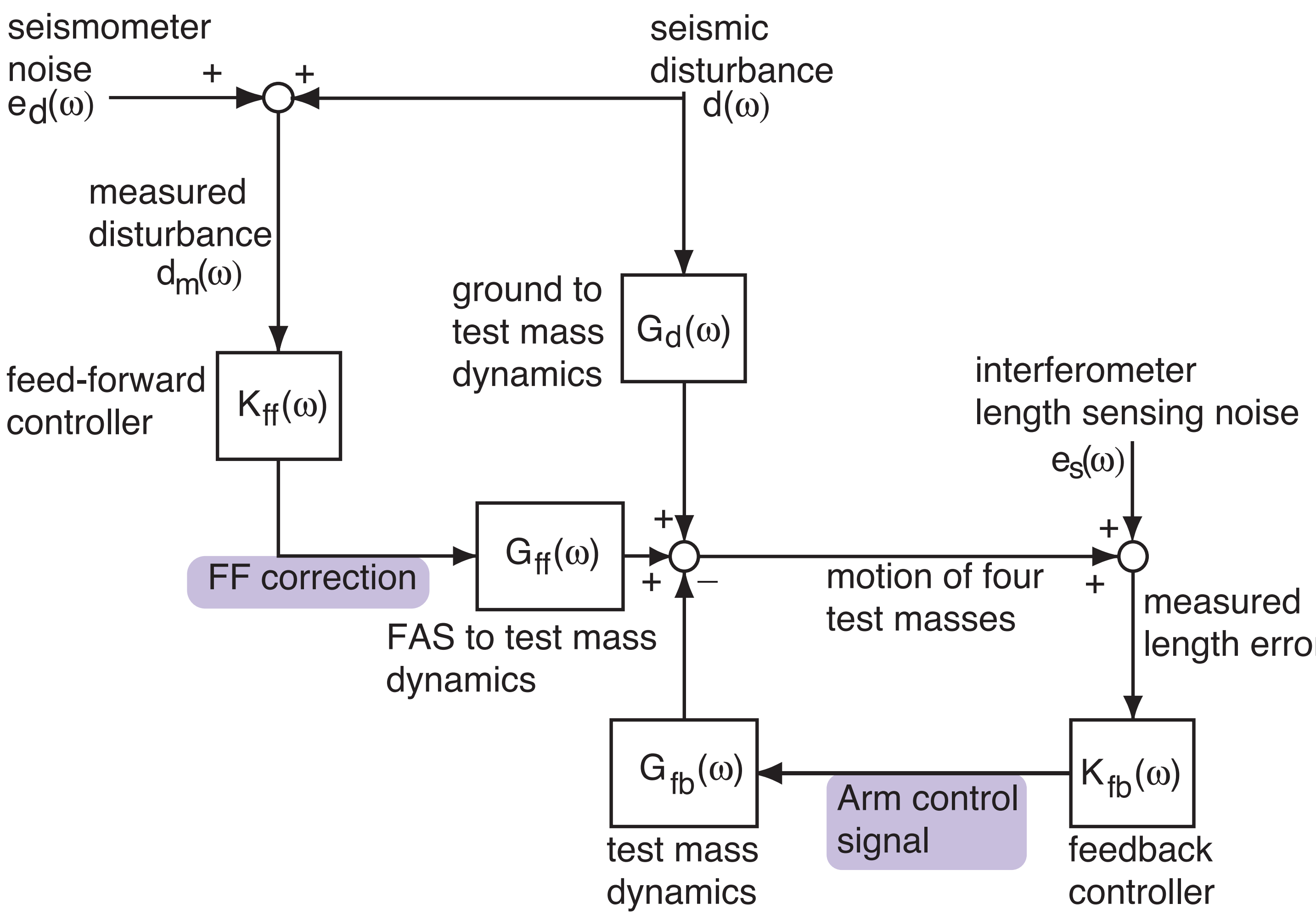


- Feedback to piezoelectric 180 μm range external actuator from local geophones placed on test mass chamber crossbeams.
- Goal is to reduce beam-direction disturbance to stack in the 0.6–3 Hz band.

PEPI Performance

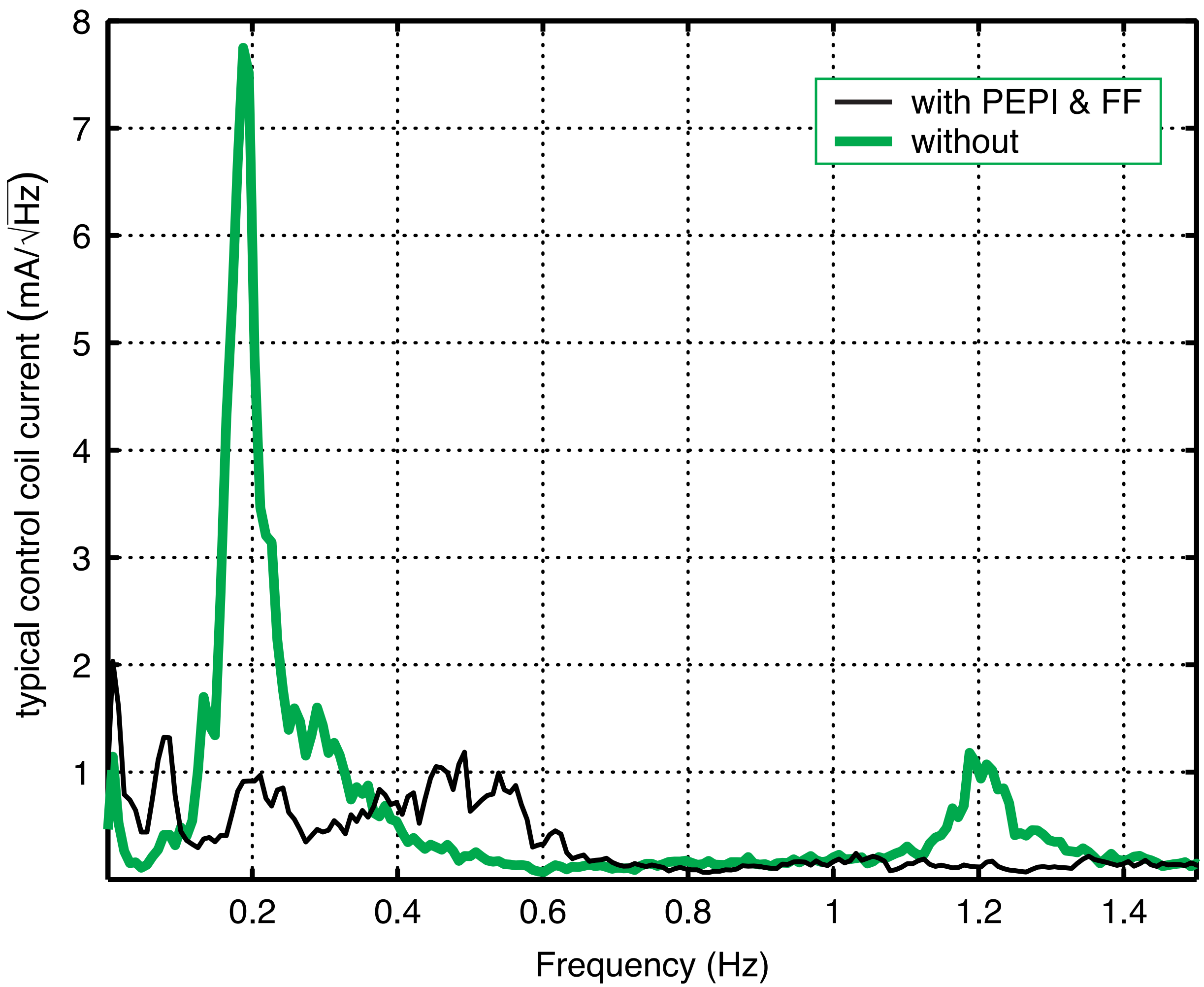


Microseism Feedforward



Combined PEPI/FF performance.

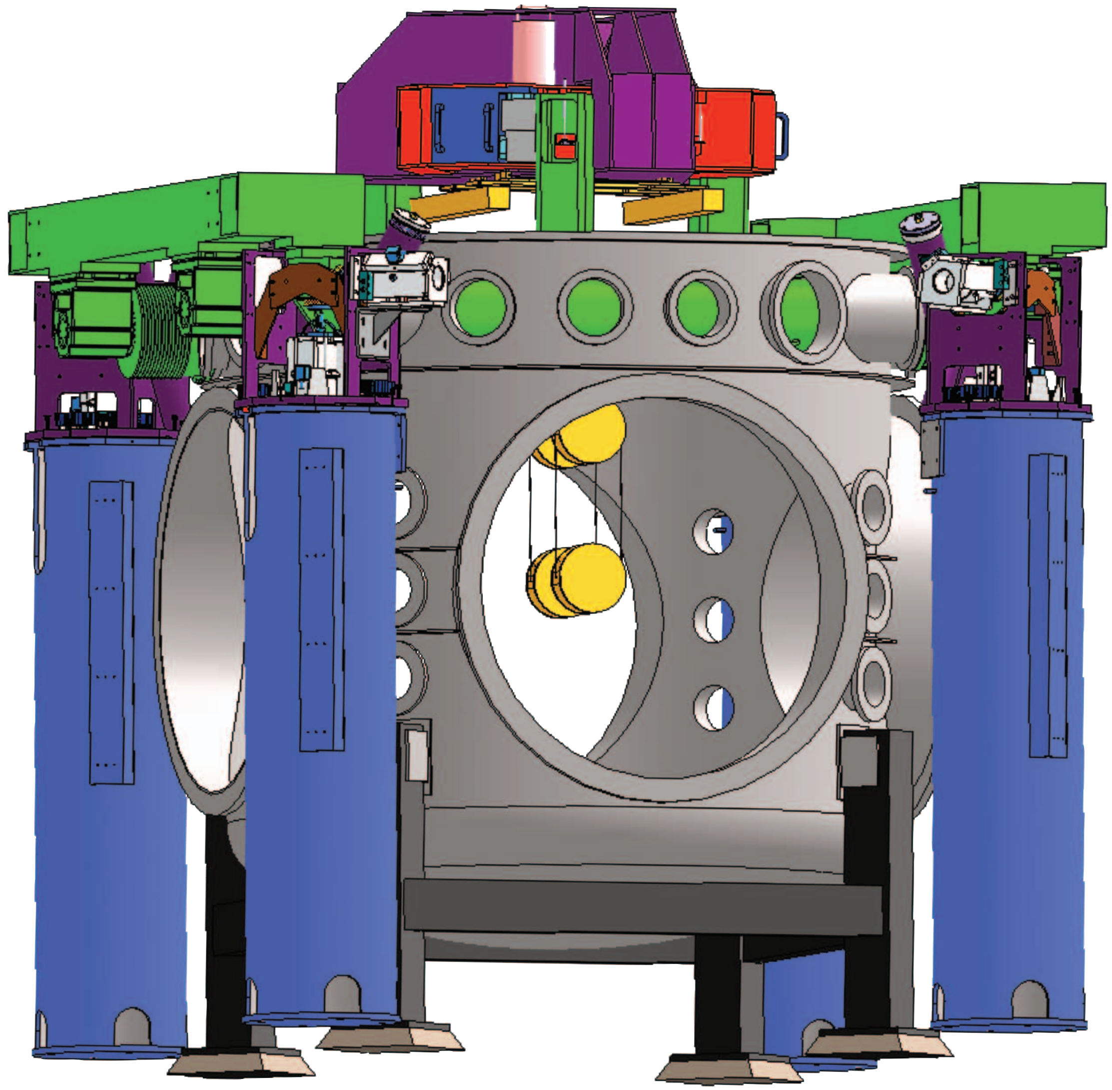
- FF reduction extended up to 0.35 Hz
- PEPI removes excess FF noise down to about 0.65 Hz
- Bad zone reduced from 0.2–0.8 to 0.35–0.65 Hz.
- RMS motion reduced by factor of 3.



Seismic isolation for Advanced LIGO

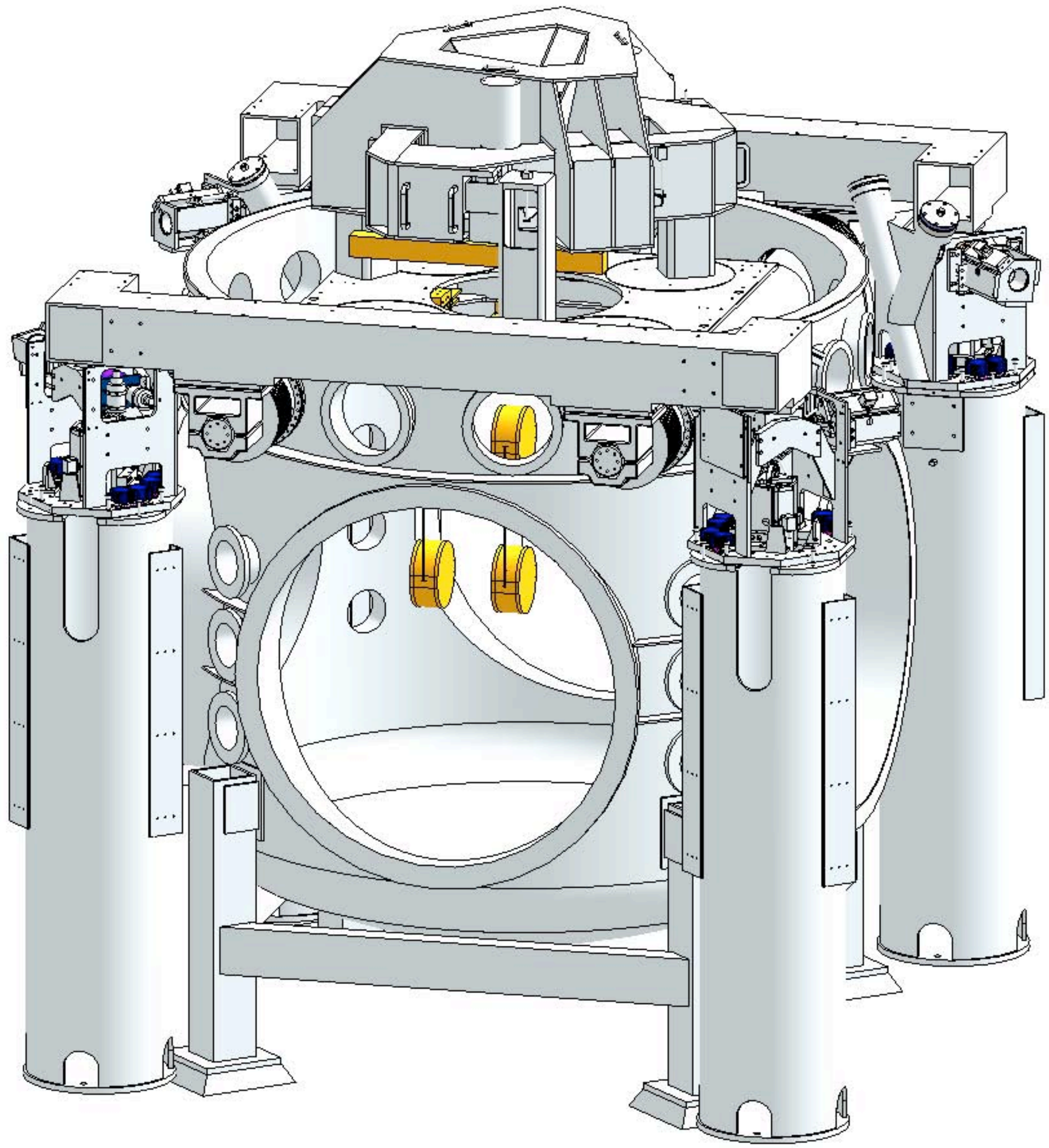
Seismic isolation takes place in three places:

- Test mass suspension.
- 2-stage in-vacuum active (inertial-feedback) platform.
- External pre-isolation stage.

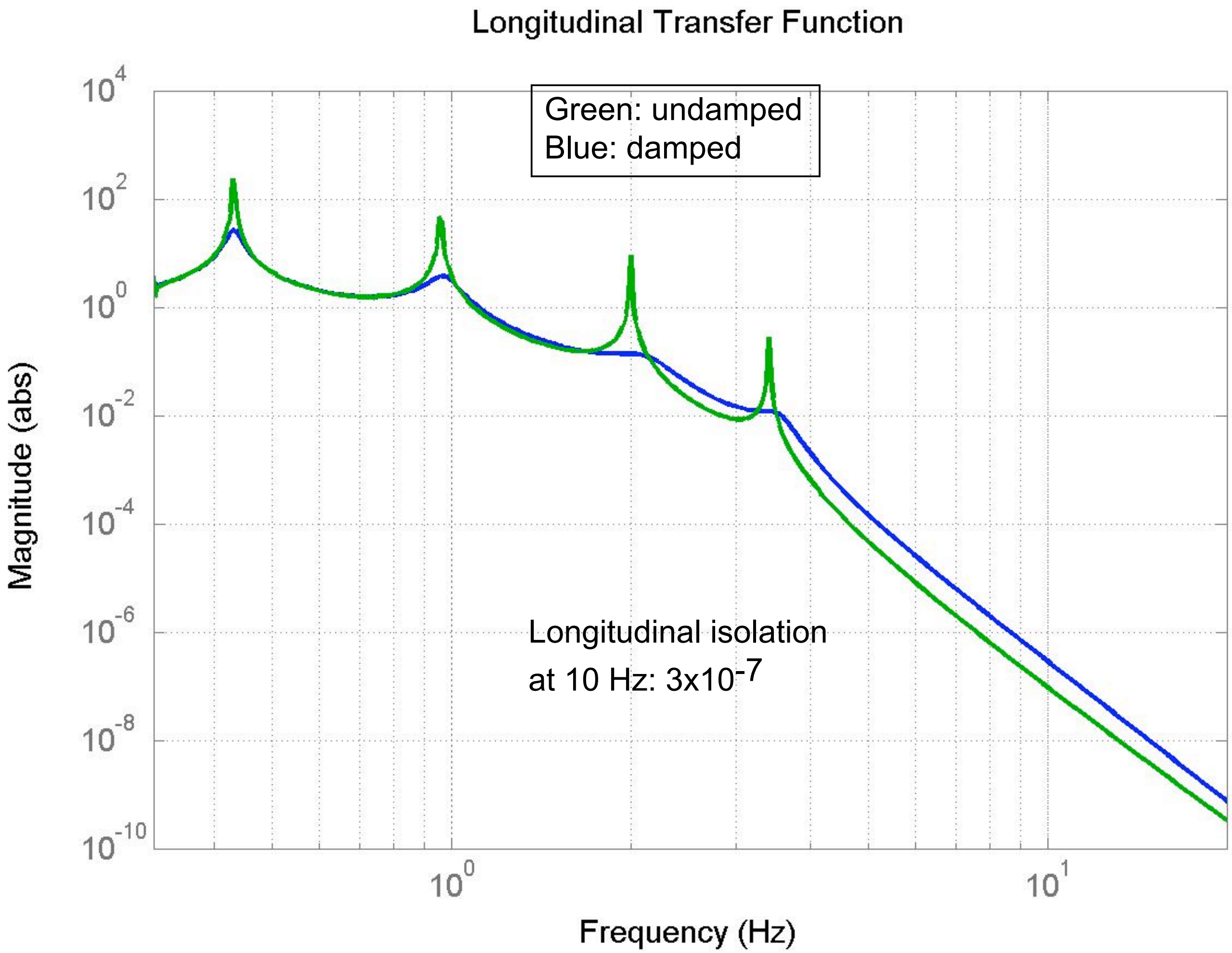


Quad Pendulum

- cascade of 4 pendulum stages
- isolates as $1/f^8$ above pendulum resonances
- 10^{-14} m_{rms} after global control
- $10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 10 Hz.

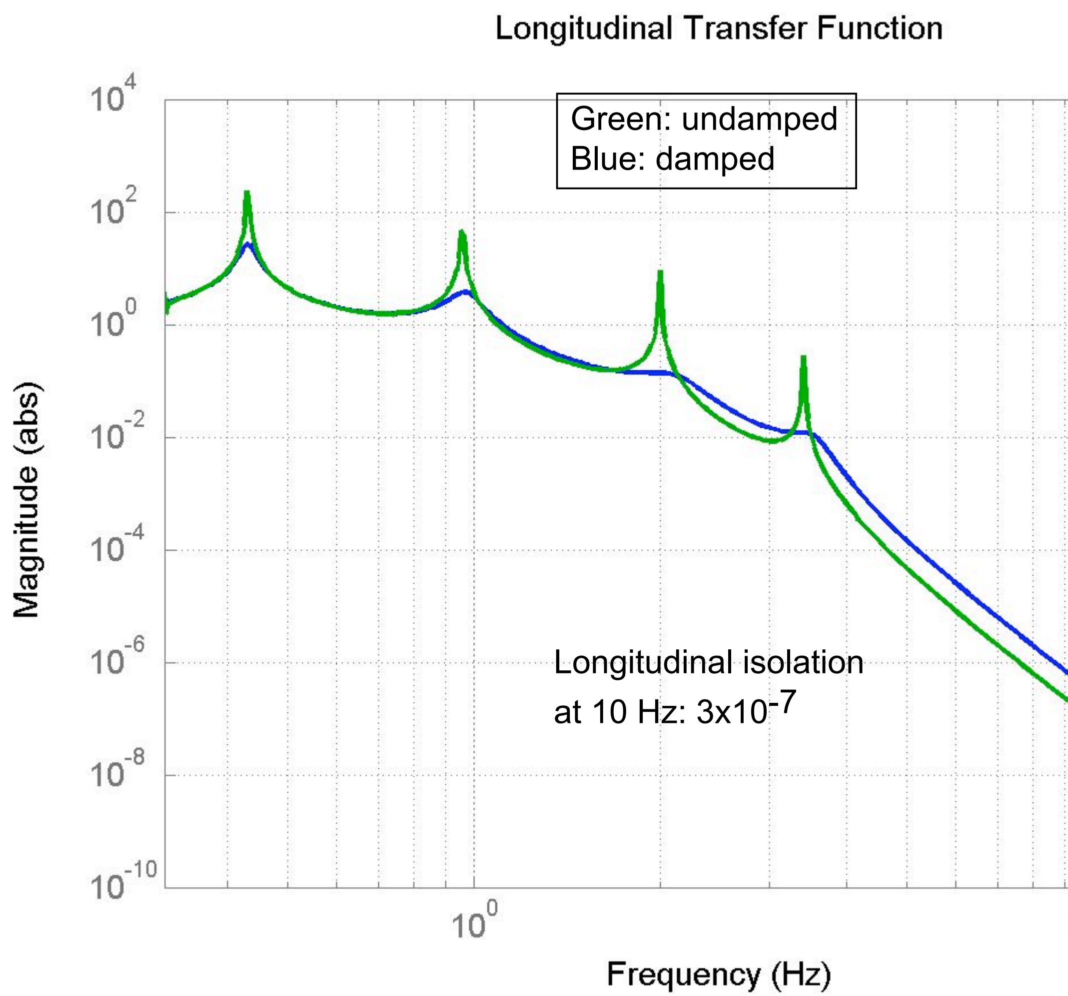


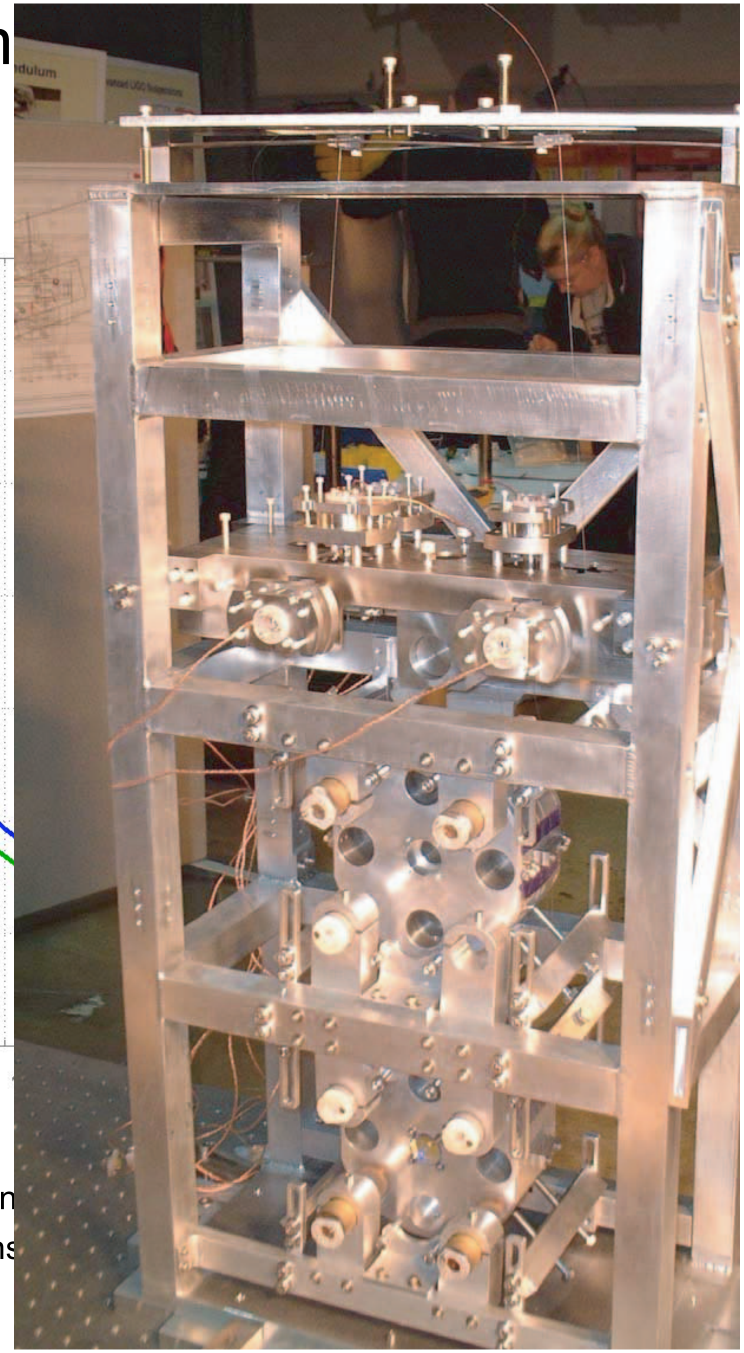
Quadruple Pendulum: Isolation Prediction



Combine with isolation system residual noise level of 2×10^{-13} m/√Hz to achieve target sensitivity

Quadruple Pendulum Isolation Prediction





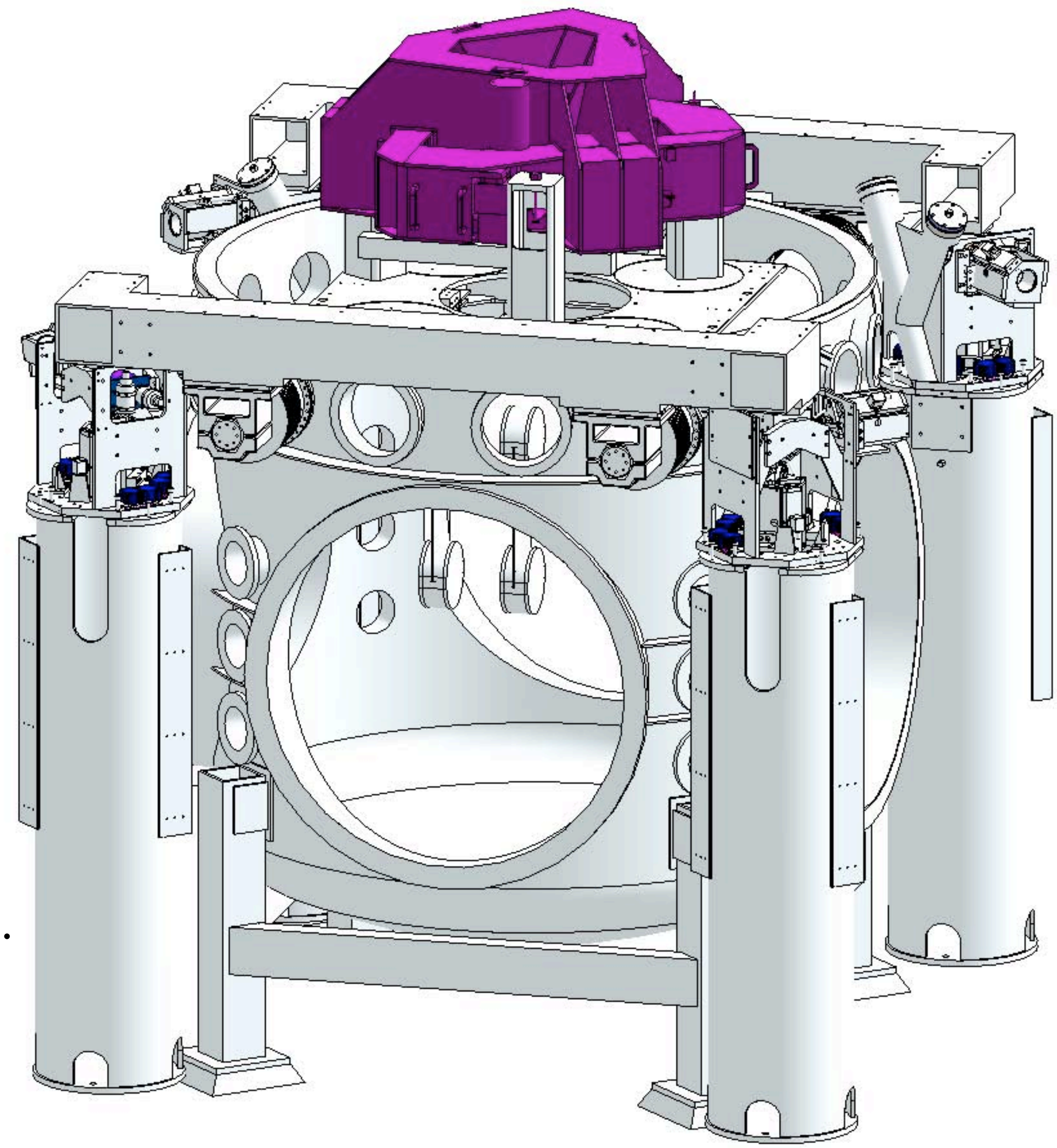
Combine with isolation system residual n
of $2x10^{-13}$ m/ Hz to achieve target sens

2 Stage active platform

- Local feedback in 6 DOFs per stage to (inertial) seismometer and (relative) displacement sensors
- Also, local sensor correction based on local seismometers.
- Should reduce the noise to:

$$10^{-11}\ \mathrm{m}/\sqrt{\mathrm{Hz}}\ \text{at}\ 1\ \mathrm{Hz}.$$

$$2 \times 10^{-13}\ \mathrm{m}/\sqrt{\mathrm{Hz}}\ \text{at}\ 10\ \mathrm{Hz}.$$



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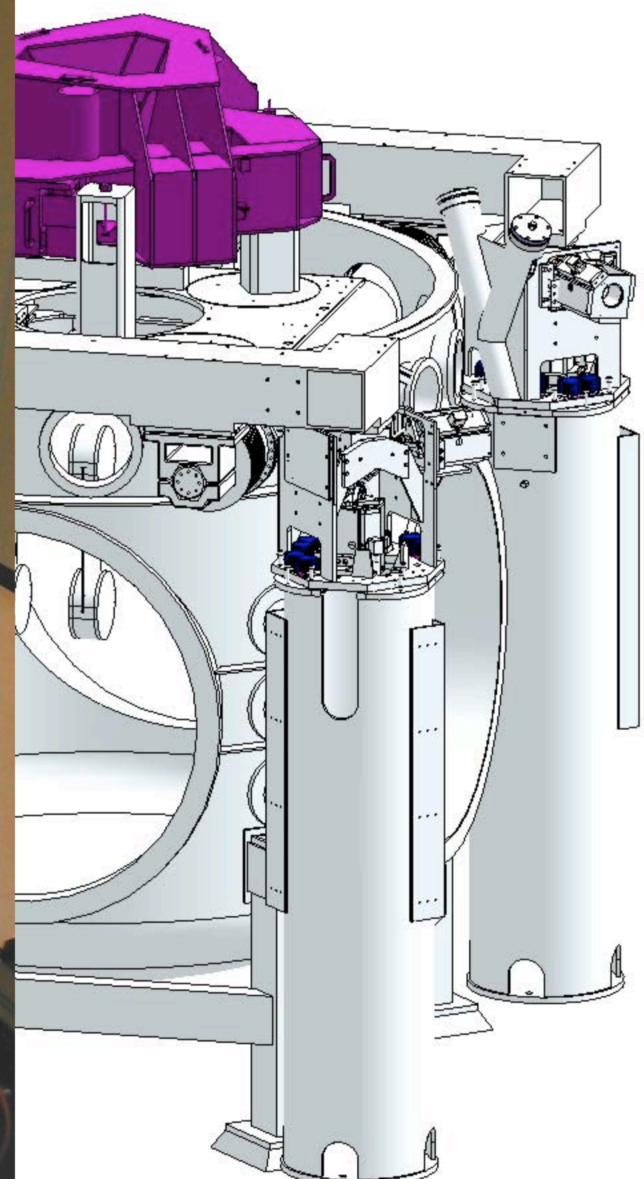
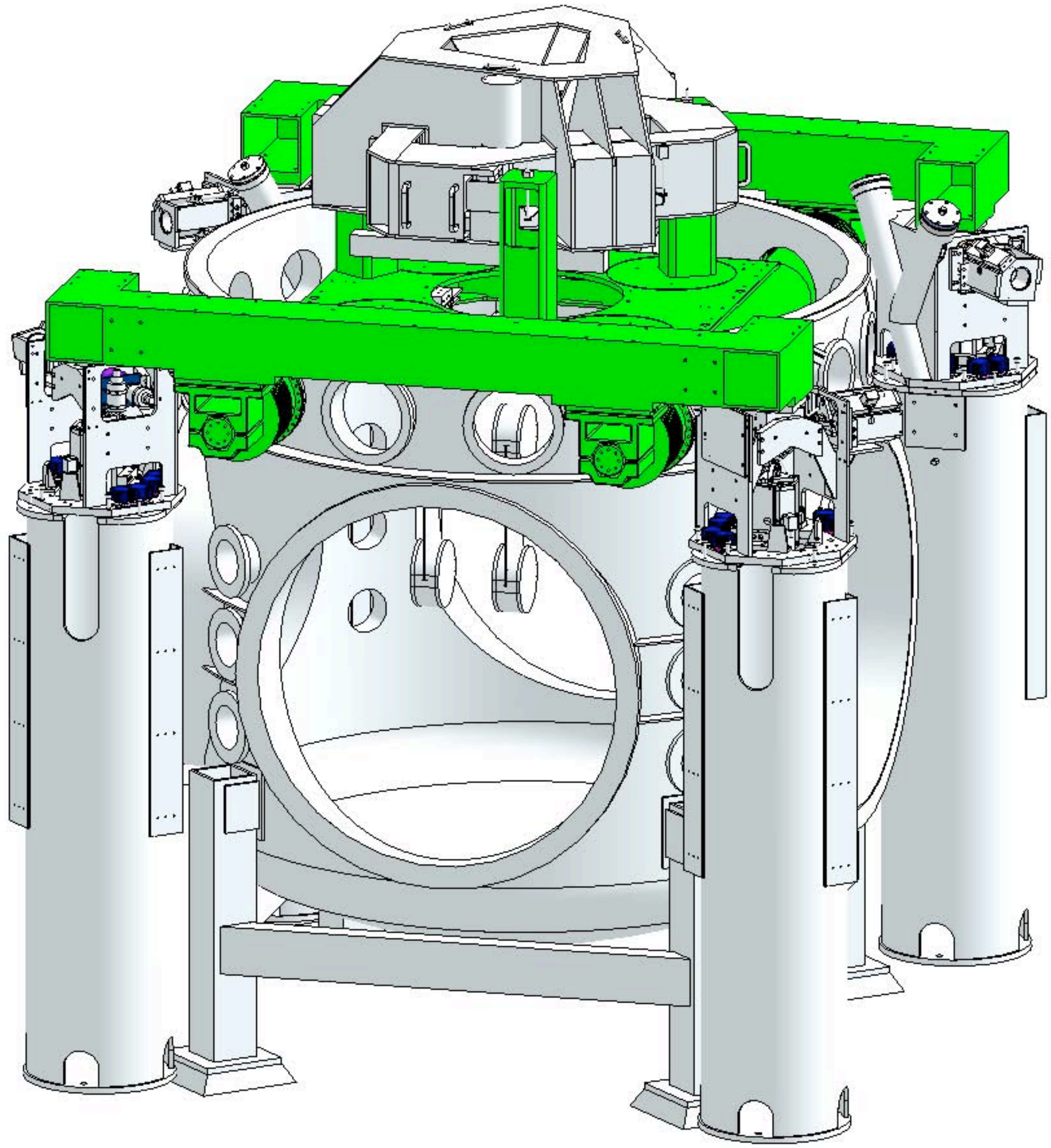


C. Hardham

Pre-Isolator Stage

- Outside-of-vacuum stage, actuated by hydraulic bridge devices: 1 mm range and 6 DOFs
- Noise reduction largely due to local feedforward and sensor correction.
- Microseism through several hertz noise reduced by approx 10.



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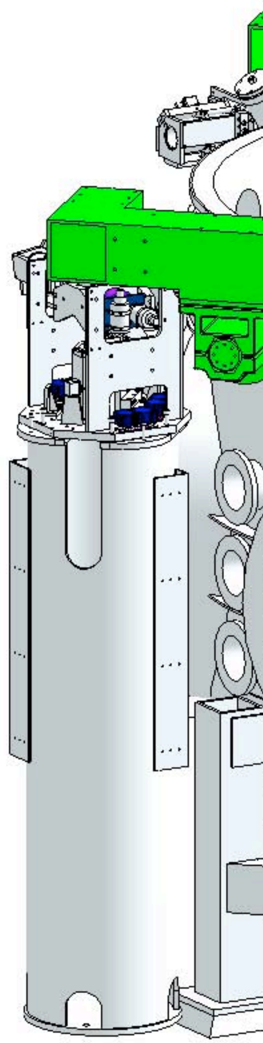
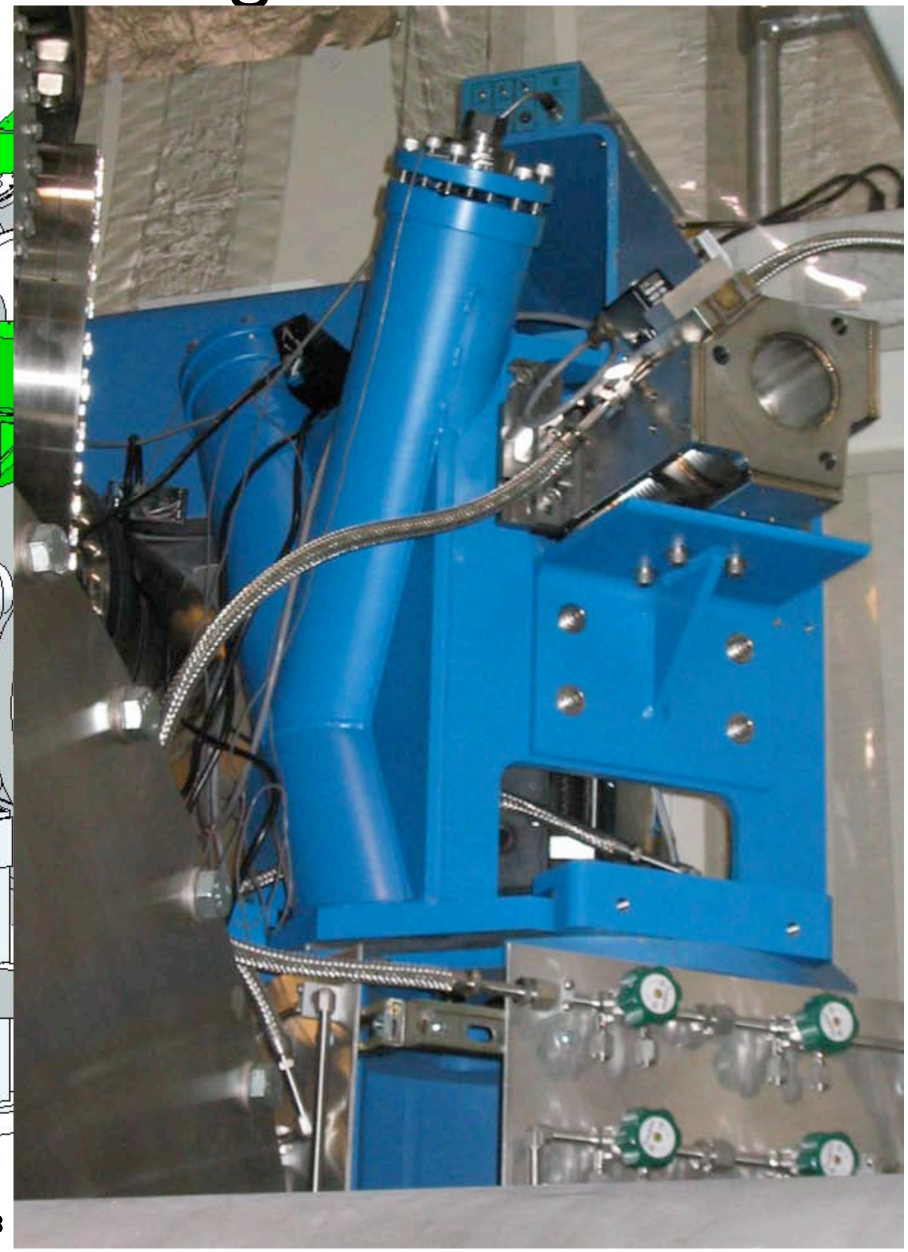
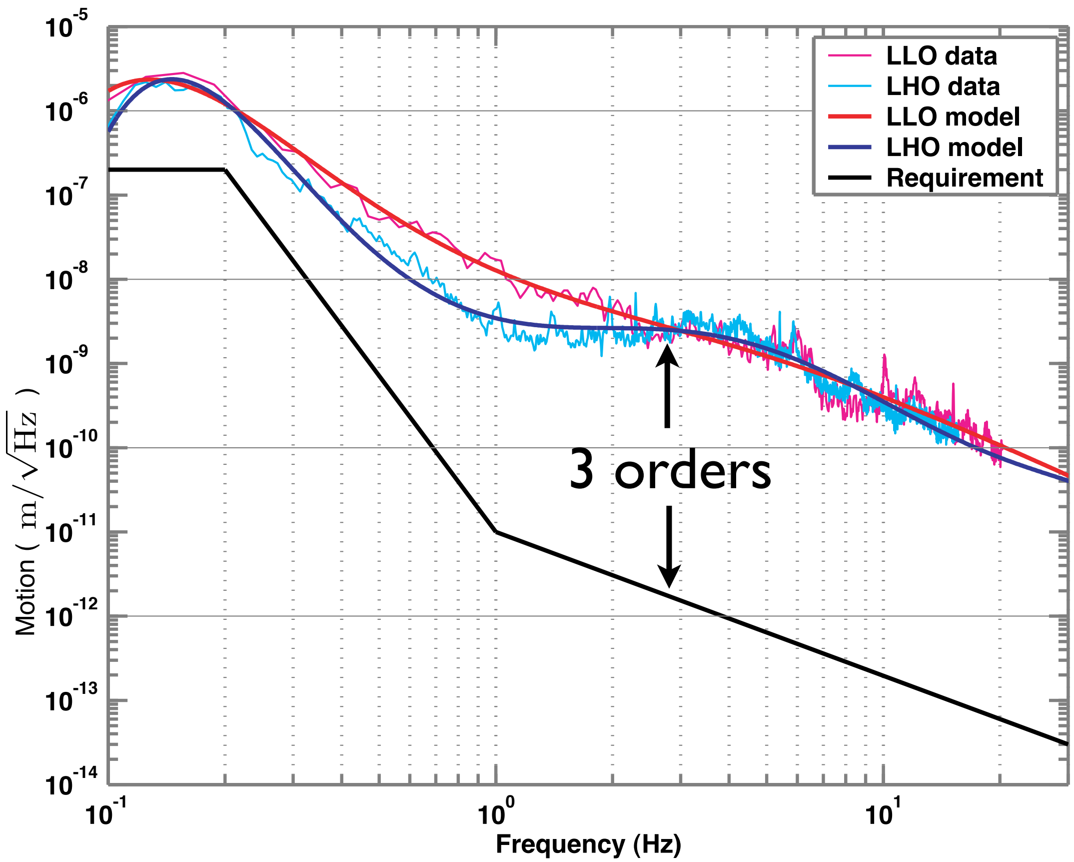




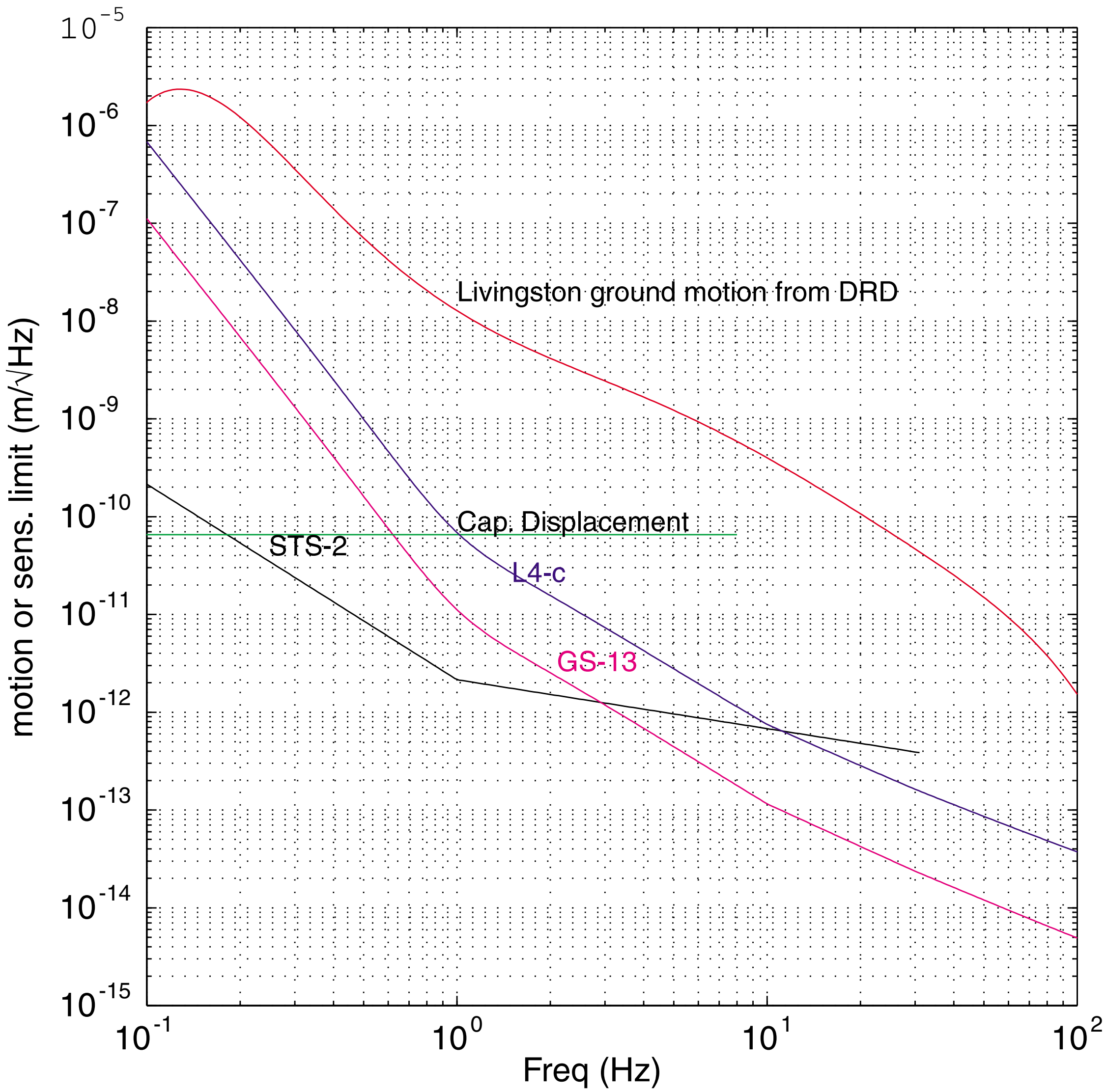
Adv. LIGO seismic isolation requirements.

- Design requirements are based on Adv LIGO ‘system’ design, to avoid seismic noise’s ever adding to detector noise floor.
- two-stage active platform could meet the requirements at LHO and the quiet times at LLO.
- The external hydraulic stage will bring LLO into compliance as well.
- Seismic team spending most of its time on the retrofit at LLO; BTL will talk on this.

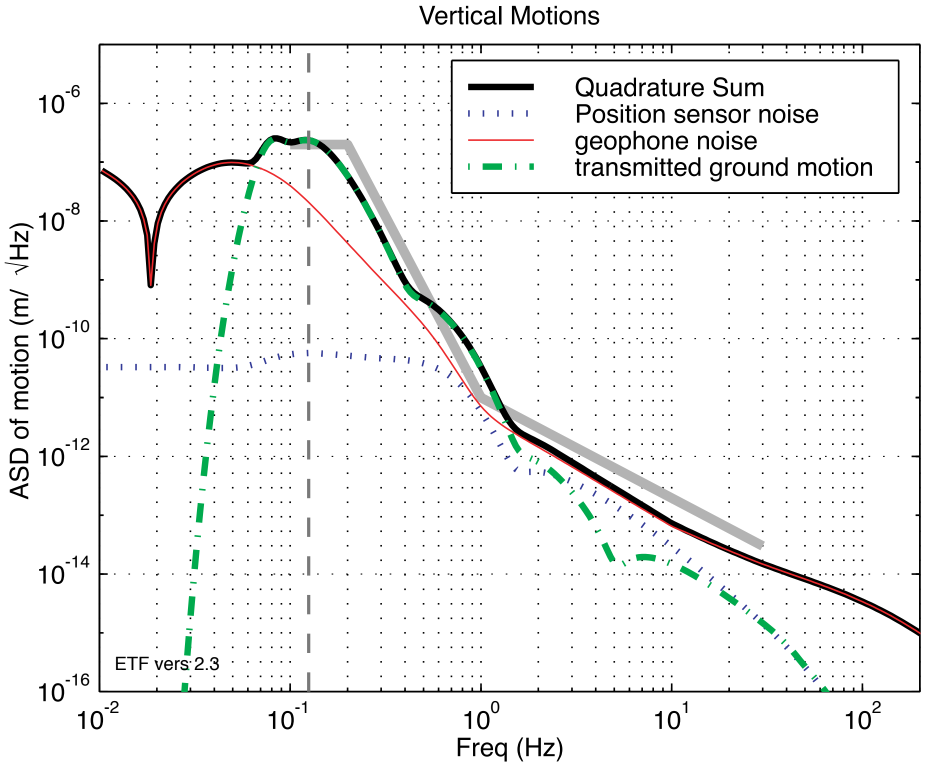


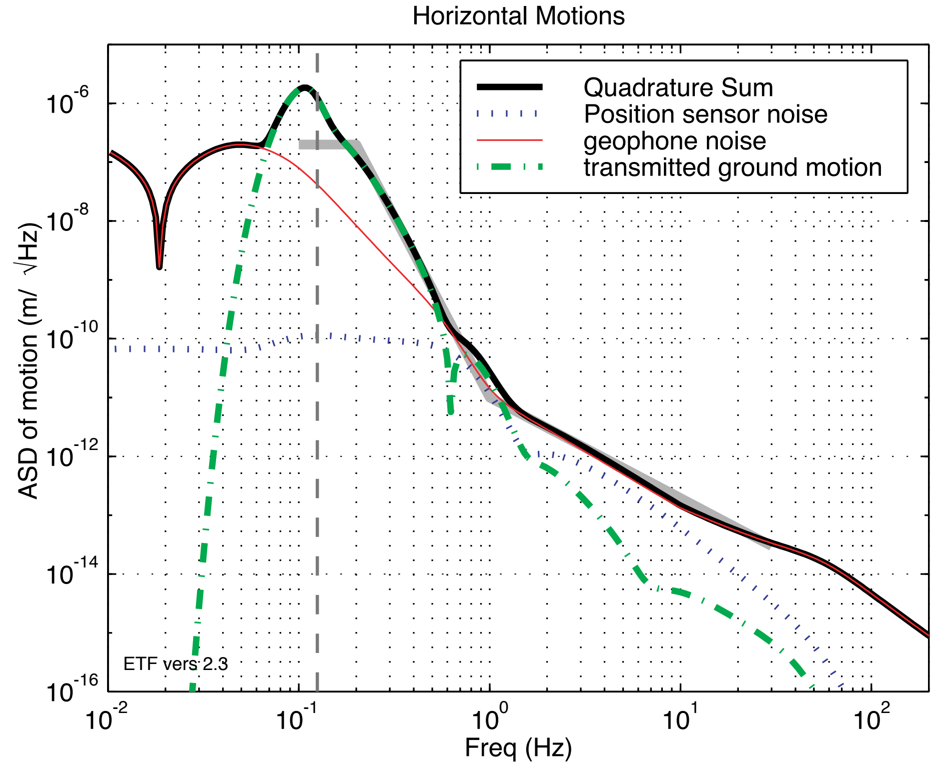
Sensor blending

- Servo error signal derived from 'Super-sensor,' a blended combination of displacement and inertial sensors, constructed for each controlled DOF, to minimize noise and artifacts.
- At very low frequencies locally follow displacement sensors, corrected by ground noise measurements and global interferometer signals.
- Mid frequency noise reduced by sensor correction and local inertial feedback.
- High frequencies get local inertial feedback.



Noise/ isolation model results for two-stage active platform



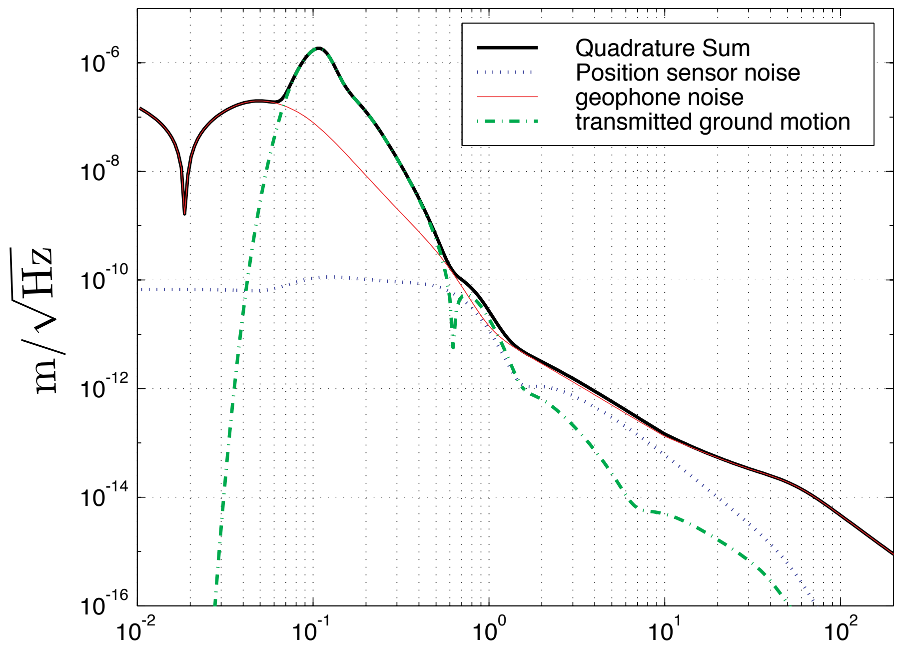


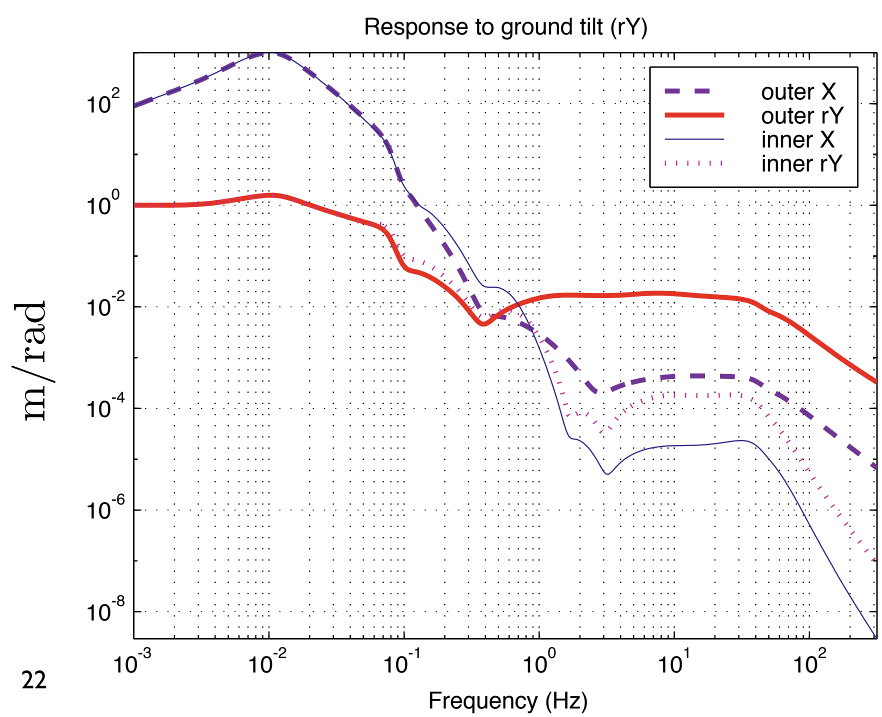
Performance estimates from dynamic model

	displacement	pitch	yaw
ASD at 10 Hz	2×10^{-13} m/$\sqrt{\text{Hz}}$	4×10^{-13} rad/$\sqrt{\text{Hz}}$	4×10^{-13} rad/$\sqrt{\text{Hz}}$
RMS deviation	1×10^{-11} m	3×10^{-11} rad	2×10^{-11} rad
RMS velocity	1×10^{-10} m/s		

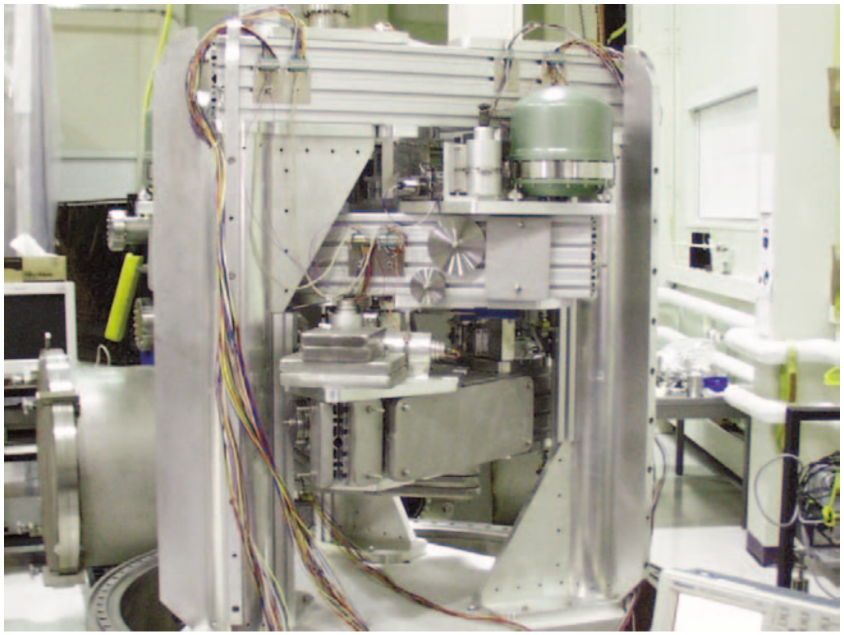
Tilt-horizontal study

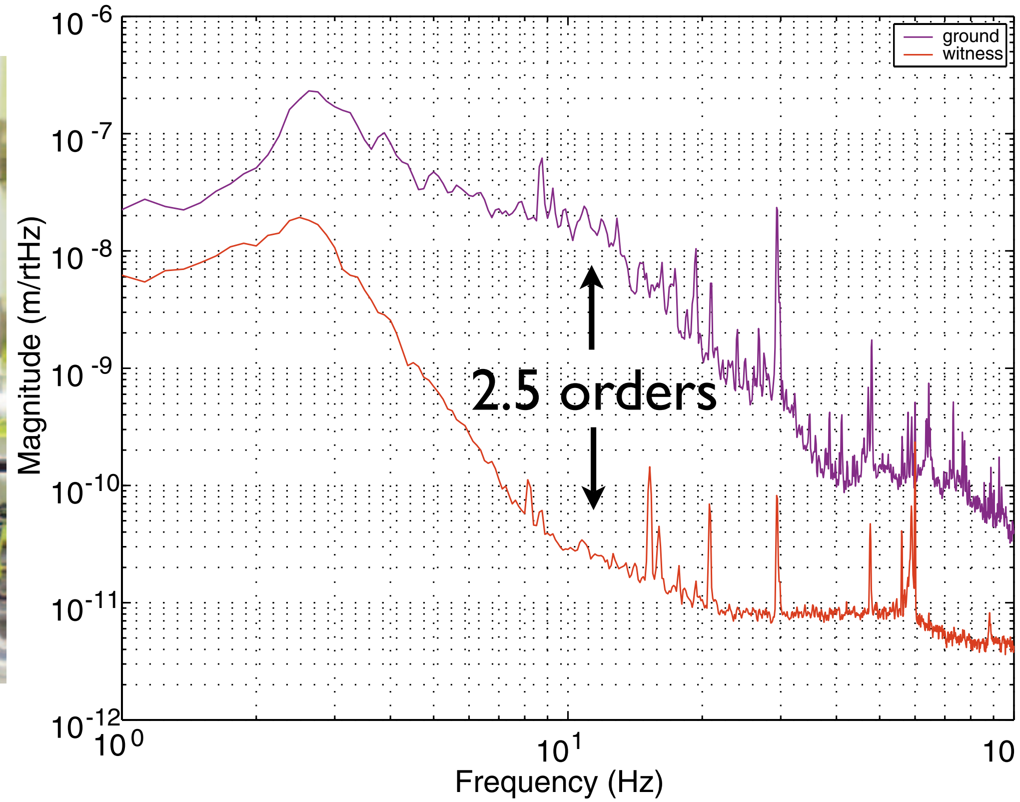
- 6 DOF dynamic model used to study our sensitivity to the tilt-horizontal coupling inherent in low-frequency feedback to inertial sensors.
- A slab tilt step function causes highly-damped horizontal excursion.
- 5 tons of equipment moved across VEA slab causes *slow* 0.5 mm excursion.
- Thanks to the LIGO-1 slab designers!
- 1×10^{-8} $\mathrm{rad}/\sqrt{\mathrm{Hz}}$ expected ground tilt causes insignificant horizontal motions at microseism.





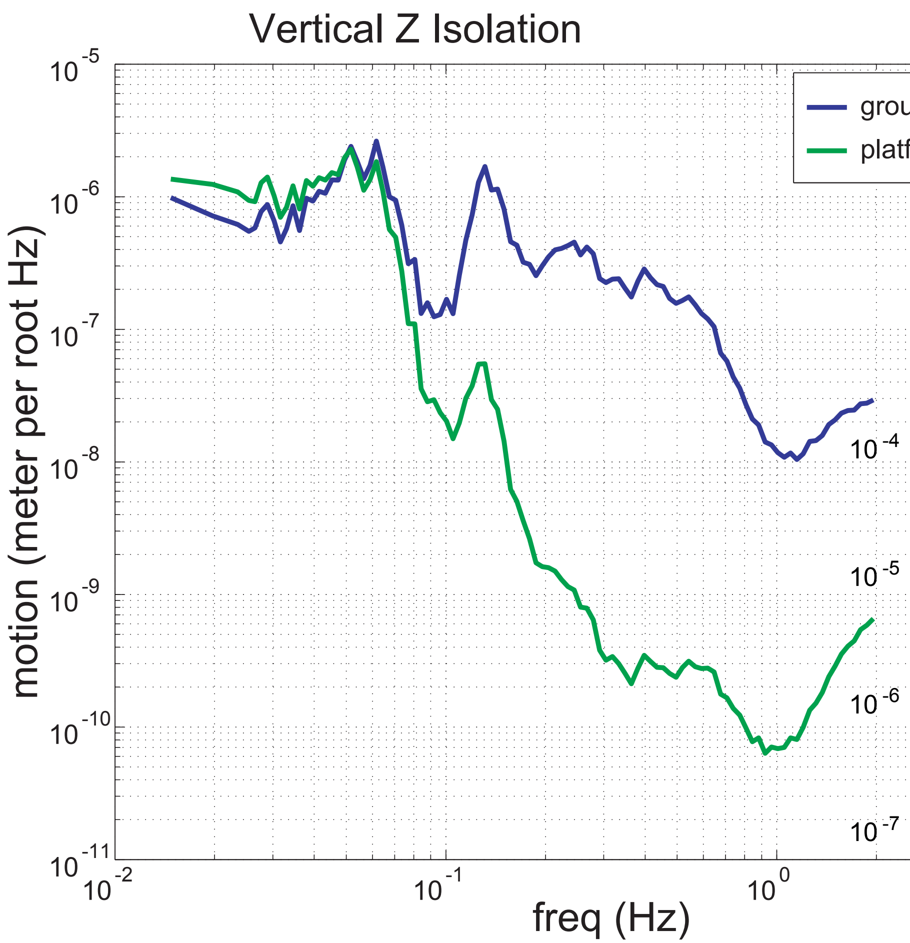
Proof-of-concept test of active platform

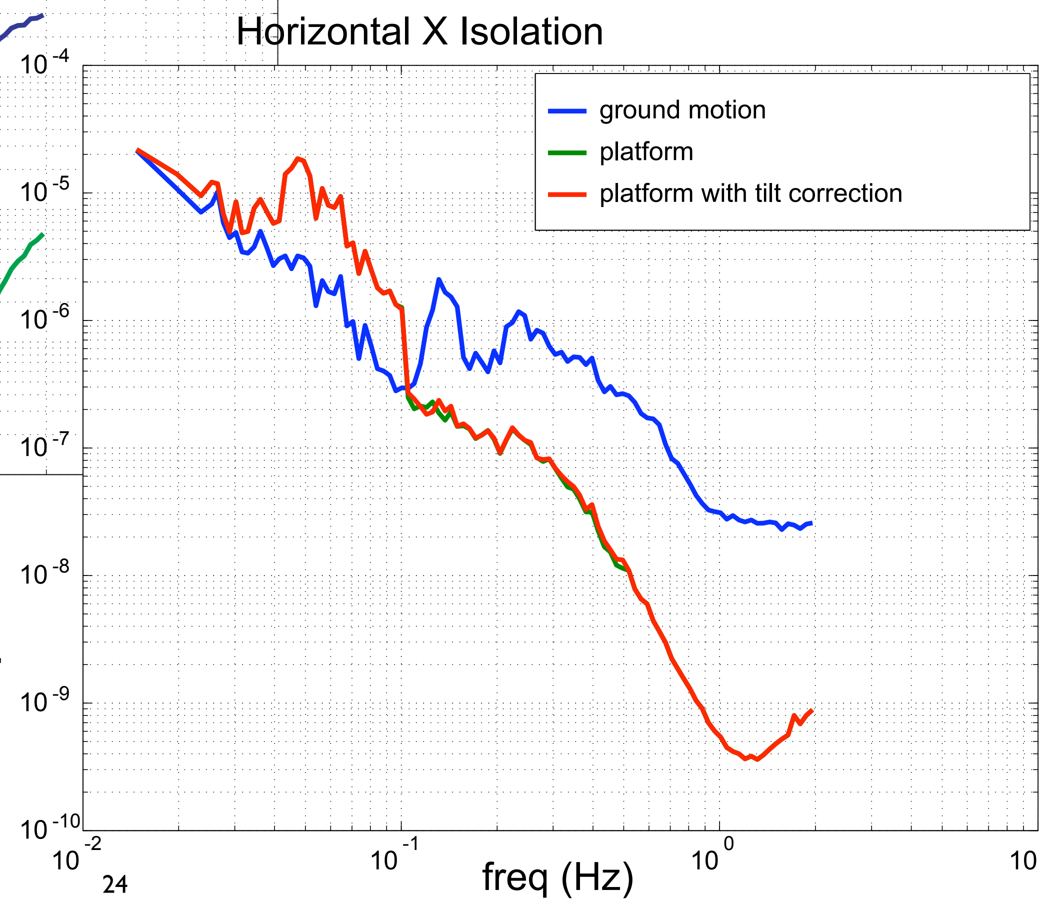




- Technique: feedback from inertial sensors (seismometers).
- Two stages give 2 1/2 orders of magnitude noise reduction at 10 Hz.
- Designed to test sub-hertz noise reduction and robust two-stage (12 DOF) controller.

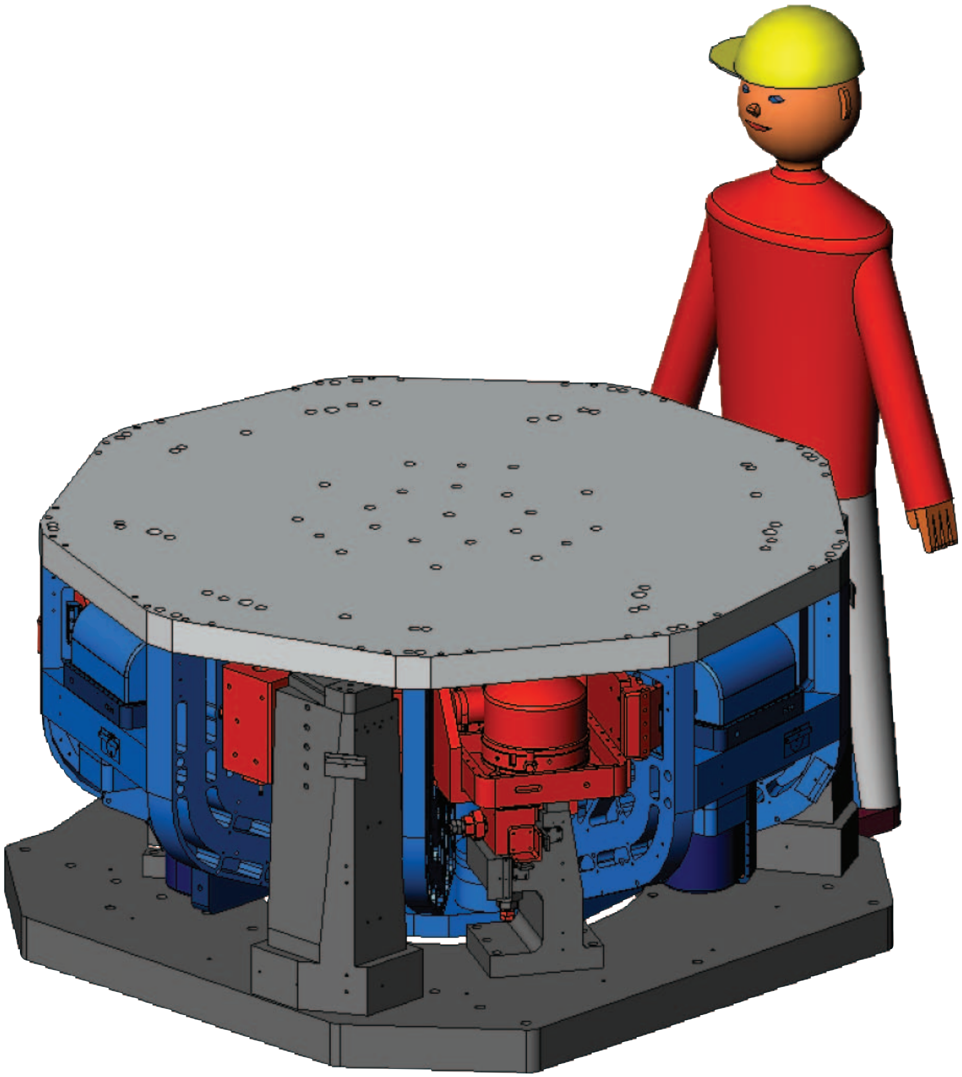
Sensor correction noise reduction on stiff platform in 3-D





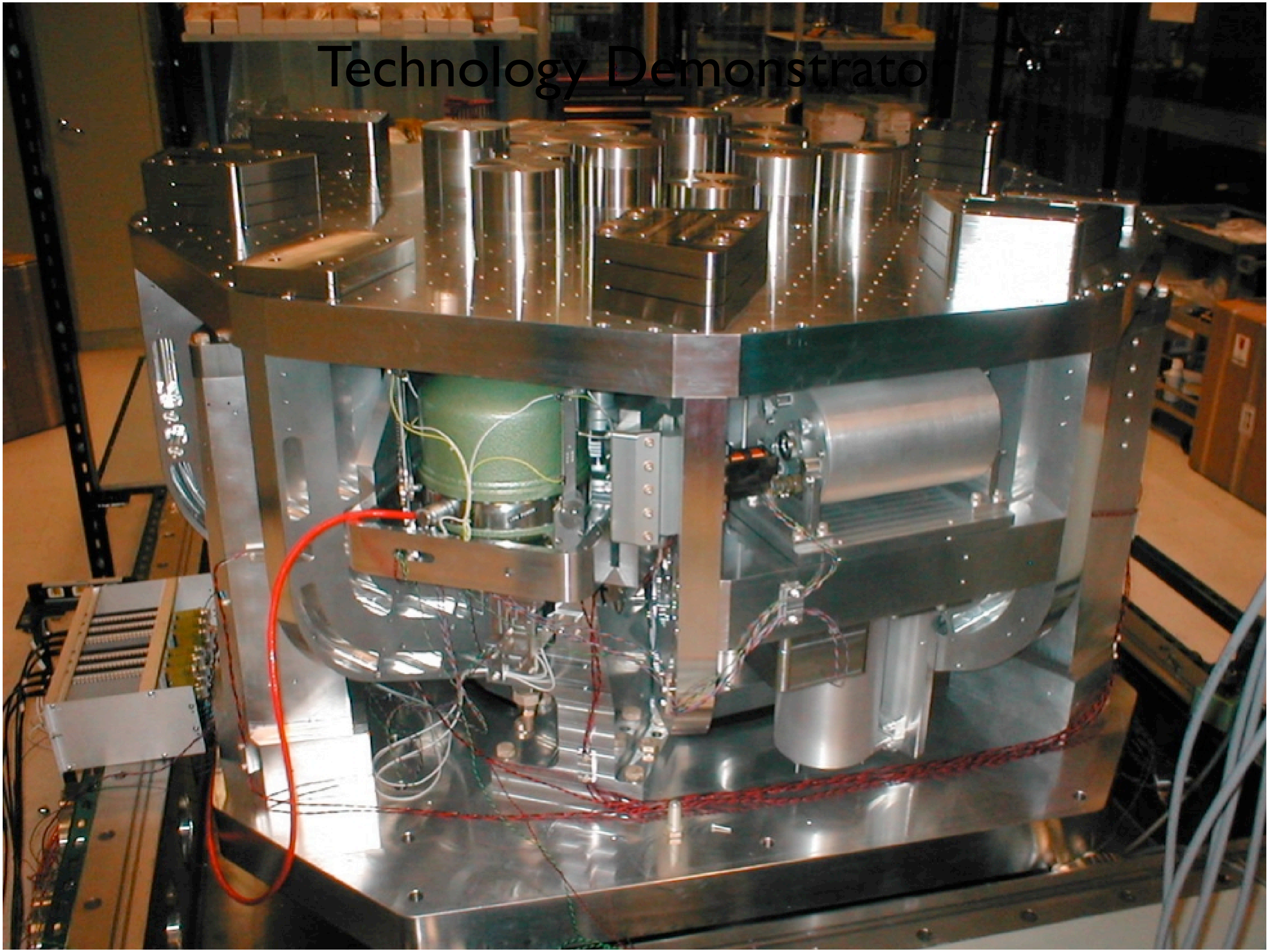
- Single-stage horiz. sensor correction gives 1 1/2 orders of magnitude *x* isolation at 1 Hz.
- even better vertically.

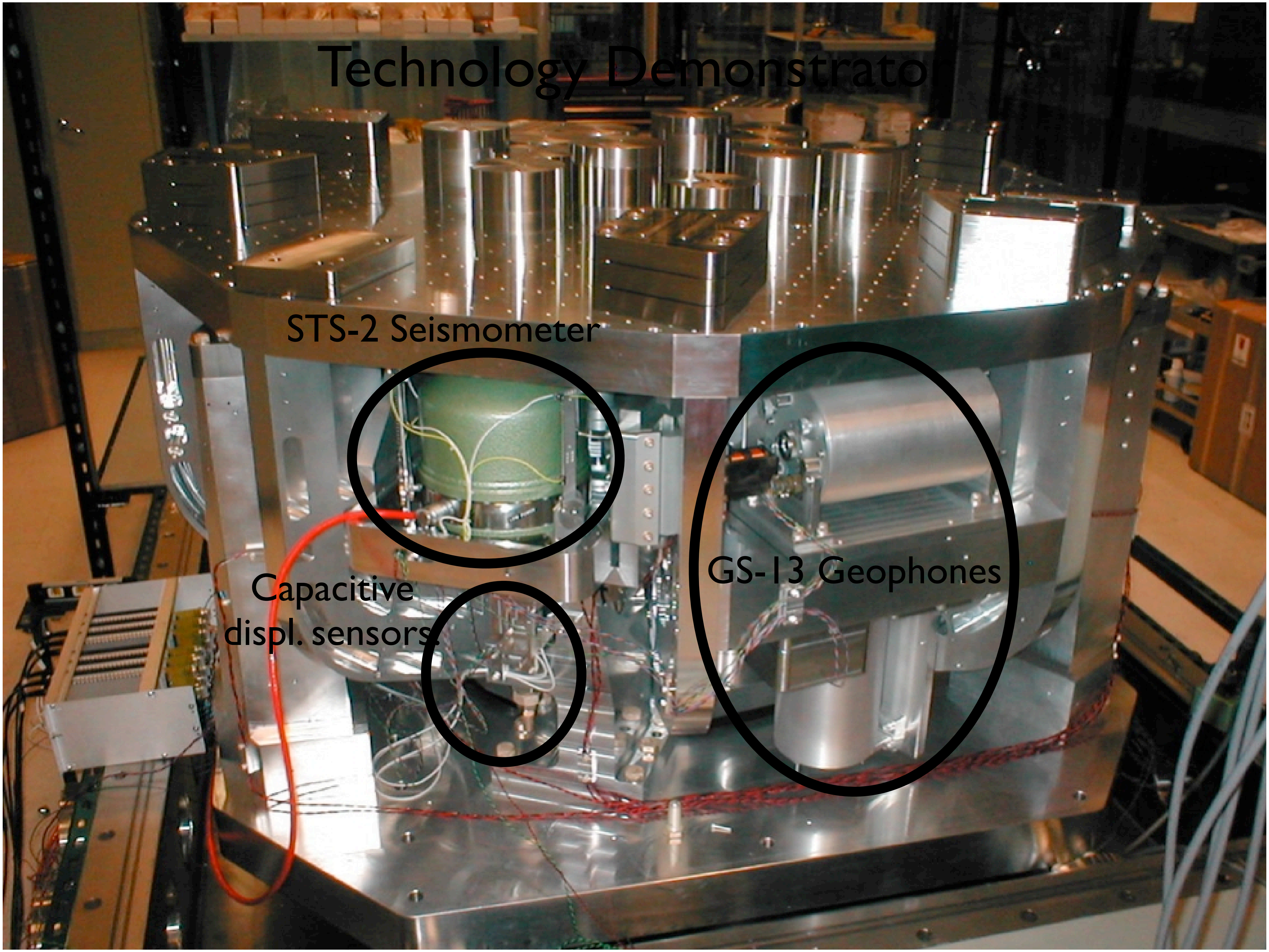
Technology Demonstrator at Stanford's ETF



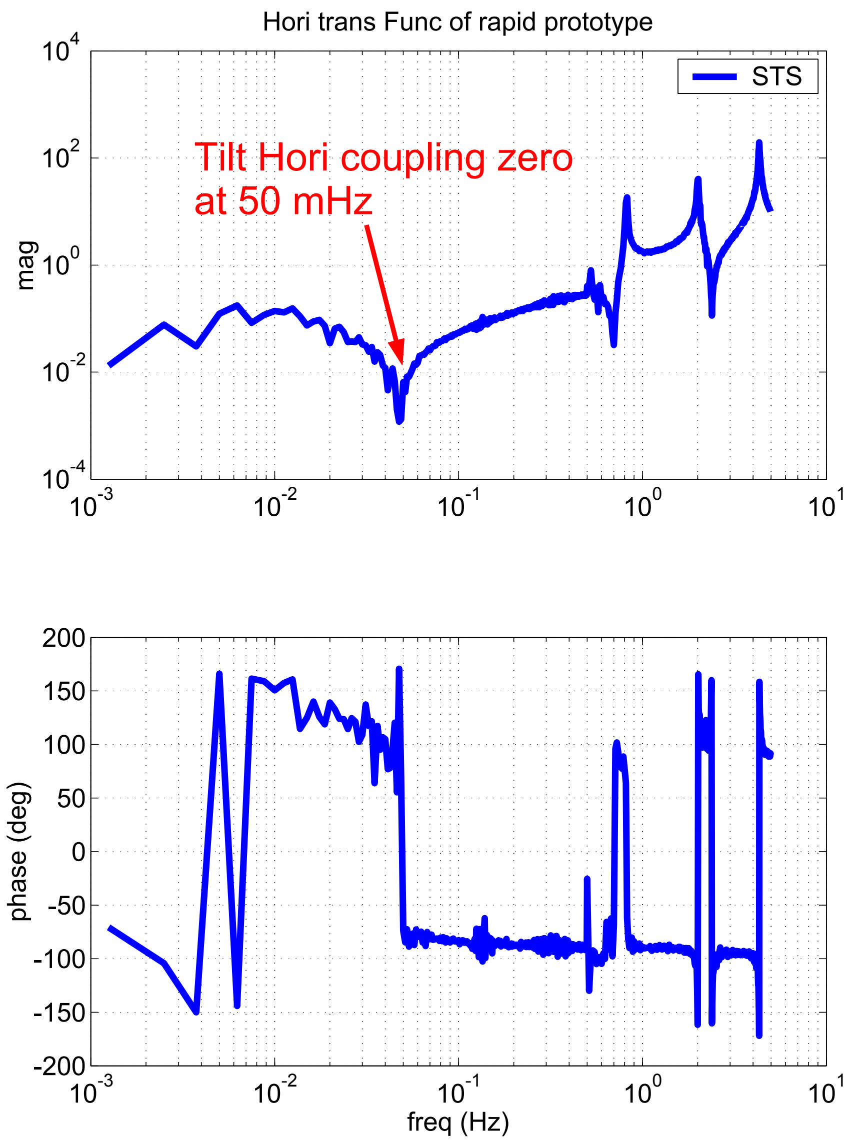
- Intended to test Adv LIGO SEI in-vacuum platform technology
- Dynamic tests underway, isolation servo design underway.
- Uses the same topology, instrumentation and materials as we expect to use in Adv LIGO's HAM chamber, *except:*
  - Payload about half.
  - actuator materials and cleaning appropriate for HV, not UHV.
  - Fits in slightly smaller ETF chamber.
  - Smaller area (higher noise) displacement sensors.

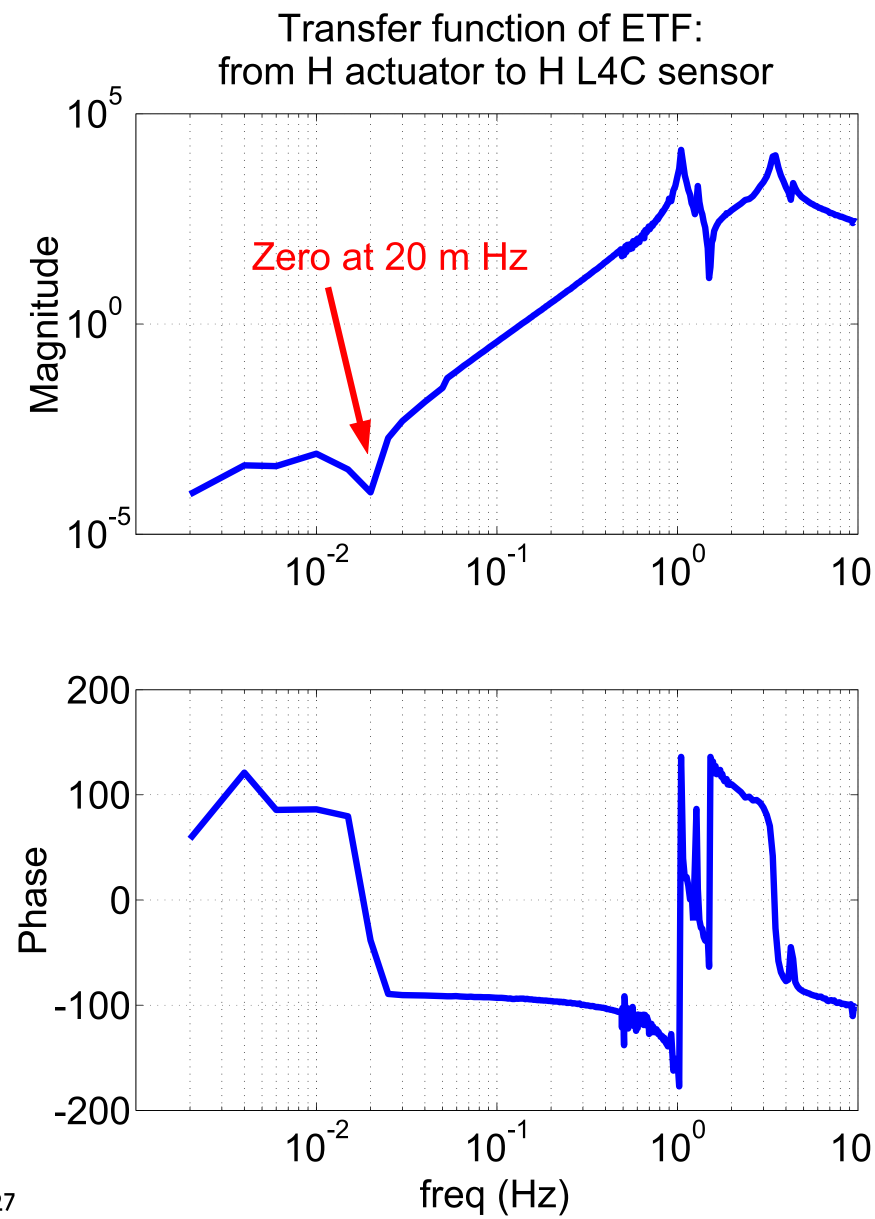
Technology Demonstrator




Technology Demonstrator
STS-2 Seismometer
GS-13 Geophones
Capacitive
displ. sensors

Reduced mechanical tilt-horizontal coupling





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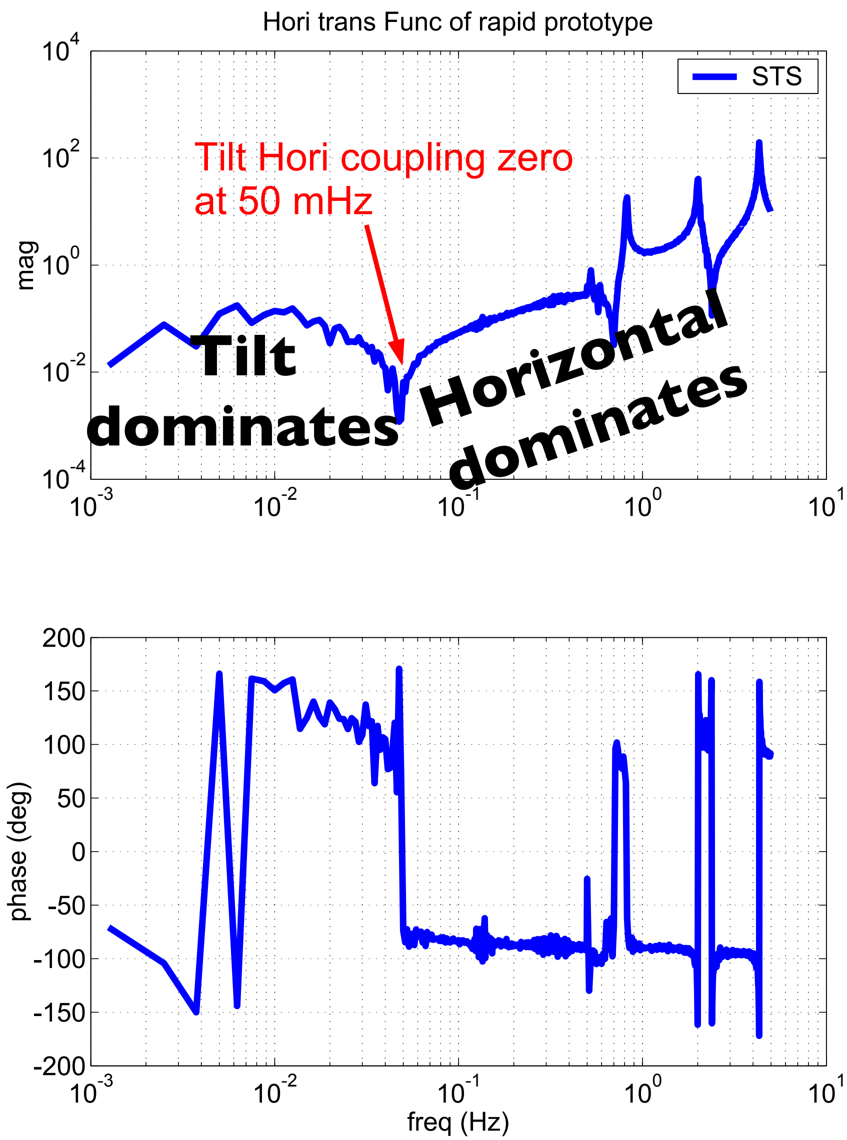
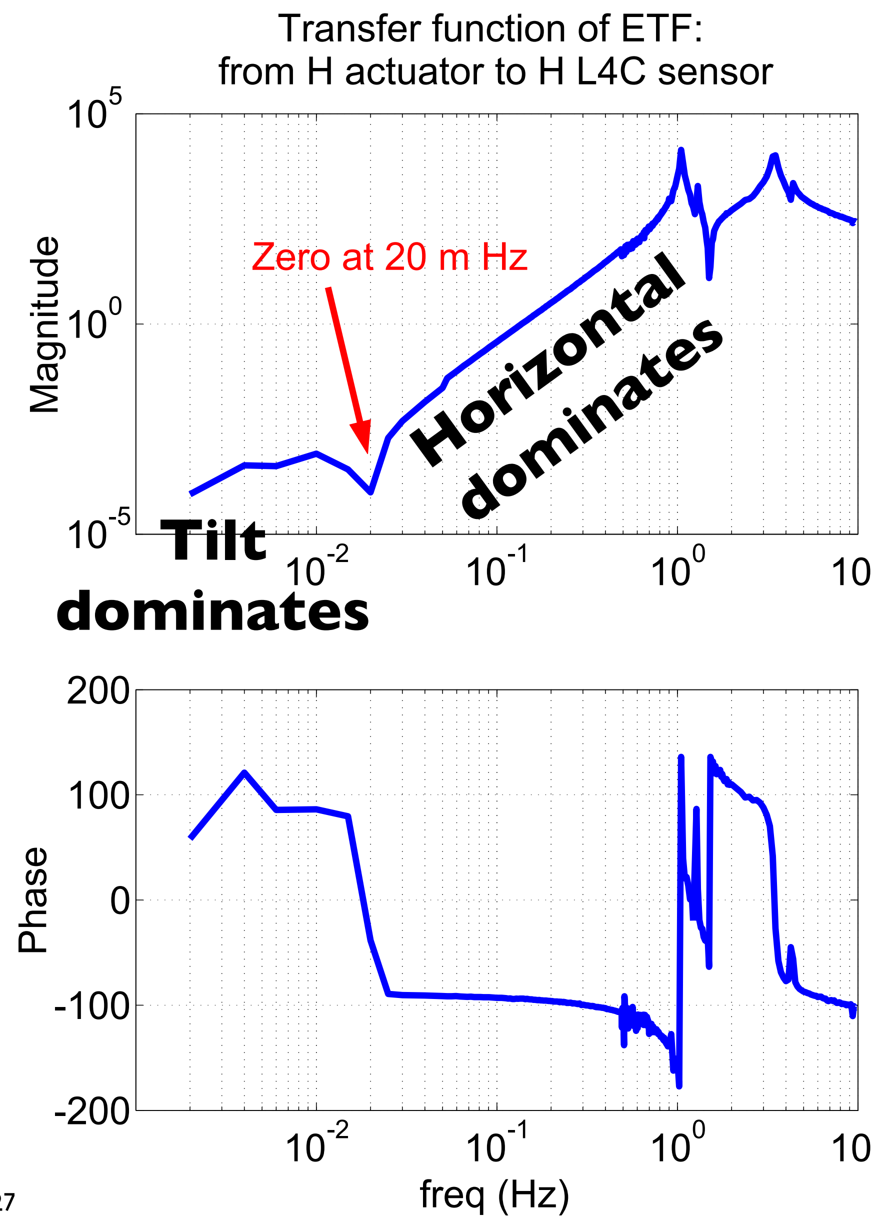
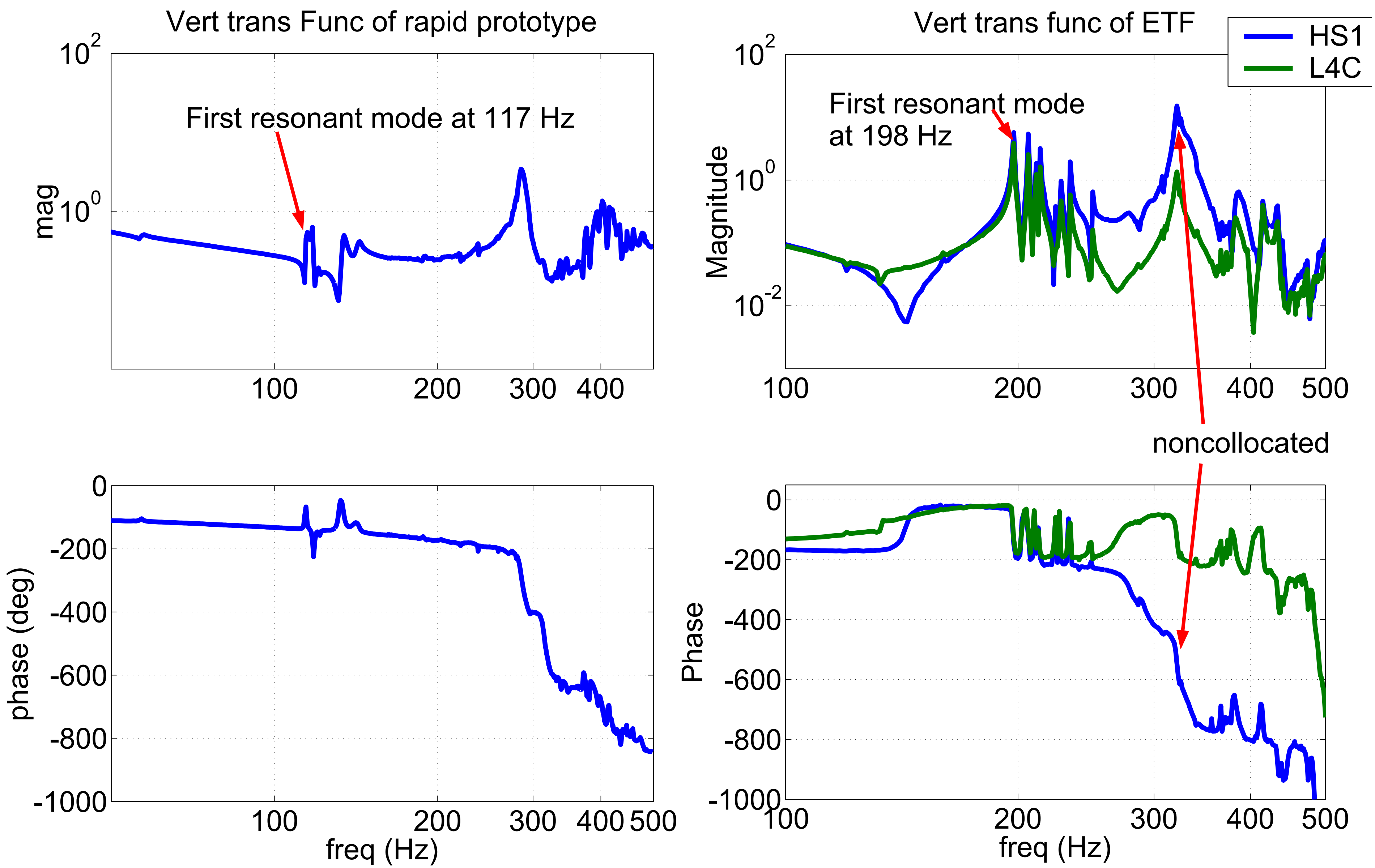


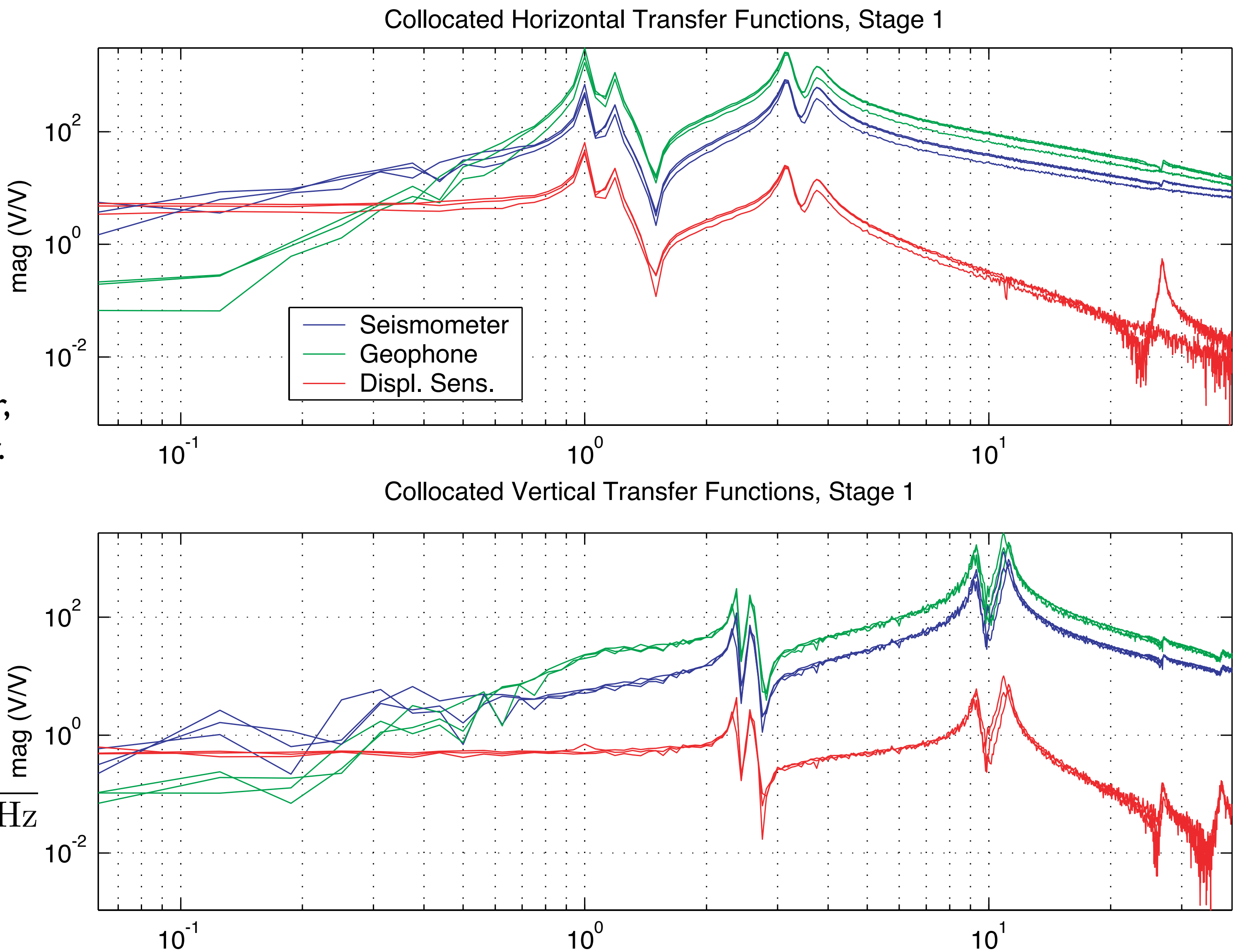


Increased structural resonance frequencies



Tech. Demo. Characterization

- All sensors and actuators worked after installation.
- Transfer functions from all 12 actuators to all 30 sensors measured 0.05–100 Hz, in air, without vac. cover.
- Next steps: servo controller development, vacuum work.
- Displacement sensors measure $\approx 1.5 \times 10^{-10}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$



Development schedule & challenges

- LASTI Prototype 2-stage platforms:
  - Mechanical design should begin 9/'03; LIGO contracting with 1 or 2 design/fab firms to produce the HAM and BSC platforms. LIGO/LSC effort will be focussed on control systems.
  - Sensor & actuator specification and electronics design in parallel with mech. design.
  - Hardware ought to be ready by end of '04. Then follows commissioning, sys-id, controller design, and testing at LASTI.
- Adv LIGO SEI design reviews in 4/'05 (PDR) and 11/'05 (FDR), if things go well.
- Challenges, to be addressed during LASTI phase:
  - ≈30 systems in LIGO, each with 12 DOFs, can't easily be hand-tuned, and so sys-id and tuning of baseline controller should be automated.
  - Control-room supervision of these servos needs to be easier to use than systems of similar complexity in LIGO-1.