Baseline LIGO-II stiff active seismic isolation system

By the stiff active seismic isolation team

members* at Stanford, MIT, JILA, and LSU.

March 16, 2000

Abstract

This talk is an overview of a candidate seismic isolation system design for LIGO-II. For further information, follow the links on:

`http://lsuligo.phys.lsu.edu/active/active.html`

*S. Cowley, D. DeBra, J. Giaime, G. Hammond, C. Hardham, J. How, W. Hua, W. Johnson, B. Lantz, S. Richman, J. Rollins, R. Stebbins, S. Traeger,. . .

LIGO-G000067-00-D

SEI requirements for LIGO-II part 1, noise.

It was not widely appreciated until recently that the displacement noise requirement on the HAM SEI, which must fit into fairly tight quarters, is more stringent than that for the BSC.

BSC test mass:

- At 10 Hz we require $x(f) \leq 1 \times 10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$.
- "long" SUS transmits 2×10^{-8}.
- so, SEI requirement on suspension mount point is $x(10\ \mathrm{Hz}) \leq 5 \times 10^{-12}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$.

HAM MC mirror:

- At 10 Hz we require $x(f) \leq 3 \times 10^{-18}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$.
- "short" SUS transmits 1×10^{-5}.
- so, SEI requirement on suspension mount point is $x(10\ \mathrm{Hz}) \leq 3 \times 10^{-13}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$.

SEI Requirements part 2, alignment.

Control of RMS displacement: K. Strain has shown that RMS test mass displacement requirements (1×10^{-14} m) can be met with 200 Hz BW feedback to quadruple pendulum alone, requiring 1×10^{-8} N RMS force to test mass. SEI should significantly relax these requirements.

Control of RMS velocity: Test mass velocity requirement is 1×10^{-9} m/s, with global control loops on. Requirement for loops-off pending design of ISC lock acquisition scheme.

Control of RMS angle: Angle control requirement is 1×10^{-9}, with $\approx 2\,\mathrm{Hz}$ BW ASC loops on.

Functional Breakdown

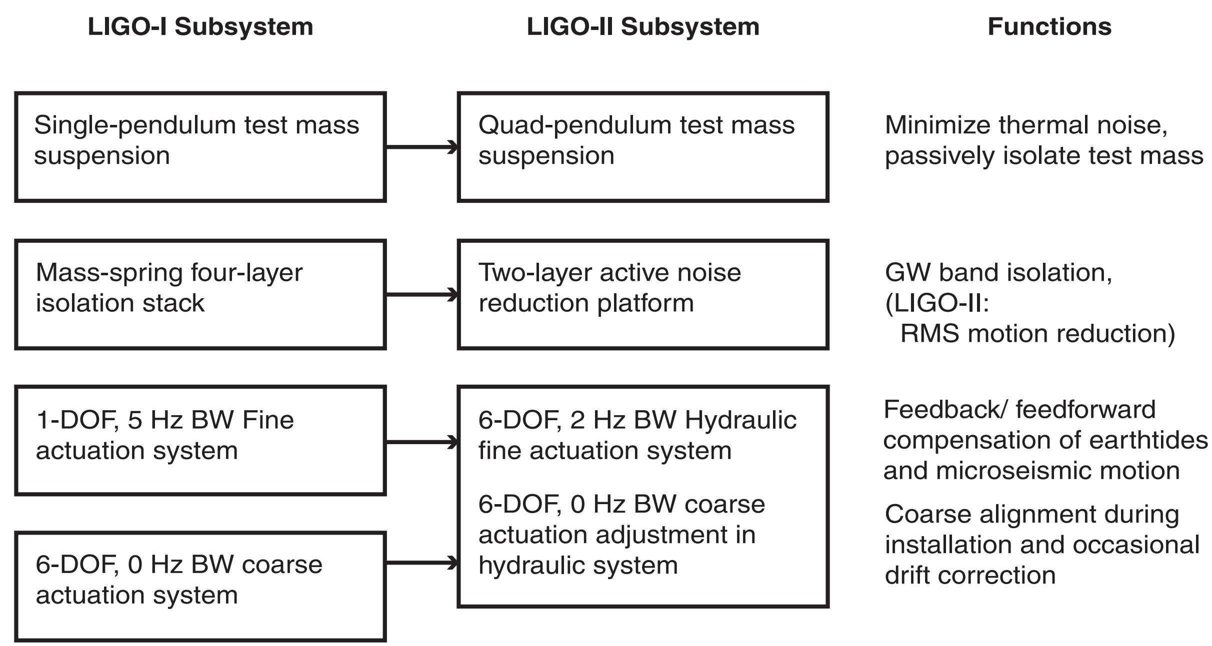

Figure 1: Seismic isolation functions in LIGO-I and LIGO-II. (The pendulum suspension, though not part of SEI, is shown because it contributes significant seismic isolation.)

Active Seismic Isolation

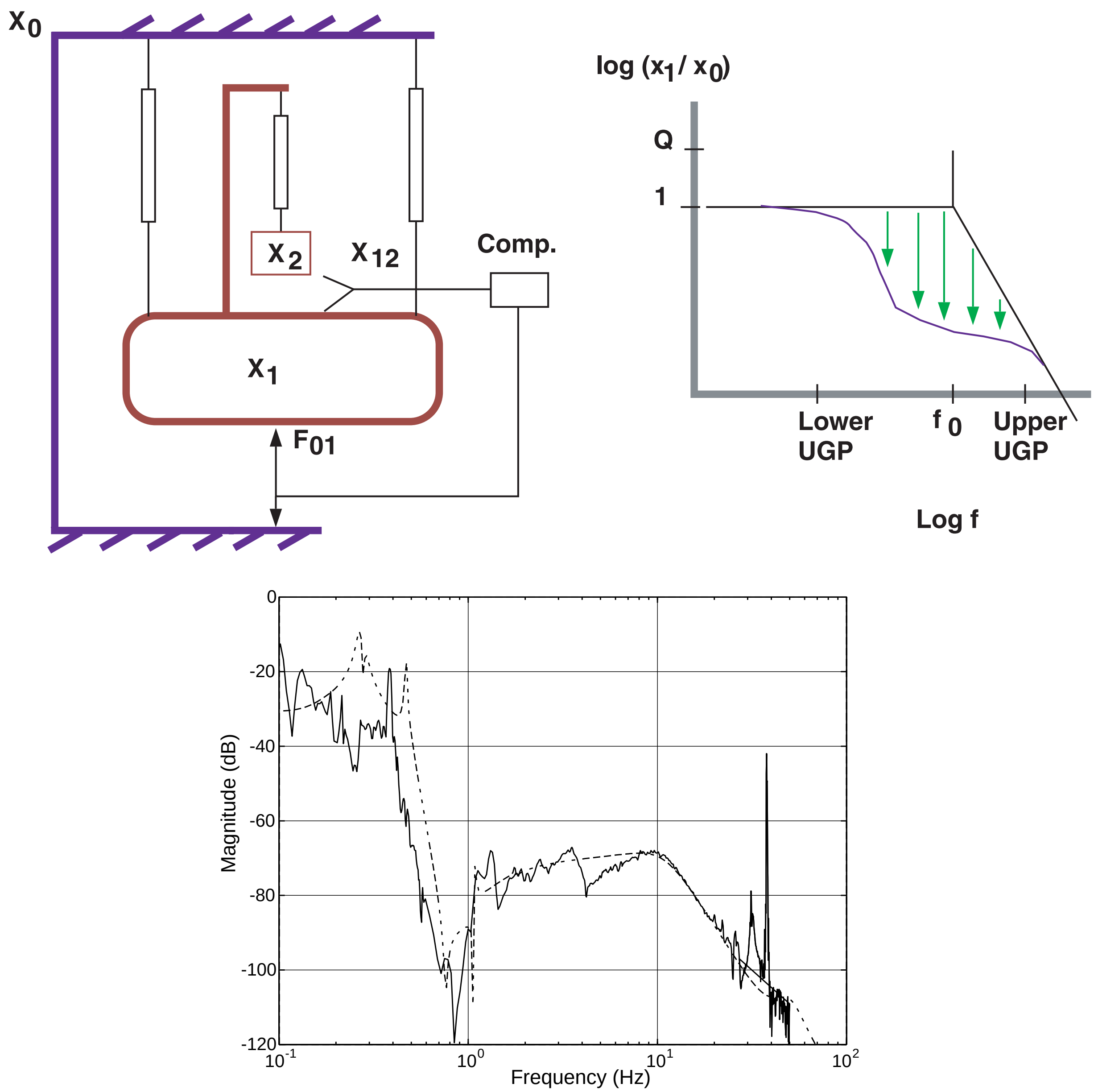

Figure 2: Active seismic isolation, with 1994 JILA results showing 70 dB of isolation.

BSC Two-stage active platform:

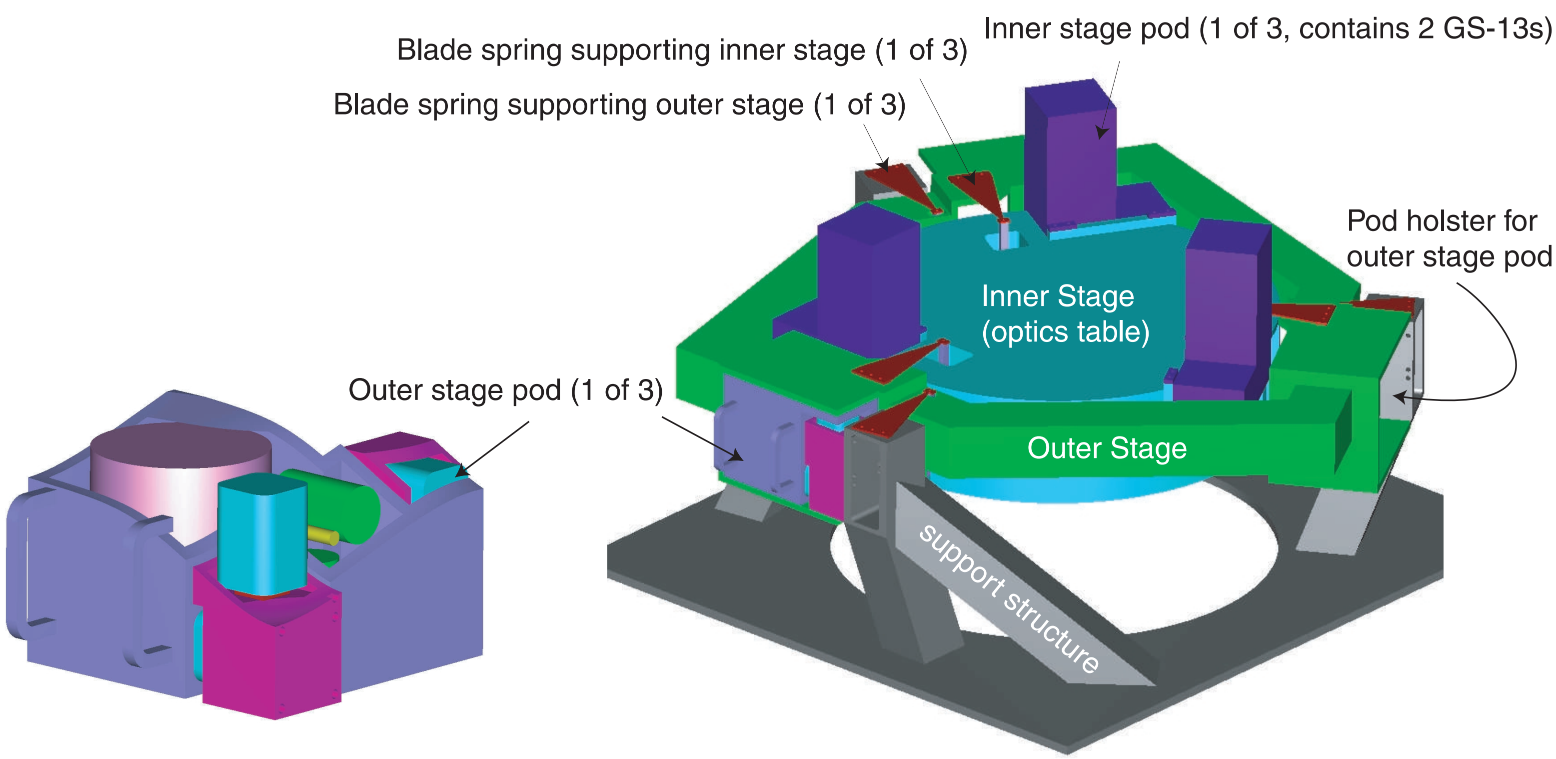

Figure 3: BSC version of the two-stage active platform.

HAM Two-stage active platform:

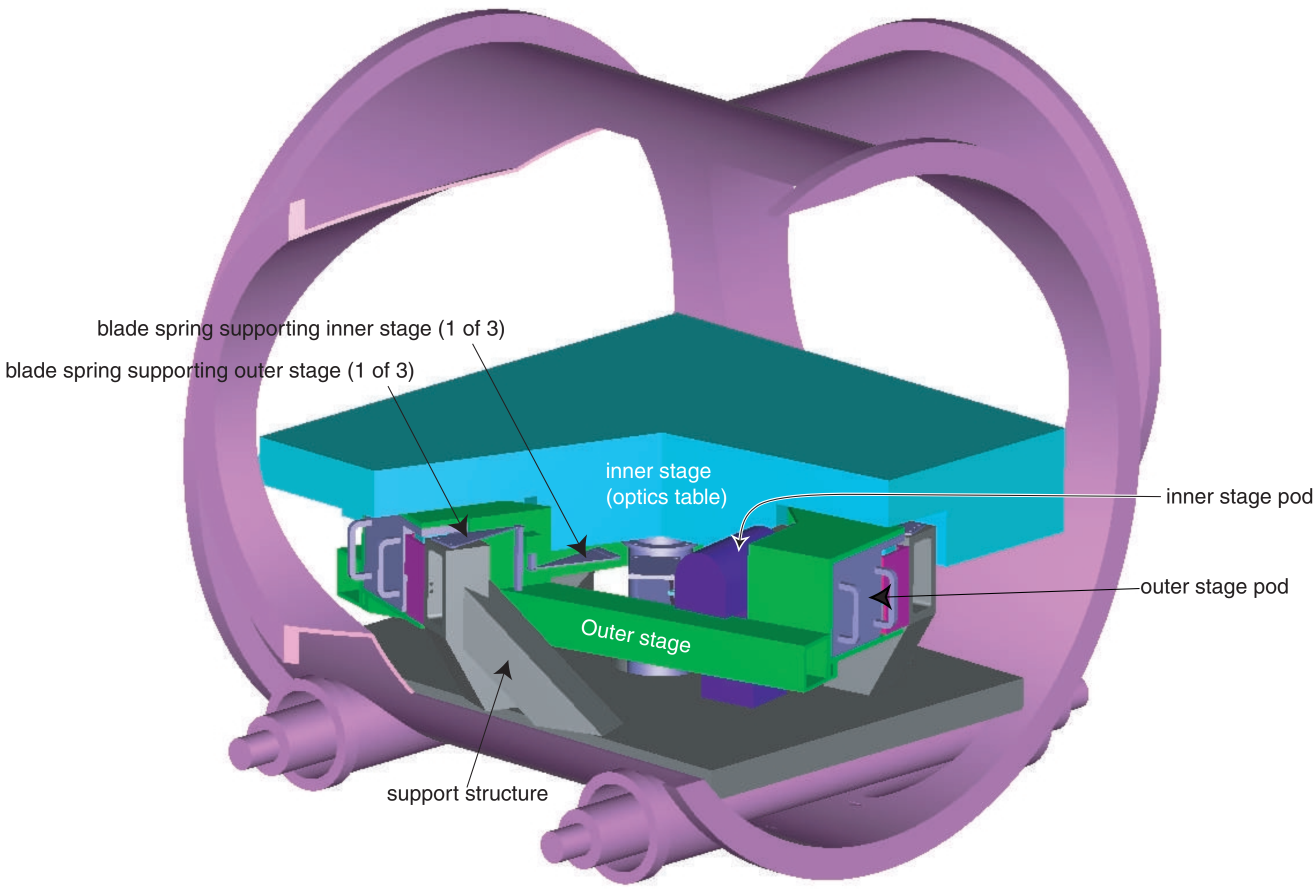

Figure 4: Rendering of the HAM design. Note that the instrumentation pods are positioned so that they are removable through the large HAM doors. The inner stage optics table (blue) is the same size as the table in LIGO-I, and in the same position.

The Quiet Hydraulic Actuator.

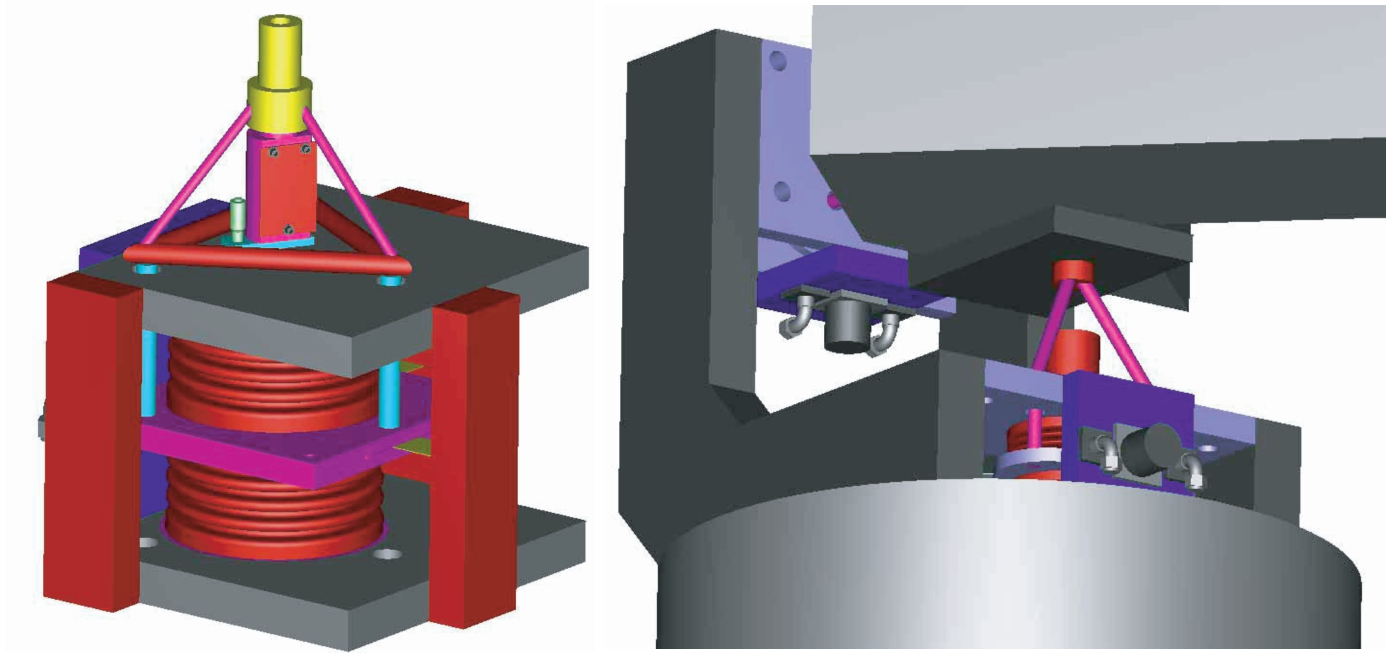

Figure 5: Hydraulic actuator will provide ± 1 mm, 2 Hz BW continuous actuation in 6 DOF. Each bellows assembly acts in 1 DOF; two DOF at each corner. Viscous fluid and remote pump assure quiet operation. Threaded connections to bellows assy will allow coarse actuation to 5 mm.

Differential bellows:

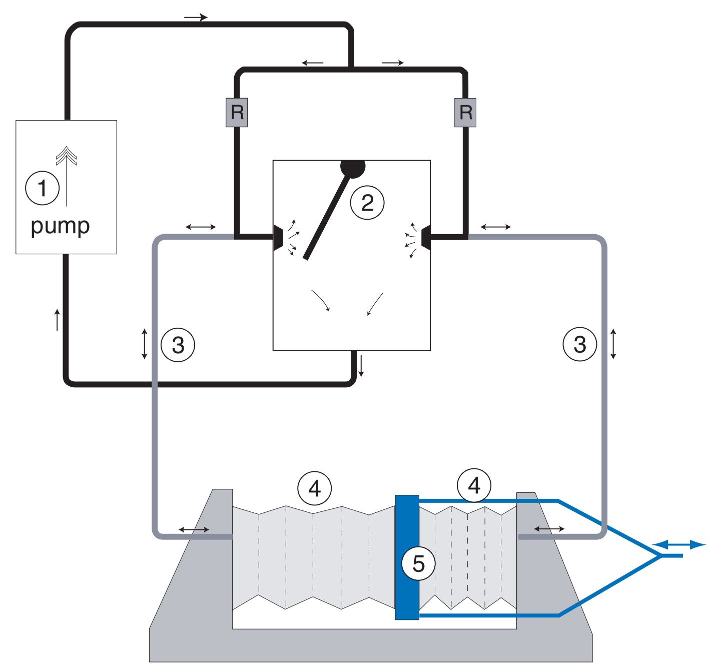

Figure 6: The control valve creates a pressure differential on the bellows. The middle plate is attached with flexures to both the base and the payload, only constraining motion in 1 DOF.

Performance

	units	optics table	BSC test mass	HAM test mass
$x(f)$ at 10 Hz	$\mathrm{m}/\sqrt{\mathrm{Hz}}$	2×10^{-13}	1.0×10^{-20} $[1 \times 10^{-19}]$	2×10^{-18} $[3 \times 10^{-18}]$
RMS displacement	m	6×10^{-7} (1×10^{-8})	4×10^{-17} $[1 \times 10^{-14}]$	
RMS velocity	m/s	3×10^{-7} (3×10^{-9})	4×10^{-17} $[1 \times 10^{-9}]$	

- System noises without (with) hydraulic stage and feedforward.
- RMS integrated down to 0.01 Hz, with the global loops.
- 5×10^{-12} N RMS global control force needed at test mass actuator.
- [requirements] are shown bracketed in red.

Stiff active SEI design advantages:

- Same compact core design used in both HAM and BSC. Only mechanical interfacing specialized for the tank geometry.
- The stiff support of the optics table mounting surface allows easy installation of the optics payload.
- Conventional wires and ribbon cables can be used to carry signals.
- Full active instrumentation allows dynamically-selectable operating modes, and continuous state monitoring.
- Stiff suspension springs can be operated at conservative low stress levels.

BSC Design:

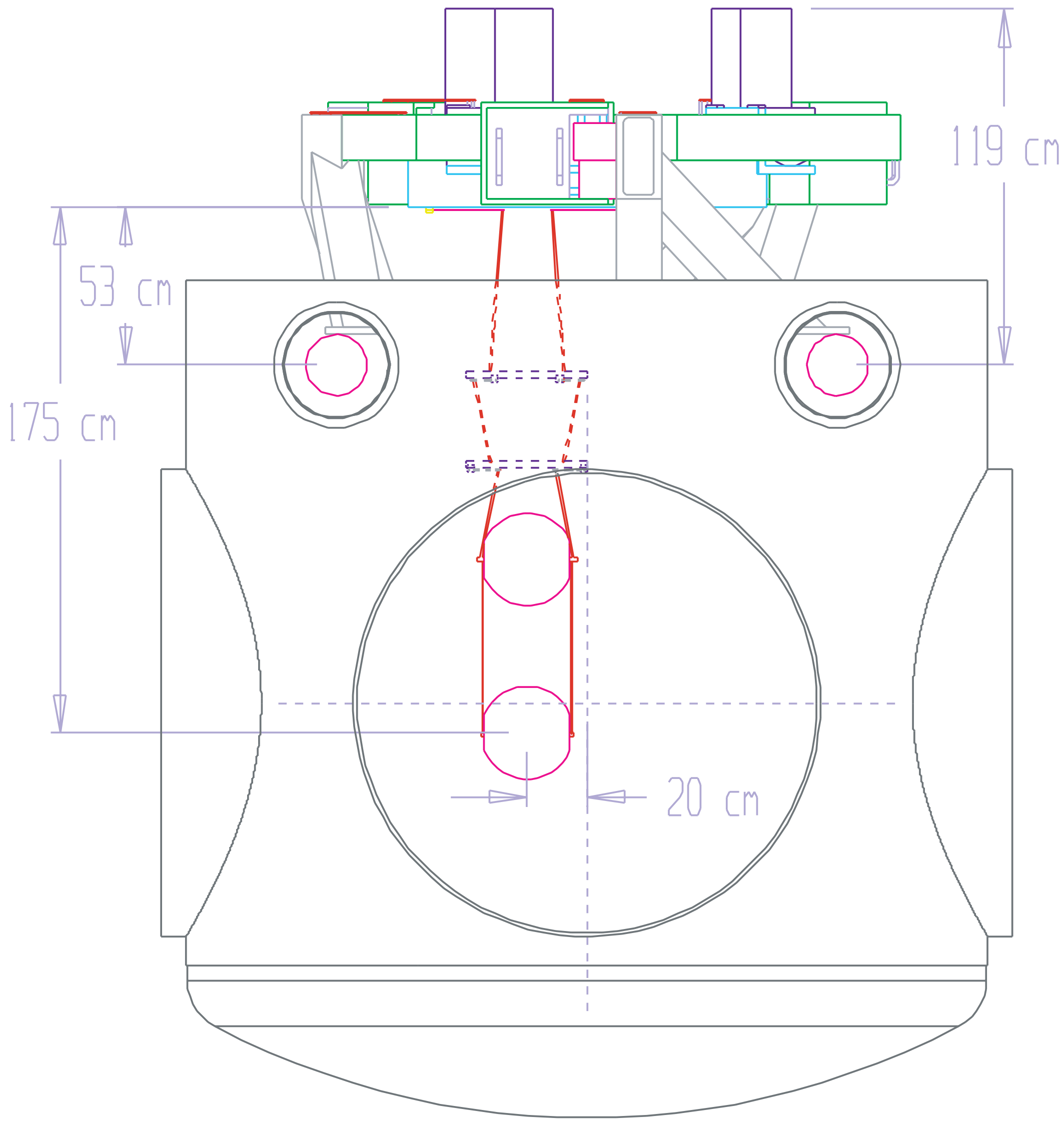

Figure 7: Elevation drawing of the baseline BSC chamber design, with GEO quadruple pendulum shown to scale.

HAM Design:

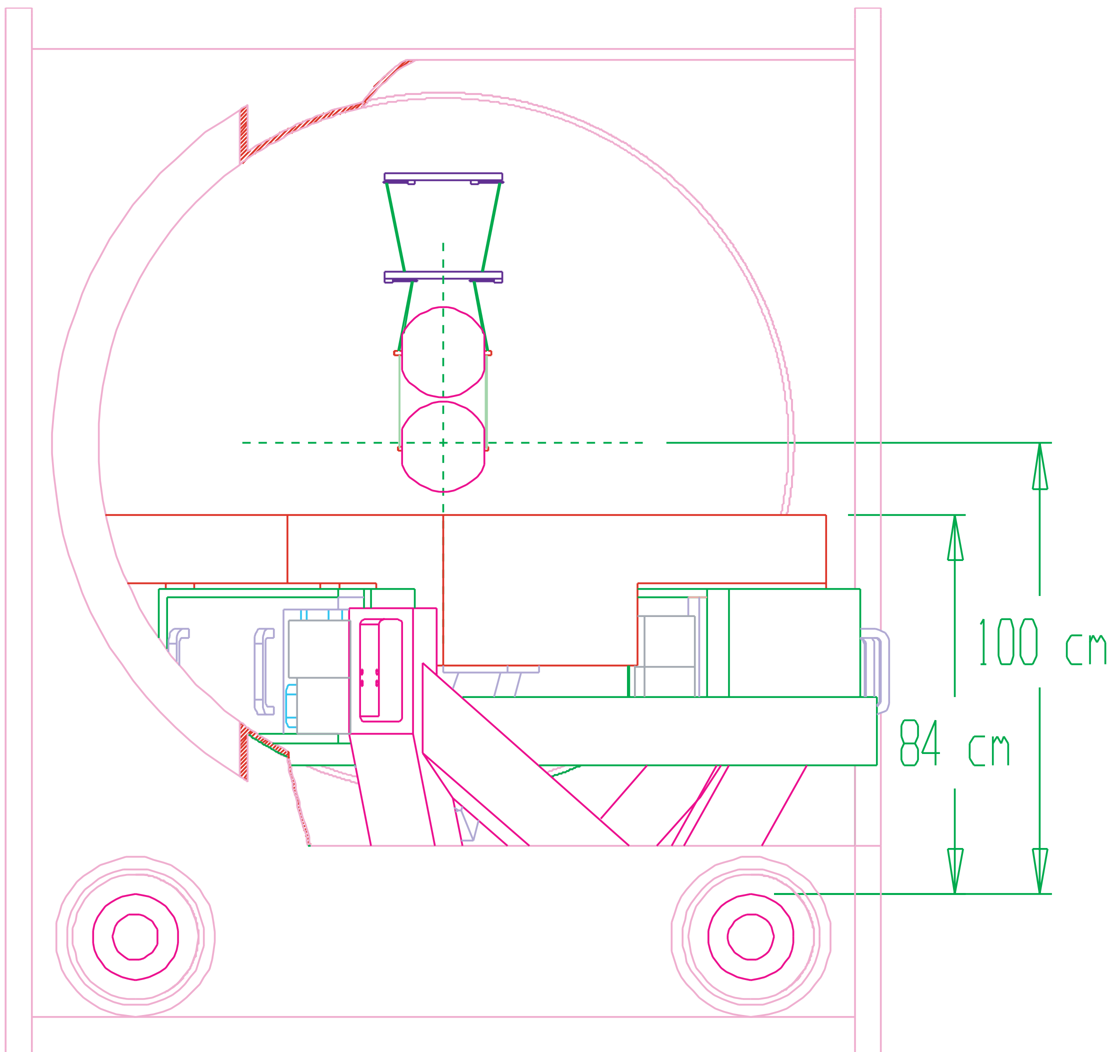

Figure 8: Elevation (cut-away) drawing of the baseline HAM chamber design. The dashed lines indicate beam center for a typical suspension position. The external hydraulic actuators are not shown here.

Sensor Noise:

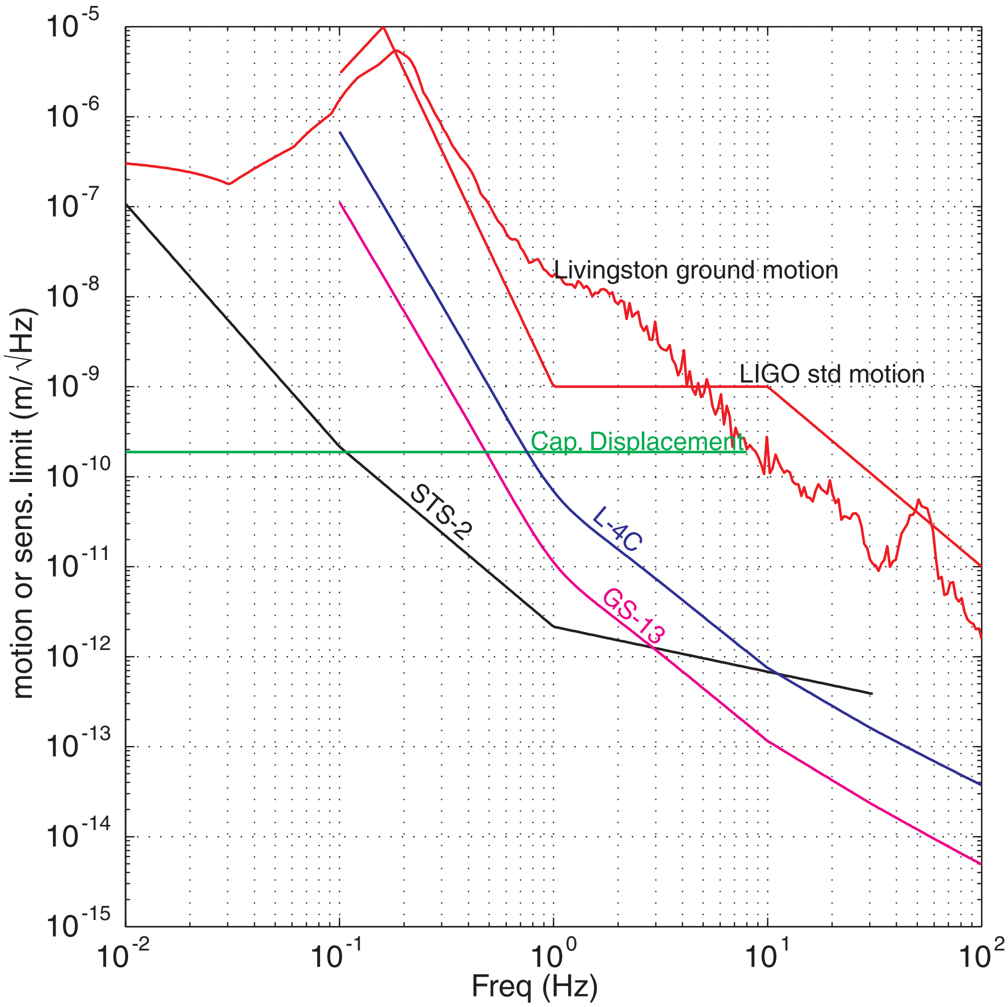

Figure 9: Displacement noise in various sensors used in the two-stage active isolation platform, compared with the LIGO standard ground noise and the measured noise at LLO.

Broadband Seismometer:

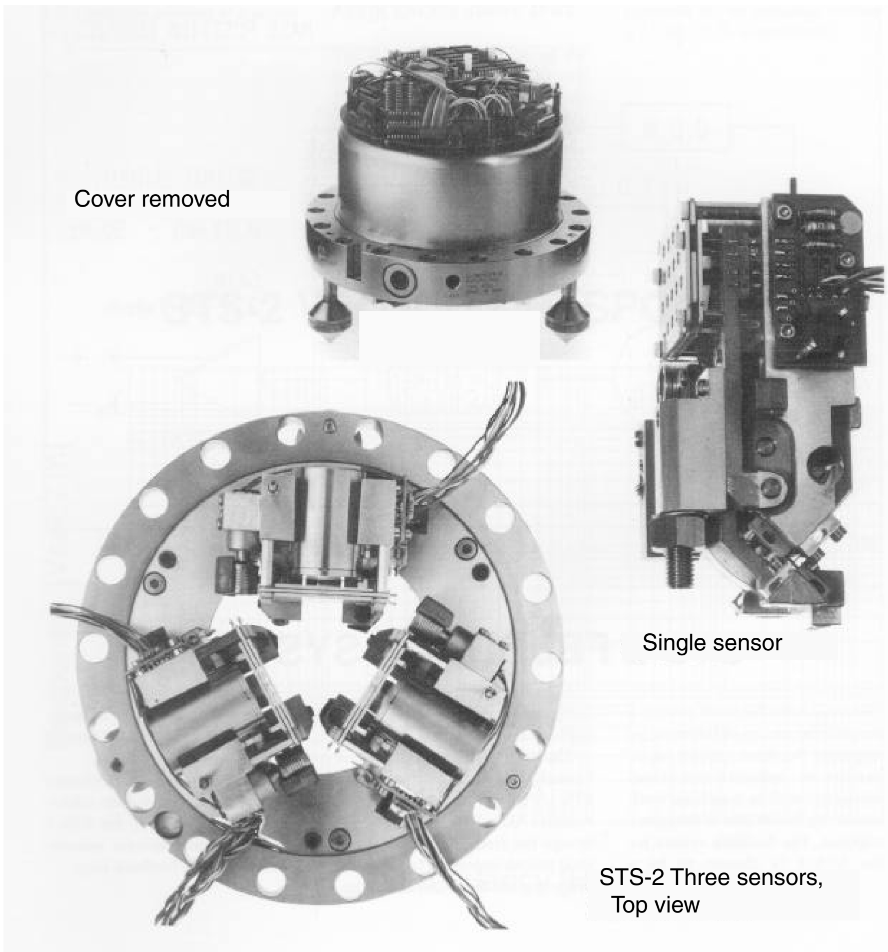

Figure 10: A broadband long-period vibration sensor usable from tens of millihertz to tens of hertz. Each STS-2 seismometer, manufactured by Streckeisen AG, measures vibration in three degrees of freedom. A vacuum-tight domed cover is included but not illustrated here.

Dynamic Model:

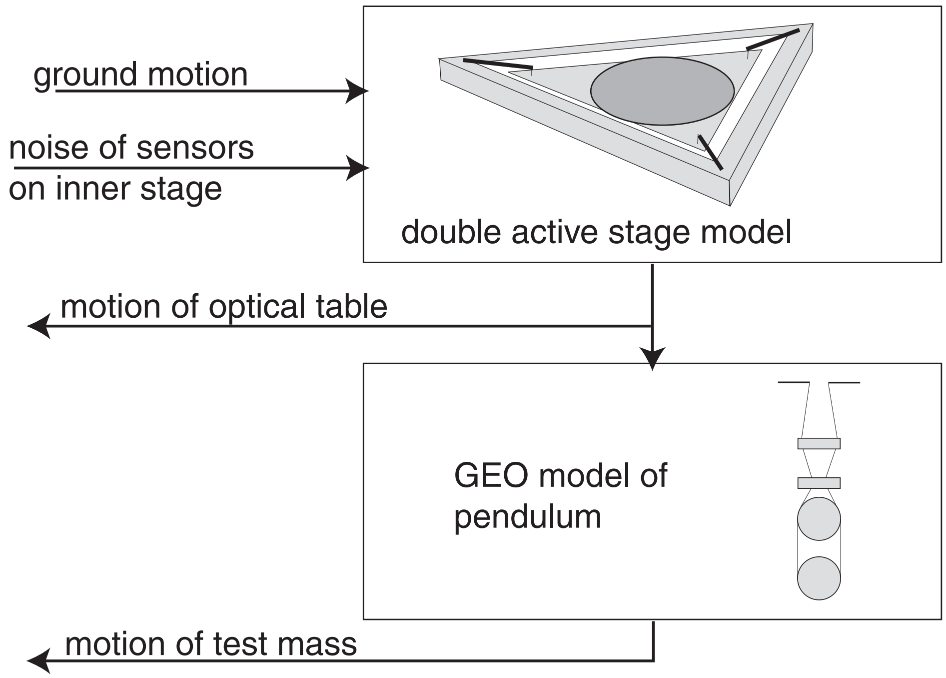

Figure 11: The Model results were generated in a two step process. First, the motion of the optical table was simulated using sensor noise and ground motion. The motion of the optical table was then used as an input to the GEO pendulum model to compute test mass motion.

Test mass noise: two-stage platform and quad pendulum

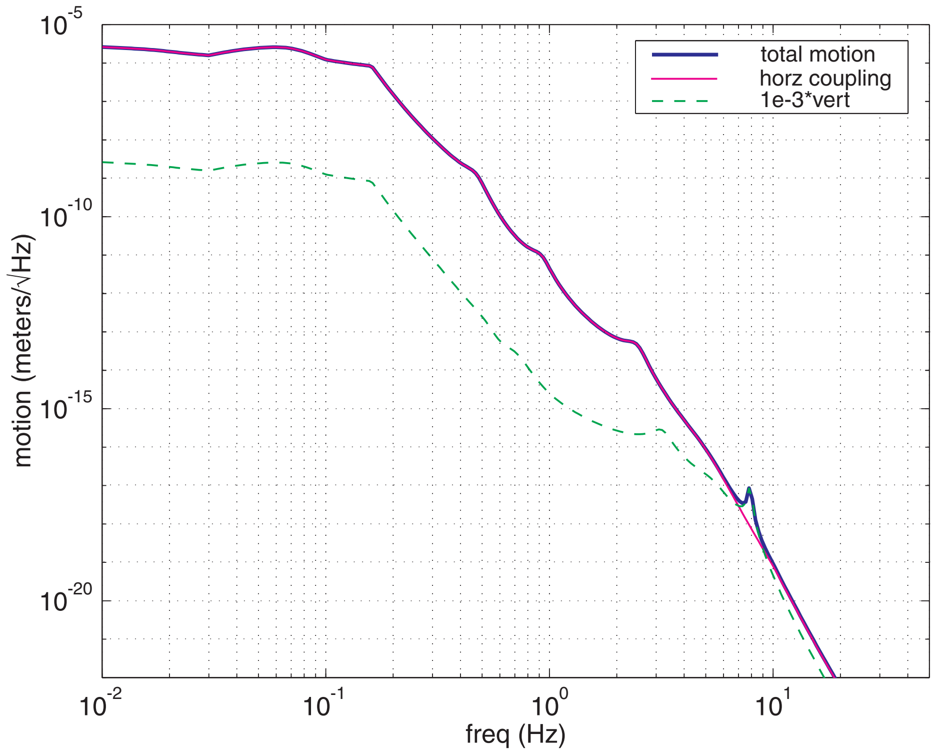

Figure 12: Motion the test mass (ITM and ETM), assuming local pendulum damping loops are on; this meets the requirement. Noise is lower with damping loops off, and still lower when feedforward stages are used.

Optics table noise performance:

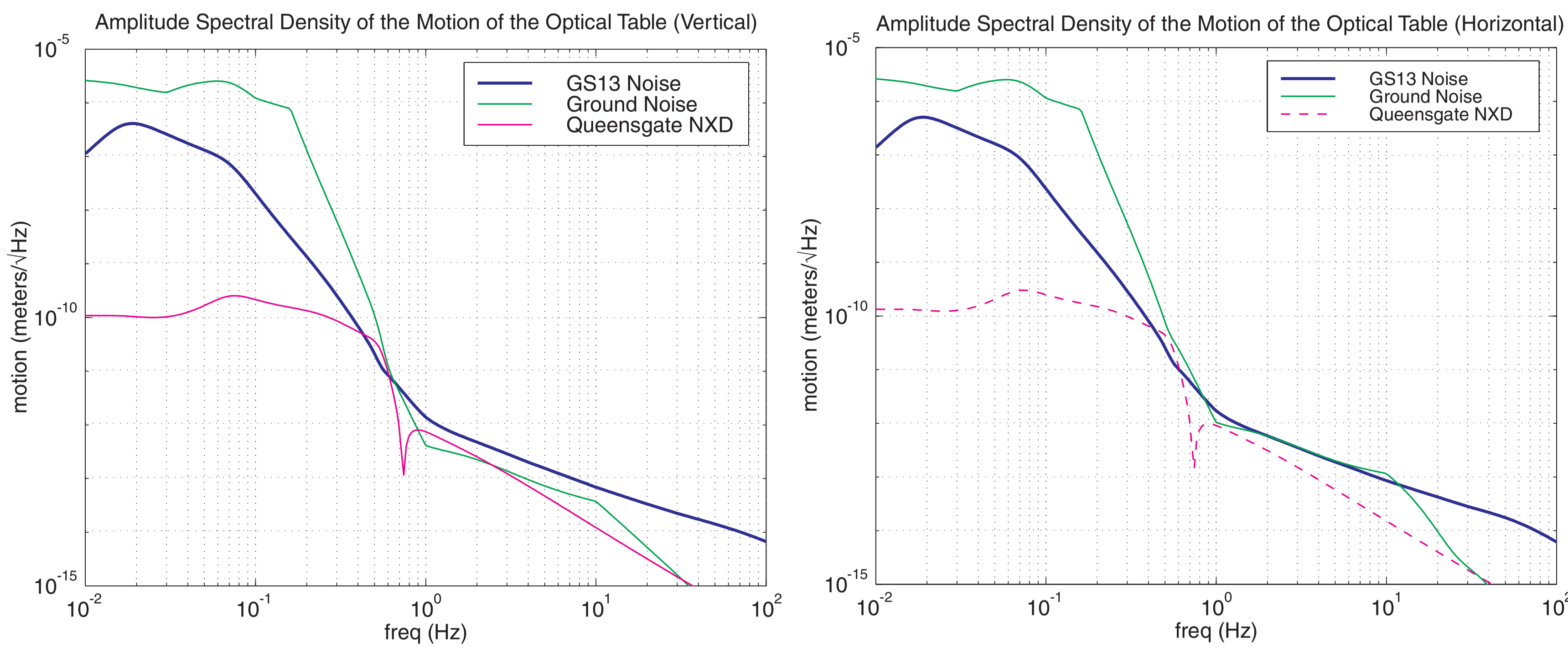

Figure 13: Performance of the two-stage active platform, without feedforward. Here we plot the contributions to the noise level at the SEI optics table, the suspension system mounting point.

Model construction:

1. a set of test inputs and outputs.
2. a mechanical model of the two stage system.
3. a set of sensors which are distributed on the outer stage.
4. filters which blend the outer stage sensors into six super-sensors.
5. a set of sensors which are distributed on the inner stage
6. filters which blend the inner stage sensors into six super-sensors.
7. a set of actuators between the outer stage and the ground.
8. a set of actuators between the inner stage and the outer stage.
9. a set of 12 SISO control laws which connect the 12 actuators with the 12 super-sensors.

Simulink Model Diagram:

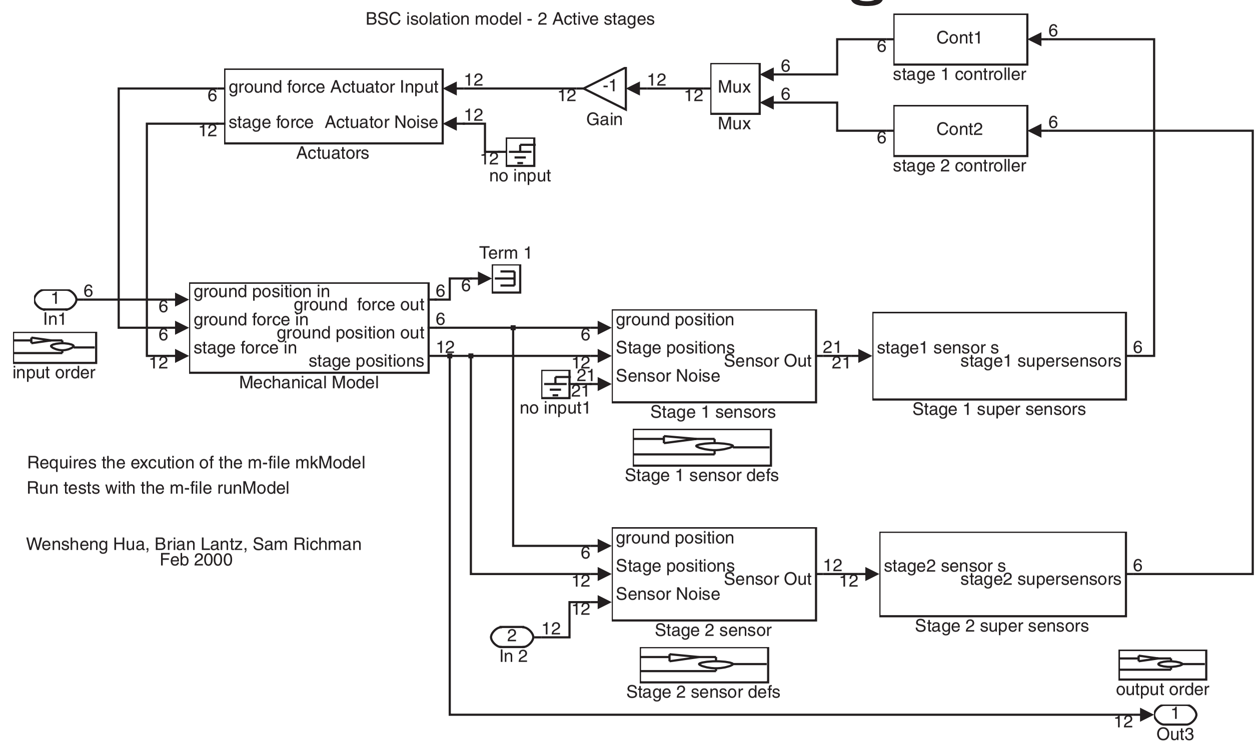

Figure 14: Model used to calculate the dynamics and servo compensation in the reference design two-stage active platform and to cross-compile the controller using the dSpace DSP hardware.

Sensor Blending:

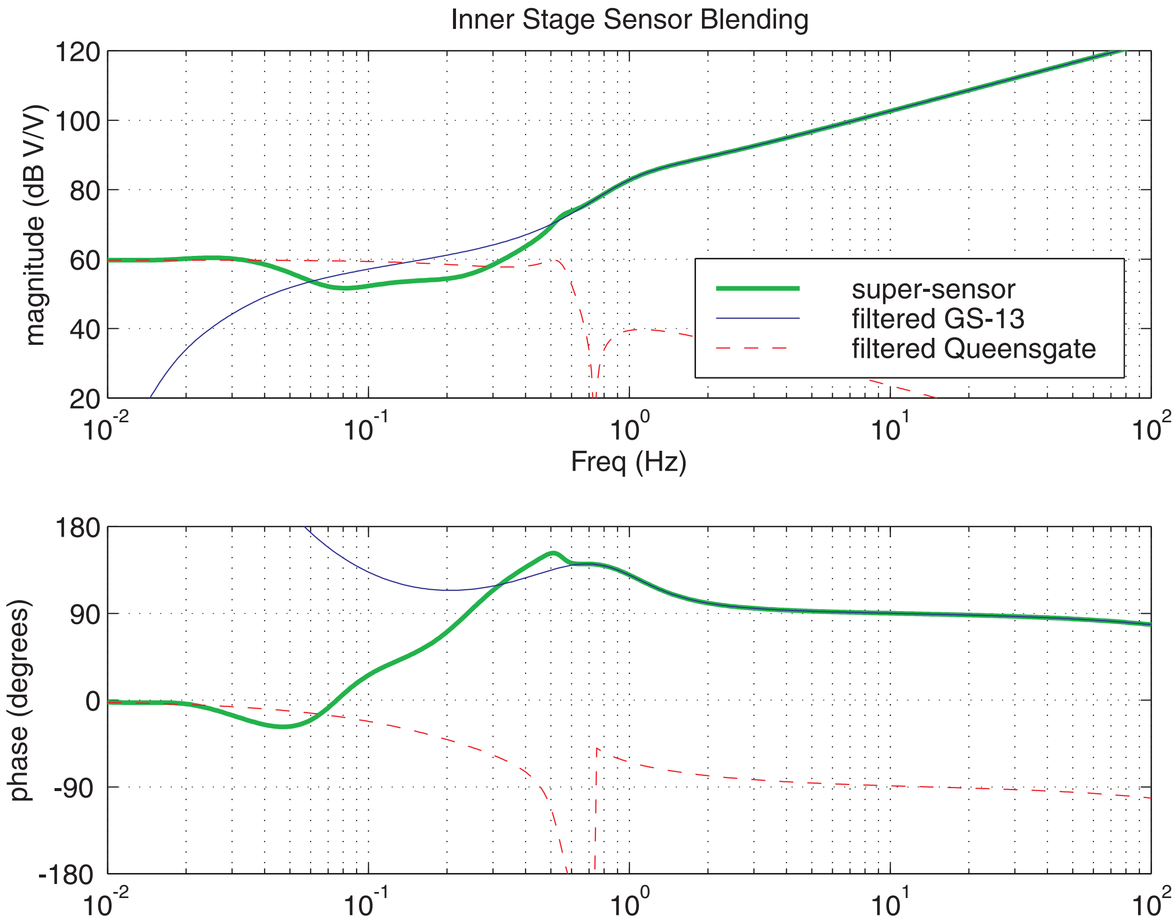

Figure 15: Aggressive filtering of the sensors occurs once the sensor is no longer the dominant signal source of the loop. This is done to improve the performance of the systems. Once the sensors have been combined, they can be thought of as a single, broadband sensor which we call a “super-sensor.”

Compensation Example:

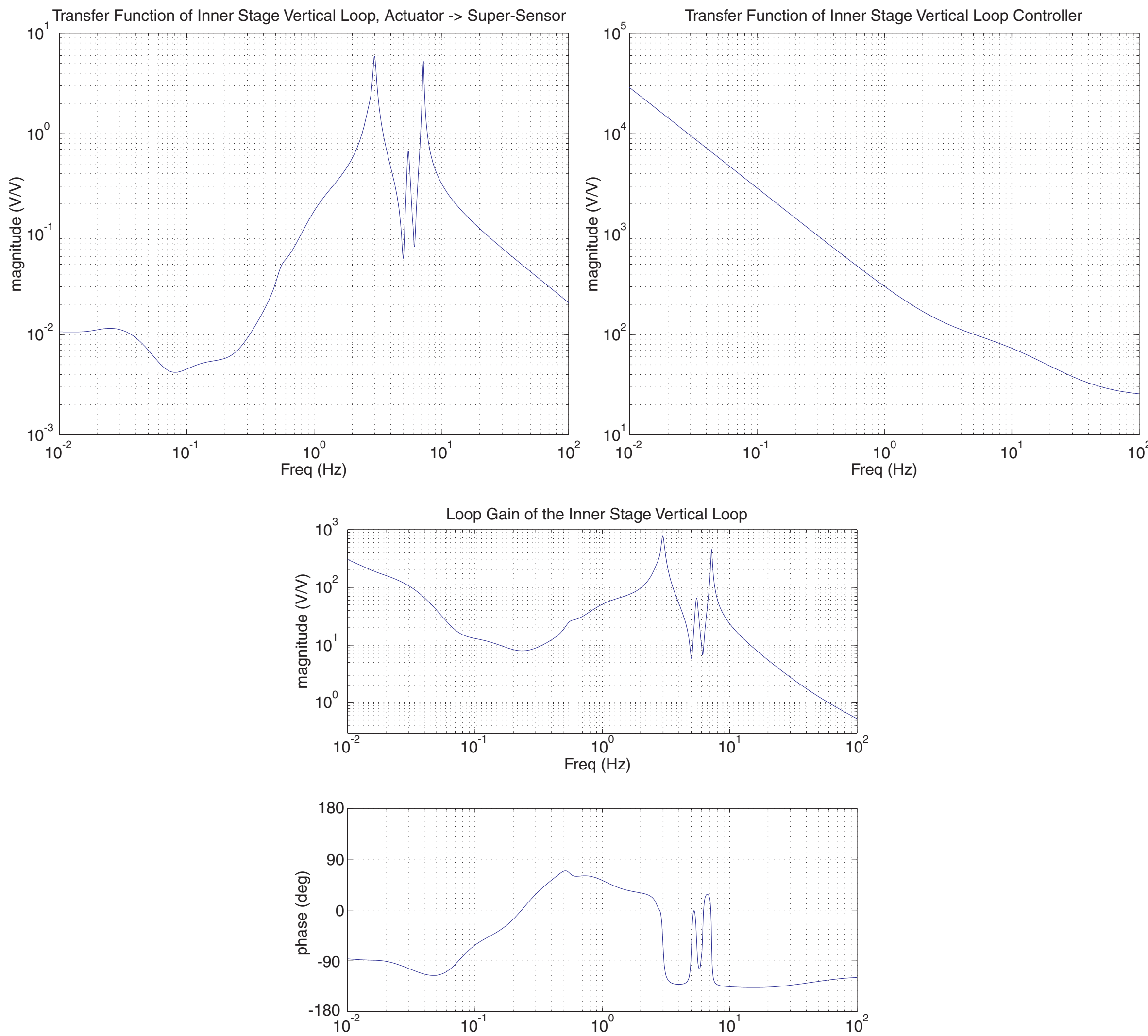

Figure 16: *upper left:* Transfer function from inner stage vertical actuator #1 to its collocated super-sensor. *upper right:* A simple system based on an integrator was chosen as the control law. *lower:* Complete open-loop transfer function.

Stanford active platform with pendulum:

Experiment is underway at Stanford's Engineering Test Facility.

Goals:

- Demonstrate 6 DOF active platform with collocated sensors and actuators and modern MIMO techniques.
- Demonstrate sensor blending.
- Validate computer model used to design LIGO system.
- Demonstrate feedforward.
- Demonstrate reliable operation with active platform and multiple pendulum working together, with control reallocation.
- Develop watchdog schemes.

Stanford active platform with pendulum:

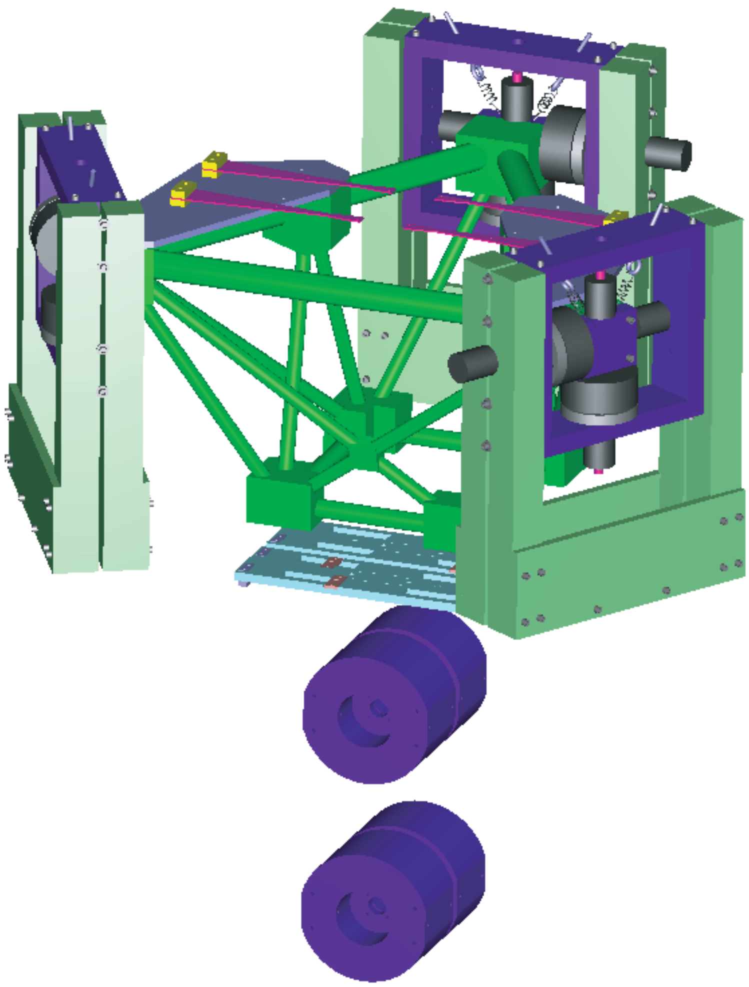

Figure 17: Drawing of the Stanford Active Platform and pendulums Prototype. A single-layer active seismic isolation platform supports two triple pendulums of a design based closely on the GEO triple pendulum.

Stanford lab work:

Figure 18: Active platform and triple pendulum.

Two-stage active platform:

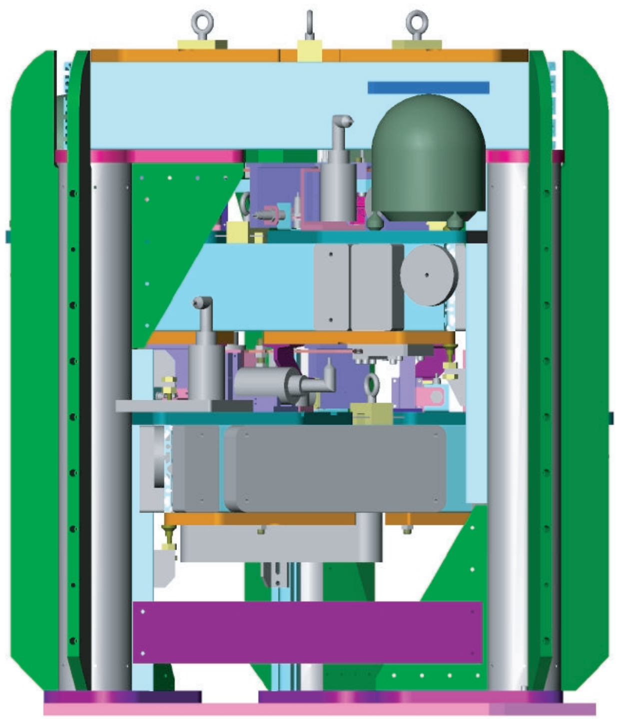

Figure 19: Rendering and installation. 3D mechanical model used to make parts and produce mass and moment inputs for compensation design.

Two-layer active platform test:

- Designed, constructed, paid for, and tested by dispersed group of researchers - scientists at JILA, MIT, Stanford and LSU; detailed engineering at HPD.
- Rapid progress - Project start 15 Oct., conceptual design done 8 Dec., vendor start 15 Jan., delivery to MIT 8 Mar., commissioning at MIT 14 Mar.
- Rapid assembly and alignment offline - First time experience: boxes delivered Wednesday 8 March at noon, assembled by Sunday 12 March, aligned by Monday 13 March, placed in vacuum Tuesday 14 March, first loop closure by the end of Tuesday 14 March.
- Parasitic resonances controlled - coupled body modes 2-9 Hz, first internal resonances above 100 Hz (modes of the external structure predicted by FEA), next resonance above 230 Hz.
- Robust - mechanically very stable, no measurable change (less than 0.003" in stage separation) under locking/unlocking and lifting into vacuum tank (puts 800 kg load on sides of upper support triangle).

First two-stage results:

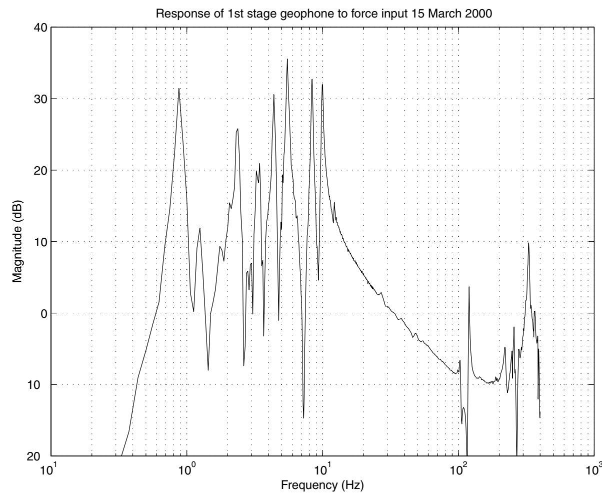

Figure 20: Magnitude of the vertical open loop uncompensated TF (forcer to geophone)

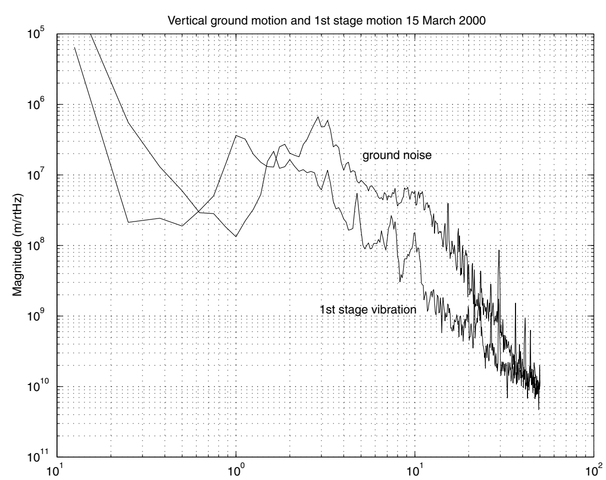

Figure 21: Vertical seismic isolation of single stage on first day after assembly. (3 DOF's closed.)