Suspension/Isolation Working Group Issues
LASTI Plans and Status
Stiff Active Isolation approach

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Caltech

LIGO PAC

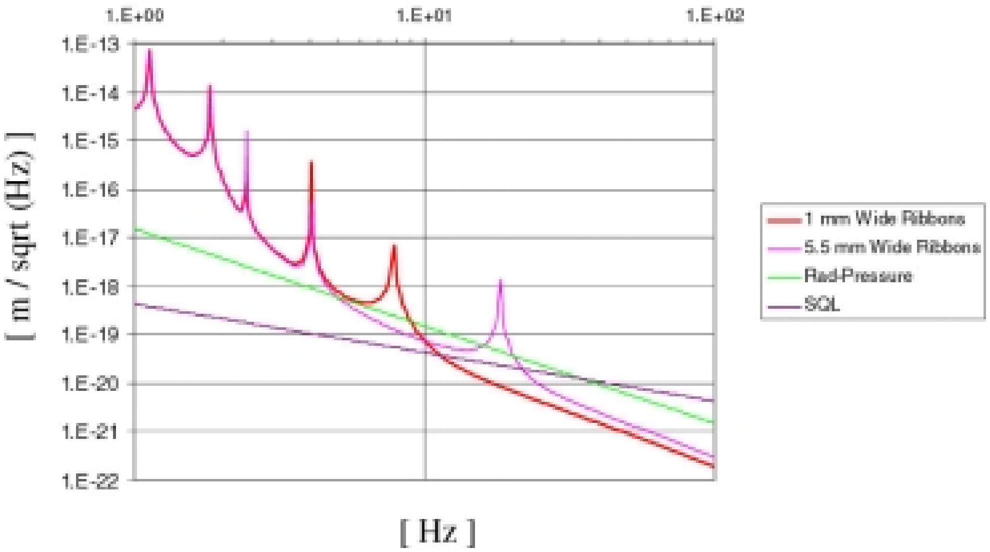
1 May 00

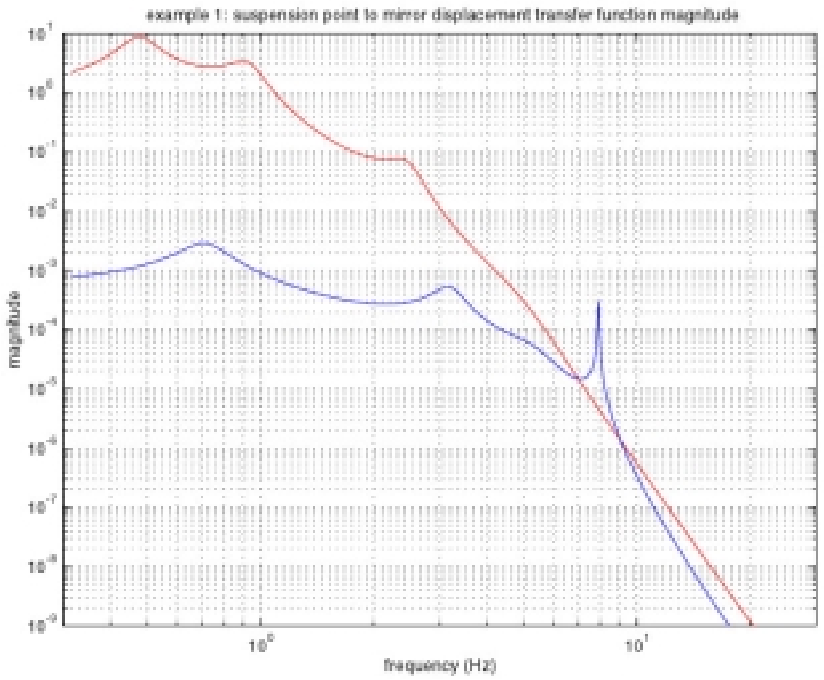
Suspension Working Group: Seismic Isolation

- Seismic Isolation
  - » requirements established
    - – interface to GEO suspension, LIGO vacuum system
    - – consistency with LIGO concept of flexibility
    - – performance requirements as per baseline LIGO II design
  - » meetings at Glasgow (December), LSC (March)
  - » two approaches under study (later this talk, and Riccardo Desalvo's talk)
    - – both workable, can meet or exceed requirements
    - – both require some extrapolation from present experience
  - » committee (under Dennis Coyne) well advanced in forming evaluation
    - – documentation revised/refined
    - – visits to the prototypes
    - – several telecon and in-person meetings
  - » anticipate a recommendation by mid-May

Fused silica Suspensions

- GEO contribution
  - » intellectual heritage
  - » tests on GEO-600
  - » (financial contribution)
- Community engaged
  - » Willems/Caltech
  - » Gonzalez/PSU
  - » Saulson/Syracuse
- Thermal noise
  - » silica ribbon suspension
  - » silicate bonding to test masses
- Seismic filtering
  - » <10^-6 transmission at 10 Hz
- Requirements review this summer
- First prototypes end 2001



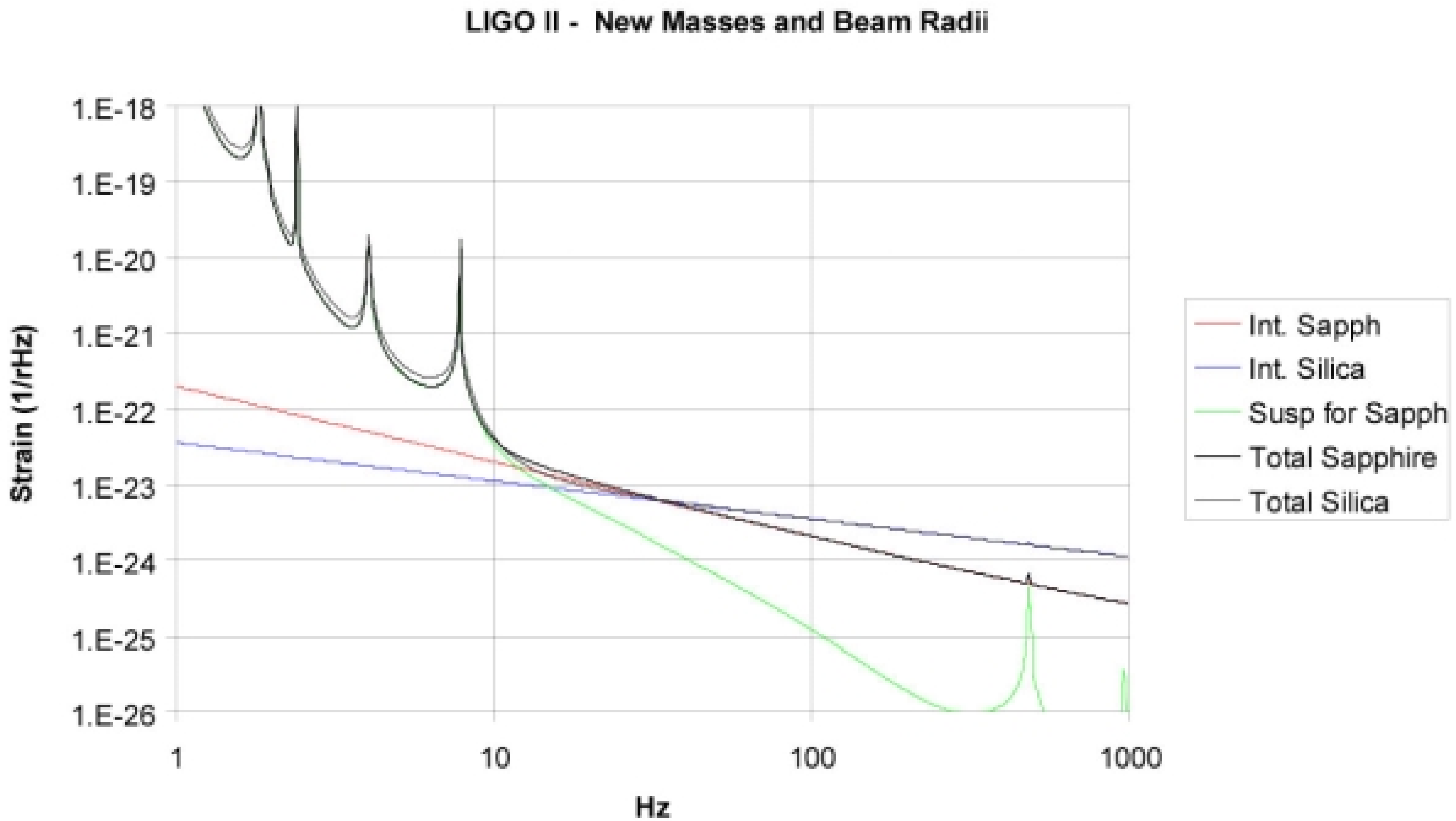


Thermal Noise

- Suspension thermal noise
  - » materials tests support predicted performance
  - » fused silica ribbons a fabrication challenge
  - » cylindrical rods a good fall-back
- Sapphire Test mass thermal noise
  - » thermoelastic damping important
  - » requires trades on test mass and beam spot sizes --- can almost recover White Paper performance curves
  - » much more difficult to prototype LIGO II displacement noise
  - » also: coating losses uncertain, photoelastic effect significant….
- Pursuing several options for performance testing and to gain confidence
  - » Thermal Noise Interferometer: demonstrates thermoelastic effect
  - » possible extension of prototype to longer arms: smaller spot, better displacement limit
  - » continued sapphire material development and characterization
  - » fused silica as backup: not ideal, easy, or cheap, but an alternative

Optimized Sapphire solution

- sapphire mass=44 kg diameter=32 cm thickness=13.7cm beam radii= 5 and 5 cm phi=5E-9
- pendulum length=60 cm ribbons= 1.21 mm X 0.121 mm phi=1.4E-7



Suspension/Isolation testbed

- LASTI: **L**IGO **A**dvanced **S**ystem **T**est **I**nterferometer
  - » Test LIGO components, systems at full mechanical scale
  - » Practice installation & commissioning
  - » Minimize delays & downtime for LIGO site upgrades
- LIGO II Specialization:
  - » Test LIGO II seismic isolation & suspension system and associated controls at full scale
  - » Develop detailed SEI/SUS installation & commissioning handbook
  - » Look for unforeseen interactions & excess displacement noise
- Goal: complementarity to 40m, other performance demonstrations
  - » technical advisory group, overlap with 40m, to help ensure this

LASTI Plan/Schedule

- 4Qq99: LASTI envelope commissioned DONE
  - The vacuum envelope is installed and aligned; the vacuum pumping system is commissioned, and the system is pumped down for the first time.
- 2Q00: LASTI infrastructure design review IN PREPARATION
  - covers noise sources; models for the performance of the system; complete costing and manpower estimates for the optical sensing system, control and data, mechanical interfaces to LASTI; and the experimental program.
- 4Q00: LASTI external structures installed
  - The seismic piers are erected around the HAMs and BSC.
- 3Q01: LASTI infrastructure complete
  - sensing system, control and data,
    and a trial cavity test of the complete system function

LASTI Plan/Schedule

- 1Q02: LASTI prototype installation complete
  - high-quality prototypes of the HAM and BSC isolation systems, and ’controls prototypes’ of the suspensions, installed and ready for tests
- 3Q02: LASTI locked
  - The optical sensing system for the Mode Cleaner and the Test Mass Suspensions functioning and the cavities locked. No performance requirement.
- 1Q03: LASTI controls test review
  - An understanding of the controls performance of the seismic isolation systems and of the suspensions
- 2Q03: LASTI noise prototype installed
  - The ’controls prototypes’ for suspensions changed out and fused silica fiber, sapphire test mass Test Mass suspensions installed.

LASTI Plan/Schedule

- 1Q04: LASTI final test review
  - This milestone should indicate the status of tests to meet the noise performance verification.
  - is only 6 months after start of noise testing phase...
- 1Q04: LASTI first article installation starts
  - using the planned installation jigs and procedures, for seismic isolation and suspensions.
- 3Q04: LASTI first article tests complete
  - may or may not include performance testing.

LASTI Issues

- What should be the sensitivity goal of displacement noise tests at LASTI?
  - » Thermoelastic thermal noise a predicted limit;
    ~30x LIGO II displacement sensitivity possible
  - » How close to the LIGO II sensitivity level do tests (in LASTI or elsewhere) need to come to convince ourselves, others that we have a robust design?
  - » When do we need results from tests?
- The White Paper schedule is very aggressive
  - » manpower, means to build up ‘familiar’ technologies (sensing system, etc.)
  - » all the contributions (isolation systems, suspension systems) must fall into place as per the schedule
- Must recruit LSC members to help with the tests in LASTI

Stiff Active Isolation approach

- Following presentation based on one by Joe Giaime, LLO LSC meeting

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,. . .

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 Description of the System

LIGO-I Subsystem		LIGO-II Subsystem
Single-pendulum test mass suspension	→	Quad-pendulum test mass suspension

Minimize thermal noise,
passively isolate test mass

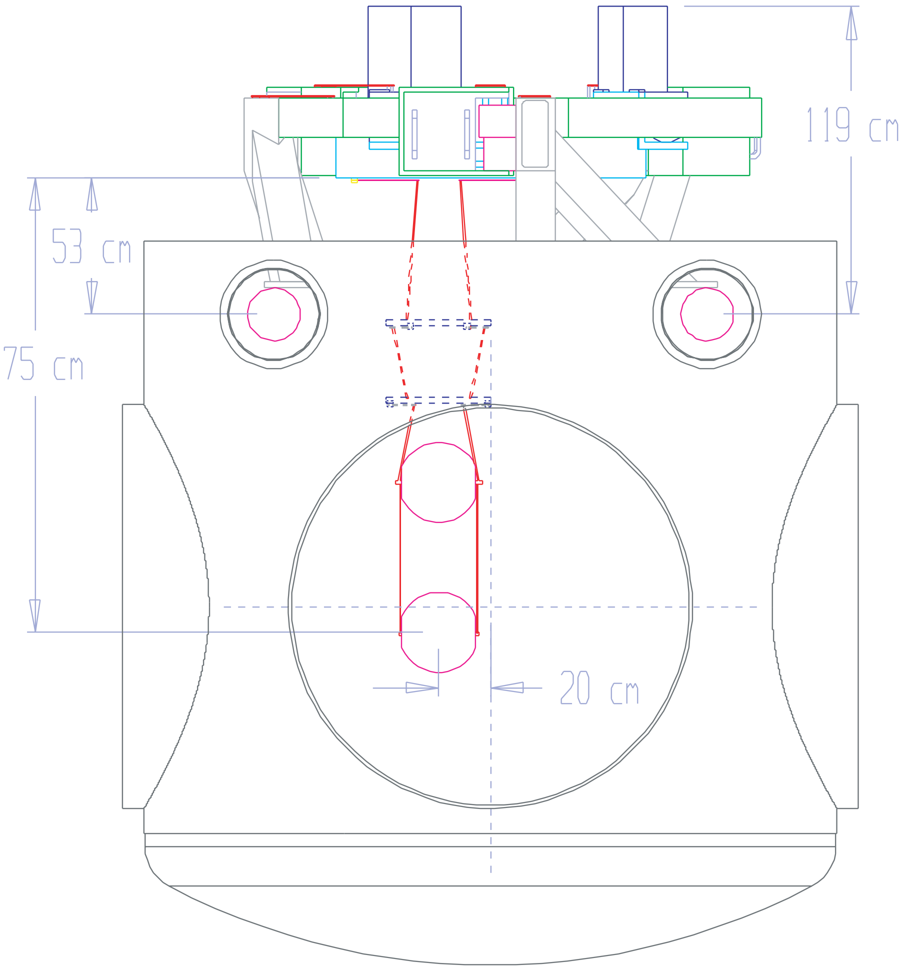
LIGO-I Subsystem		LIGO-II Subsystem
Mass-spring four-layer isolation stack	→	Two-layer active noise reduction platform

GW band isolation,
(LIGO-II: RMS motion reduction)

LIGO-I Subsystem		LIGO-II Subsystem
1-DOF, 5 Hz BW Fine actuation system	→	6-DOF, 2 Hz BW Hydraulic fine actuation system
6-DOF, 0 Hz BW coarse actuation system	→	6-DOF, 0 Hz BW coarse actuation adjustment in hydraulic system

Feedback/ feedforward compensation of earthtides and microseismic motion

Coarse alignment during installation and occasional drift correction



BSC Two-stage active platform:

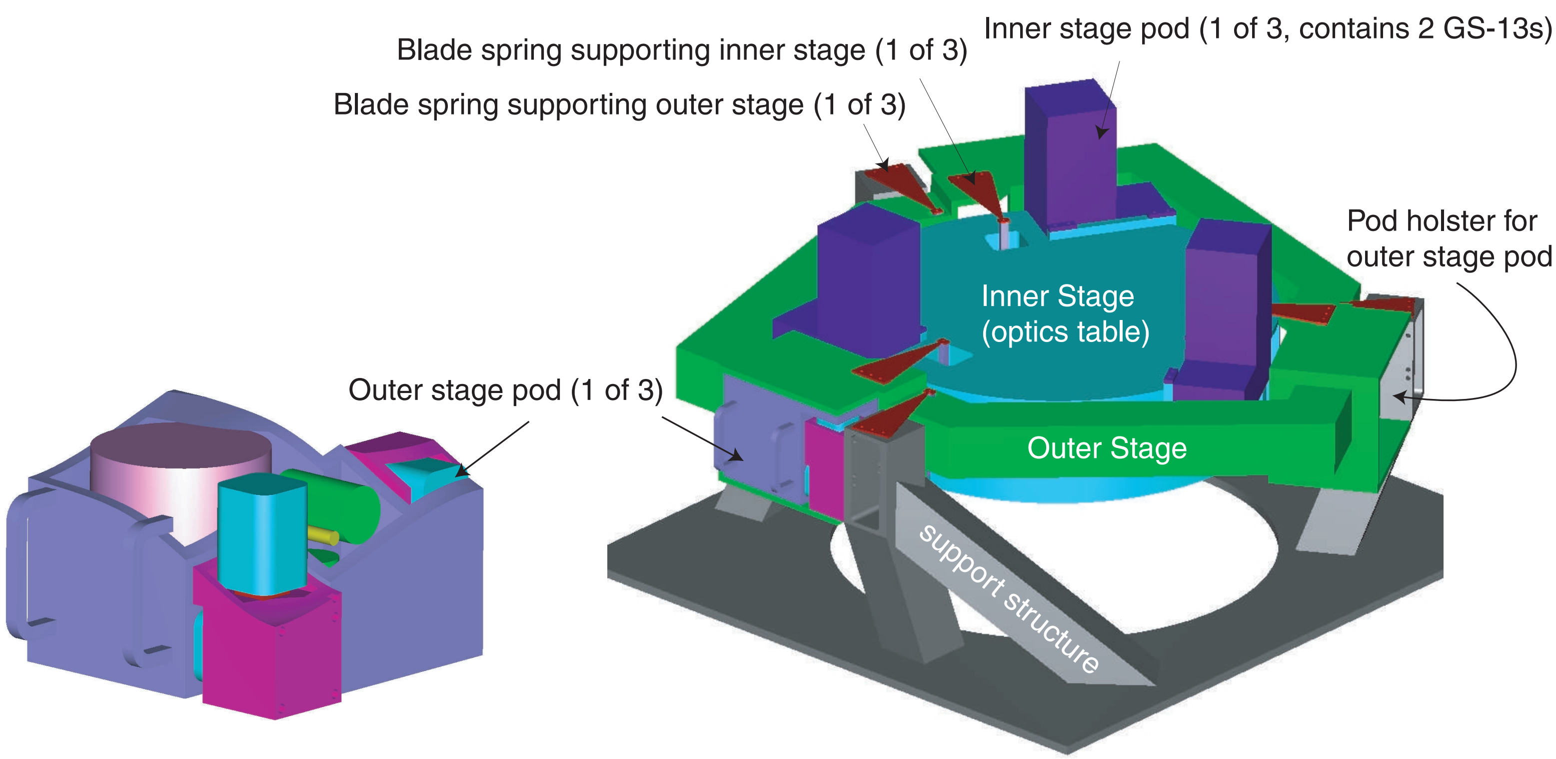


Figure 3: BSC version of the two-stage active platform.

BSC Design:

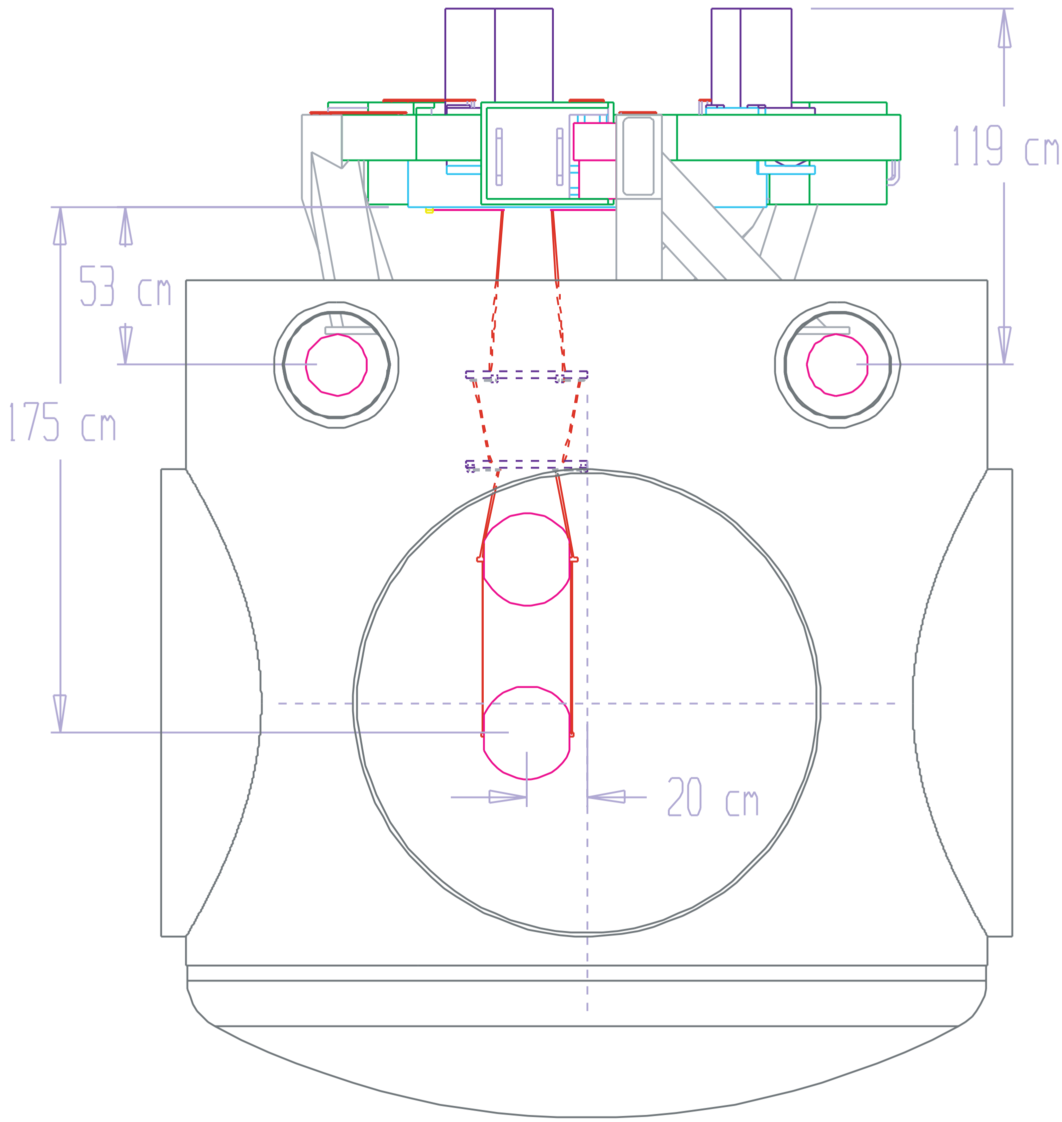


Figure 7: Elevation drawing of the baseline BSC chamber design, with GEO quadruple pendulum shown to scale.

HAM Two-stage active platform:

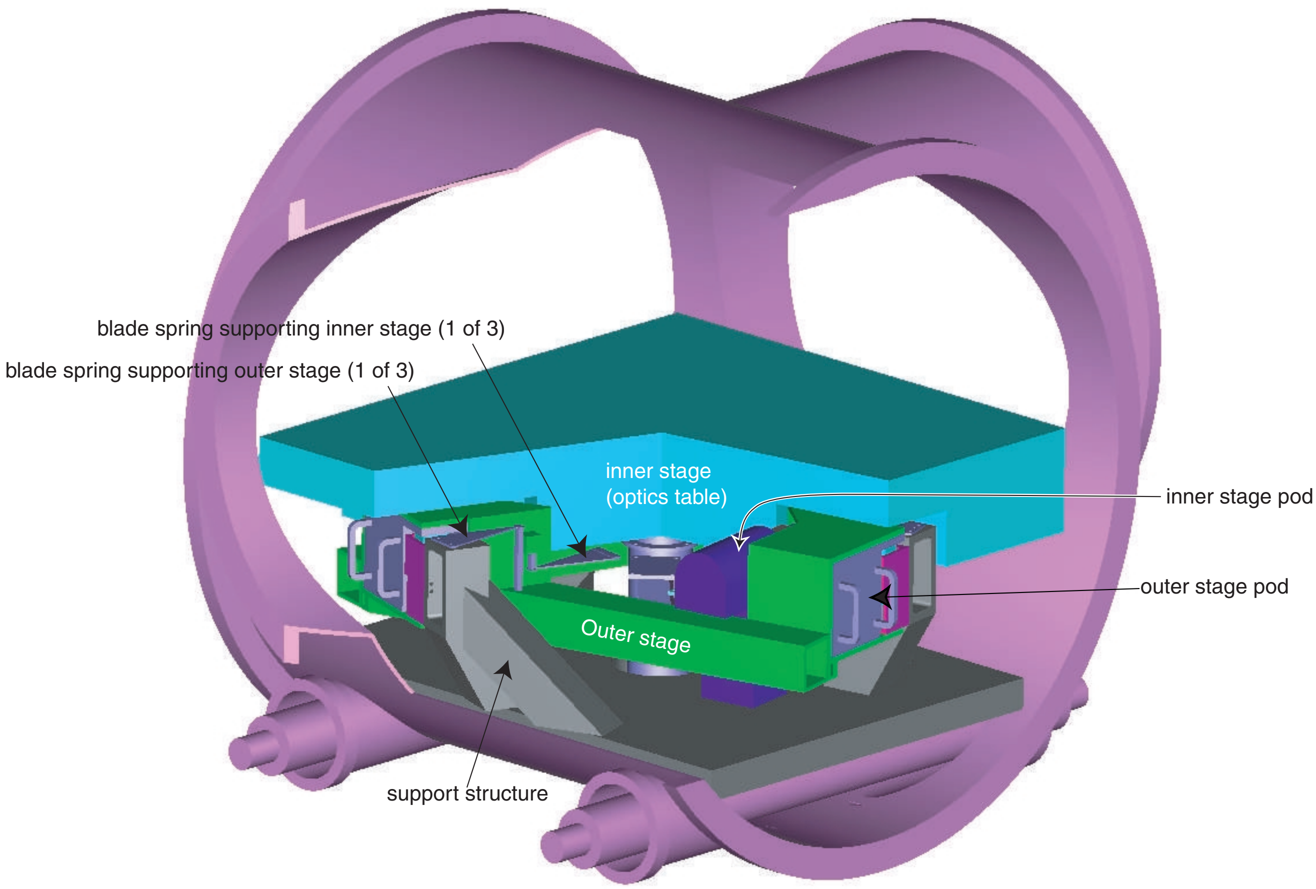


Figure 4: Rendering of the HAM design. Note that the instrumentation pods are positioned so that they are removable through the large HAM doors. The inner stage optics table (blue) is the same size as the table in LIGO-I, and in the same position.

HAM Design:

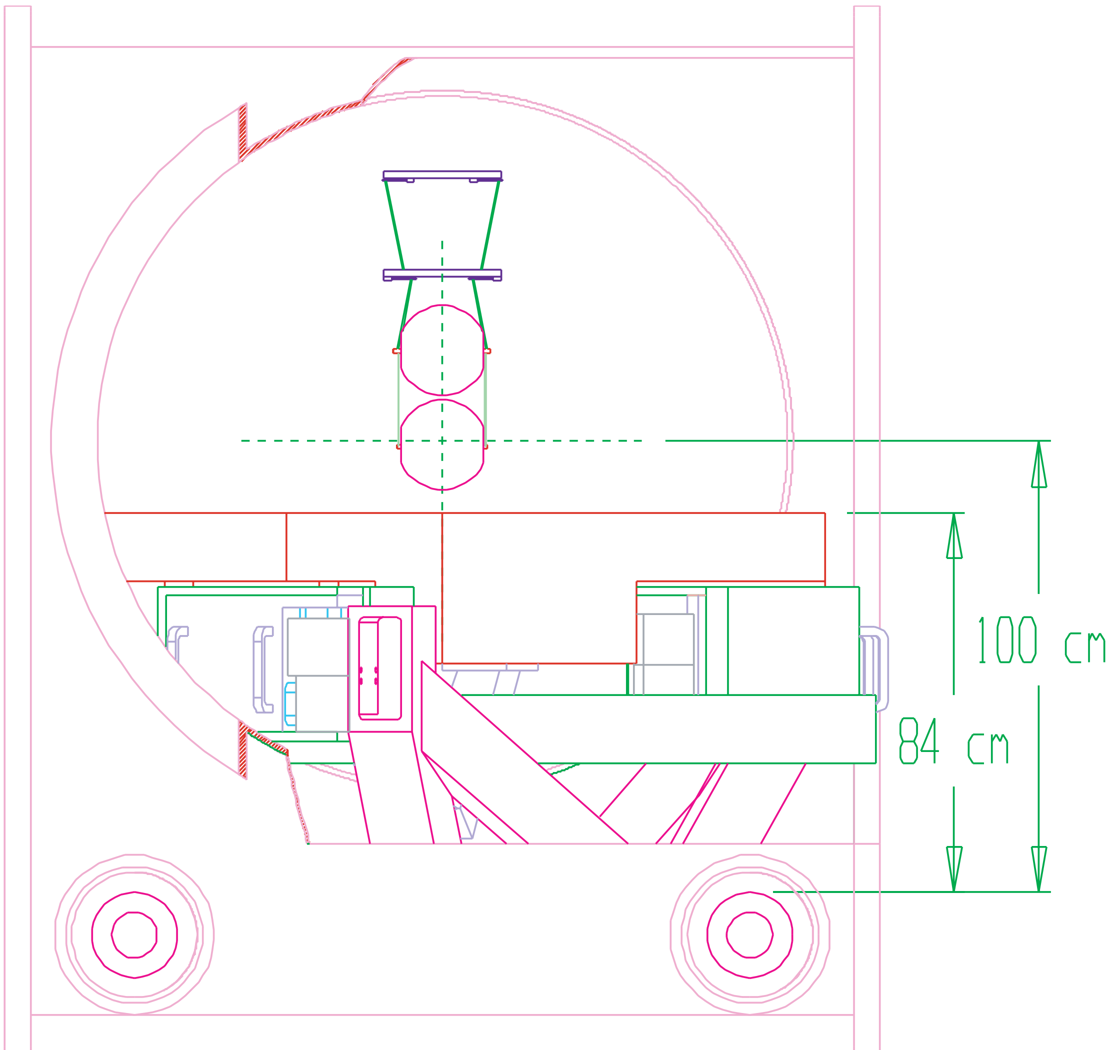


Figure 8: Elevation (cut-away) drawing of the baseline HAM chamber design. The dashed lines indicate beam center for a typical suspension position. The external hydraulic actuators are not shown here.

The Quiet Hydraulic Actuator.

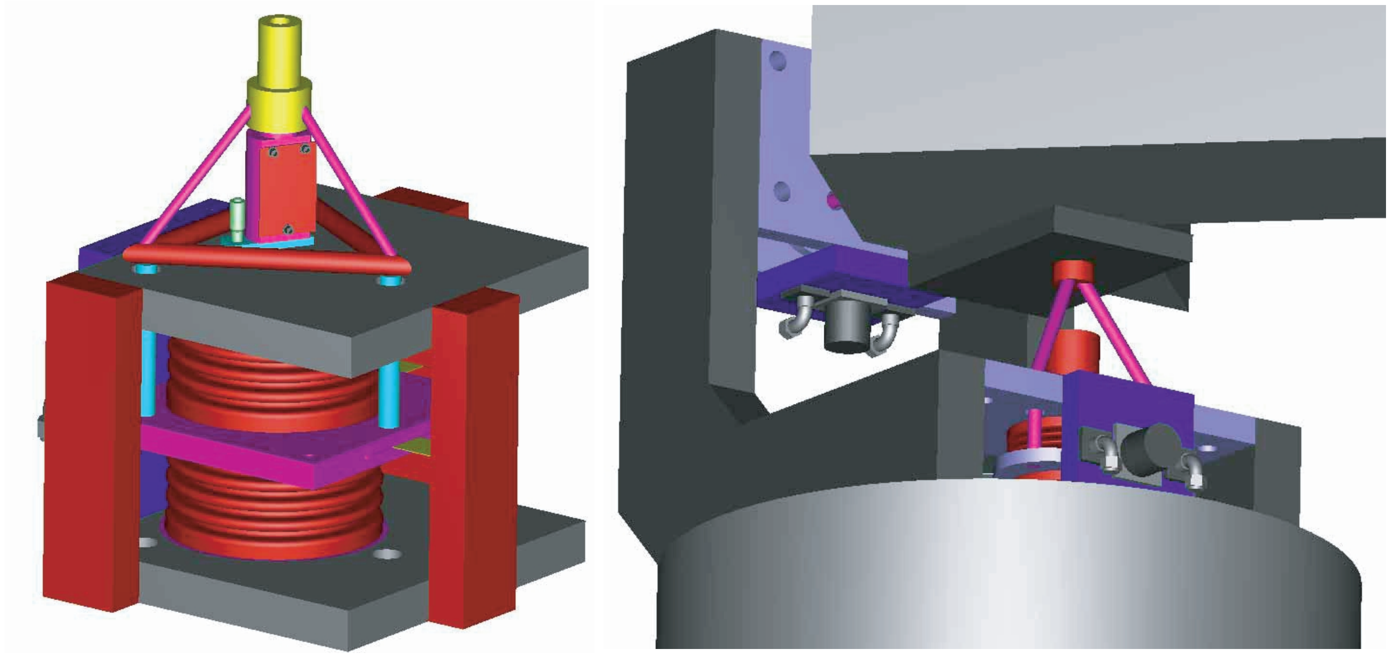


Figure 5: Hydraulic actuator will provide ± 1 mm, 2 Hz BW continuous actuation in 6 DOF. Each bellows assembly acts in 1 DOF; two DOF at each corner. Viscous fluid and remote pump assure quiet operation. Threaded connections to bellows assy will allow coarse actuation to 5 mm.

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.

Sensor Noise:

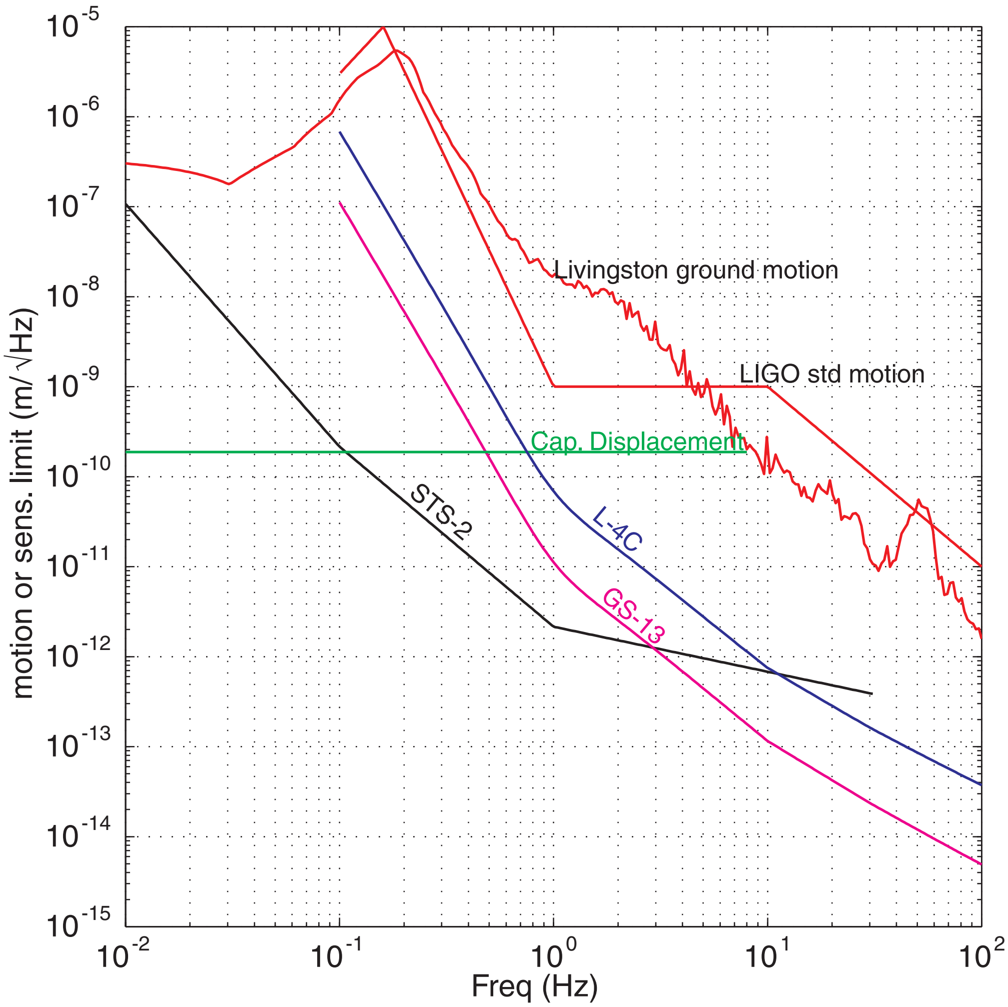


Figure 9: Displacement noise in various sensors used in the two-stage active isolation platform, compared with the LIGO standard ground noise and the measured noise at LLO.

Dynamic Model:

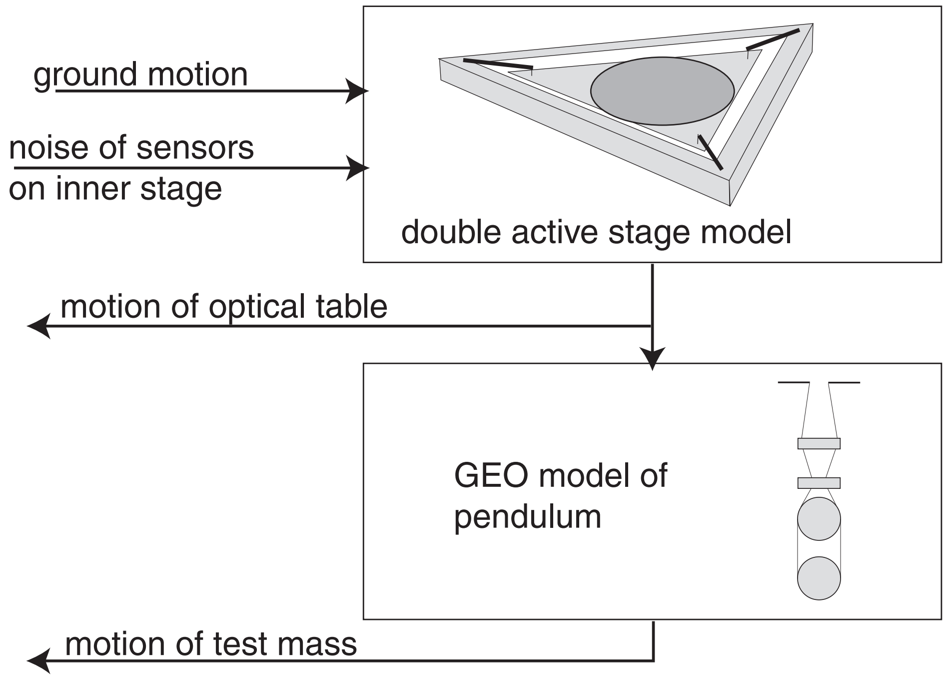


Figure 11: The Model results were generated in a two step process. First, the motion of the optical table was simulated using sensor noise and ground motion. The motion of the optical table was then used as an input to the GEO pendulum model to compute test mass motion.

Simulink Model Diagram:

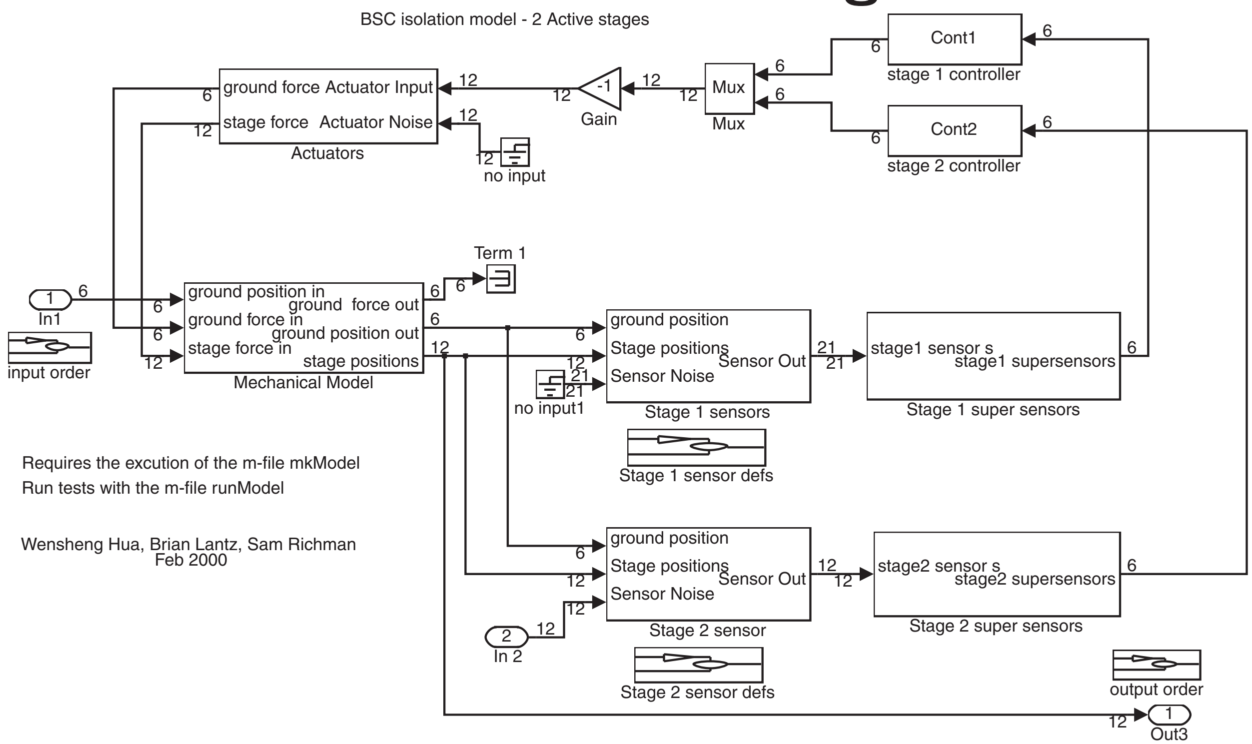


Figure 14: Model used to calculate the dynamics and servo compensation in the reference design two-stage active platform and to cross-compile the controller using the dSpace DSP hardware.

Test mass noise: two-stage platform and quad pendulum

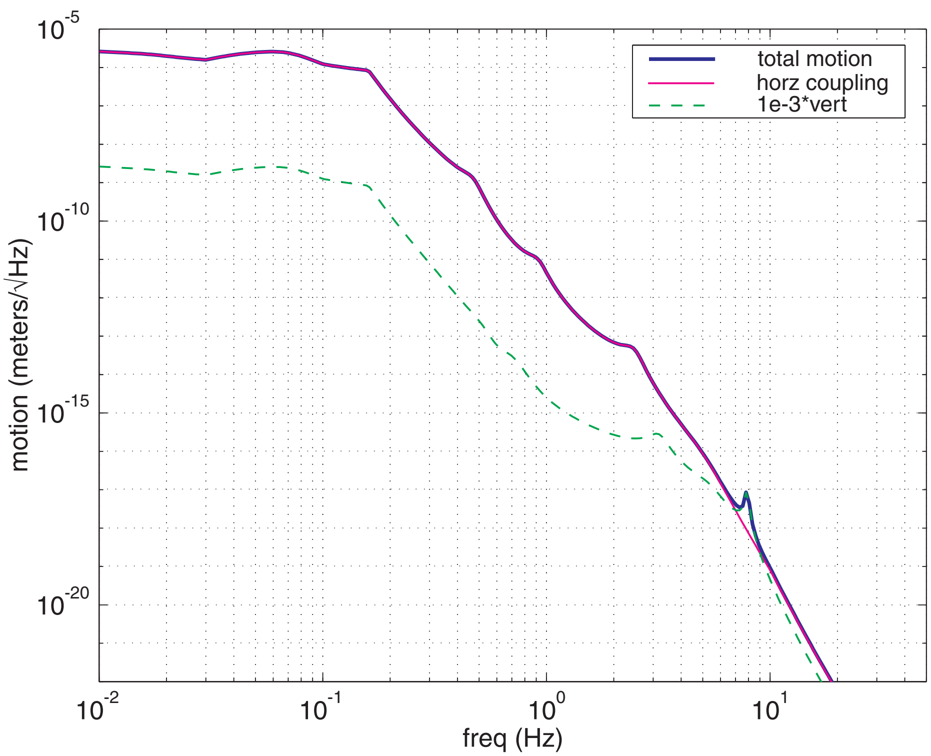


Figure 12: Motion the test mass (ITM and ETM), assuming local pendulum damping loops are on; this meets the requirement. Noise is lower with damping loops off, and still lower when feedforward stages are used.

Optics table noise performance:

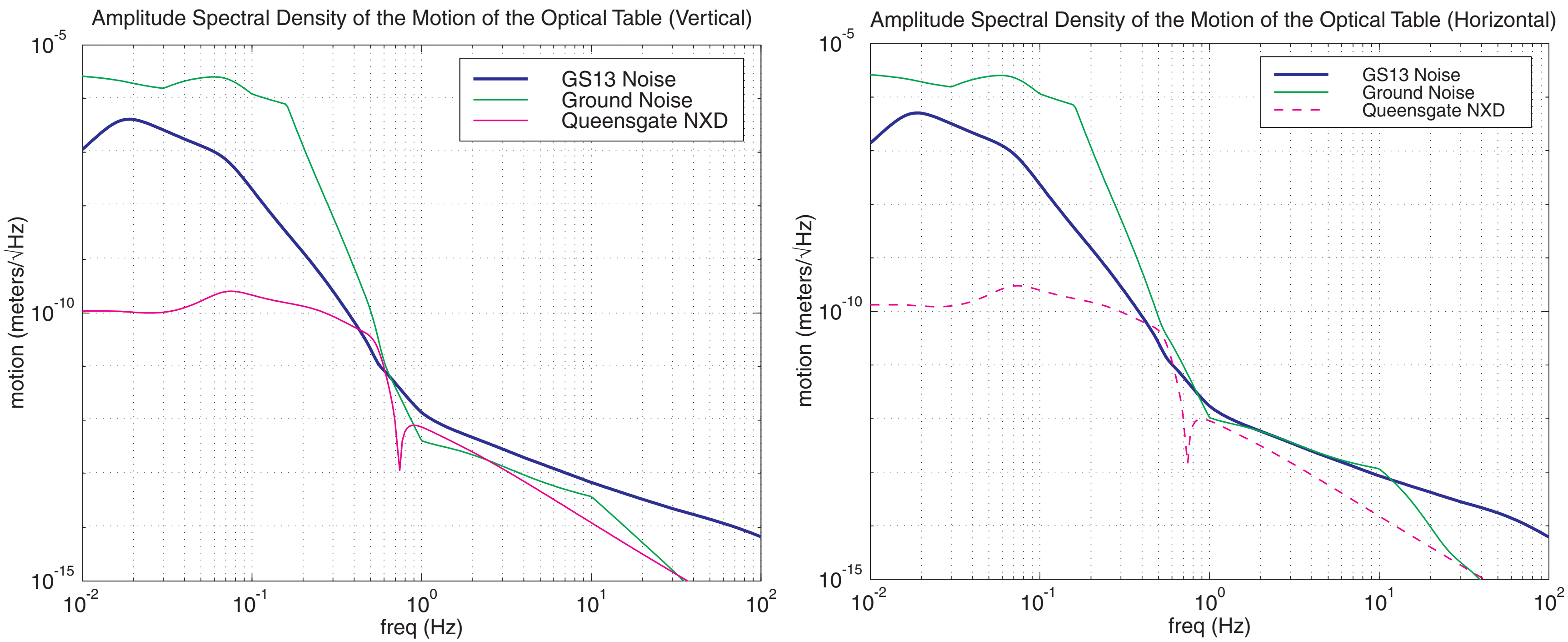


Figure 13: Performance of the two-stage active platform, without feedforward. Here we plot the contributions to the noise level at the SEI optics table, the suspension system mounting point.

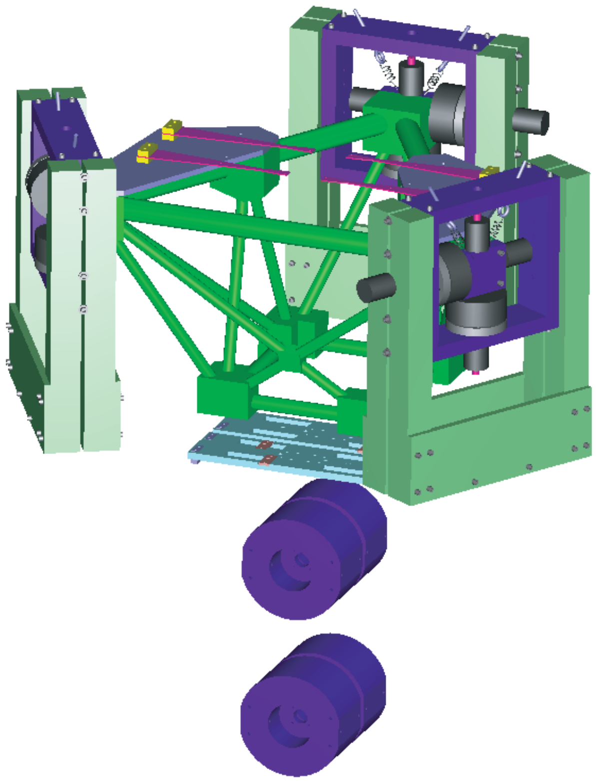
Stanford active platform with pendulum:

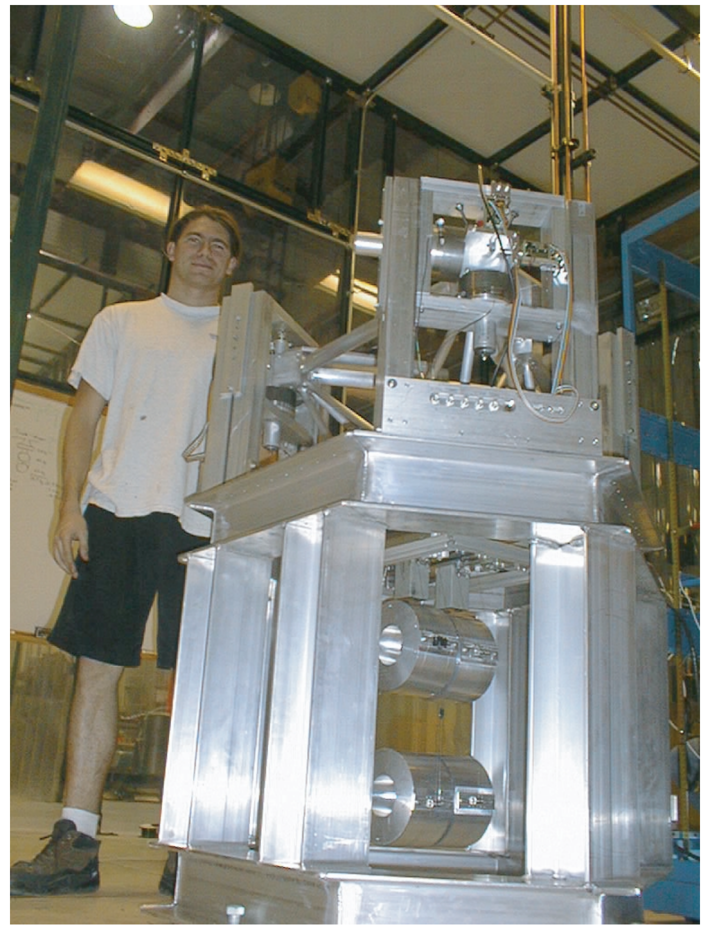
Experiment is underway at Stanford's Engineering Test Facility.

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.

Active platform plus triple pendulum (Stanford)





Two-stage active platform:

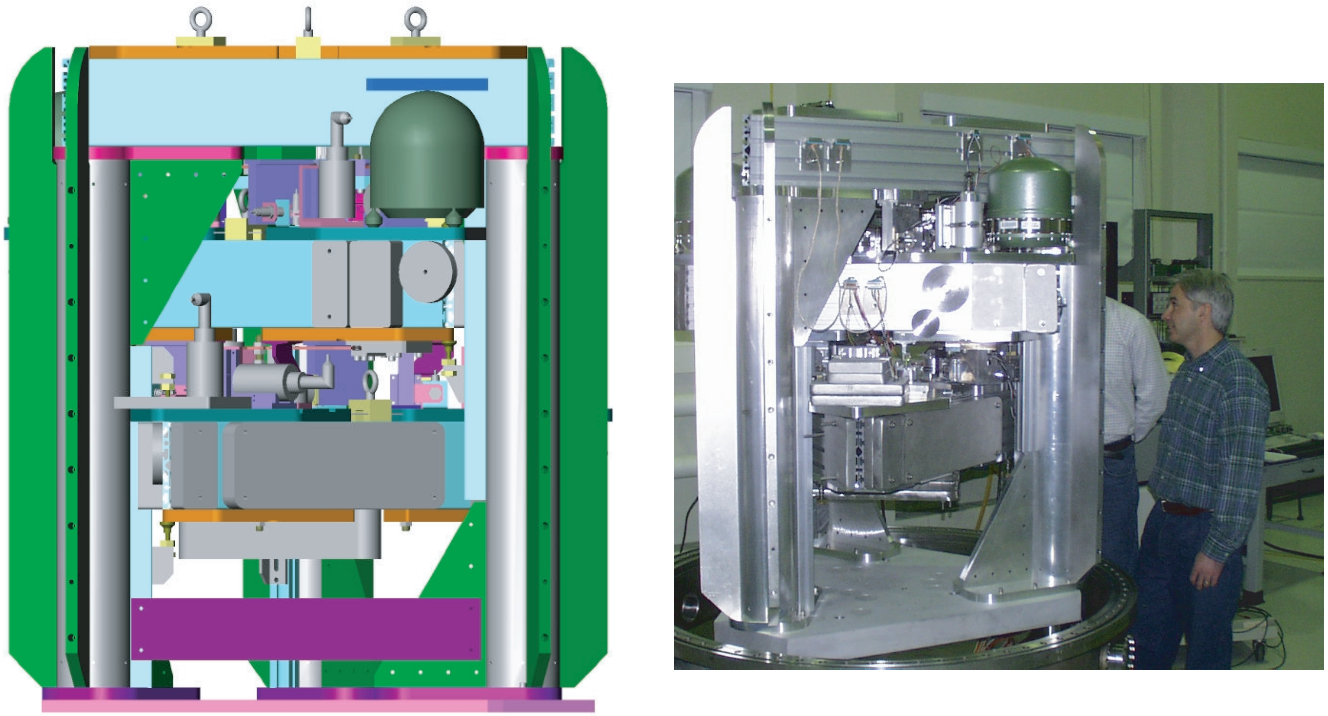
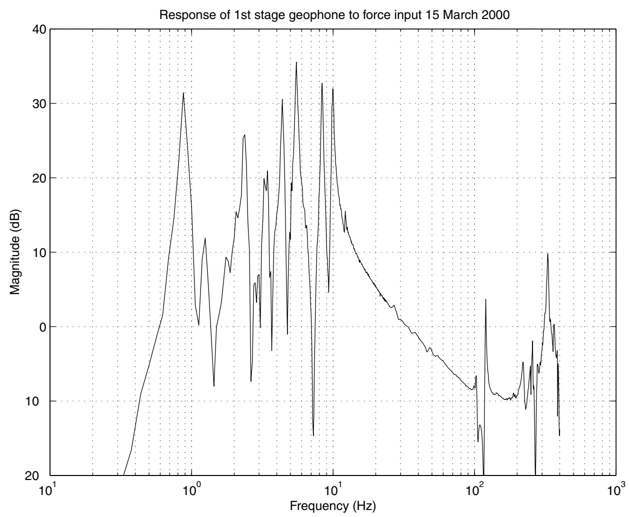


Figure 19: Rendering and installation. 3D mechanical model used to make parts and produce mass and moment inputs for compensation design.

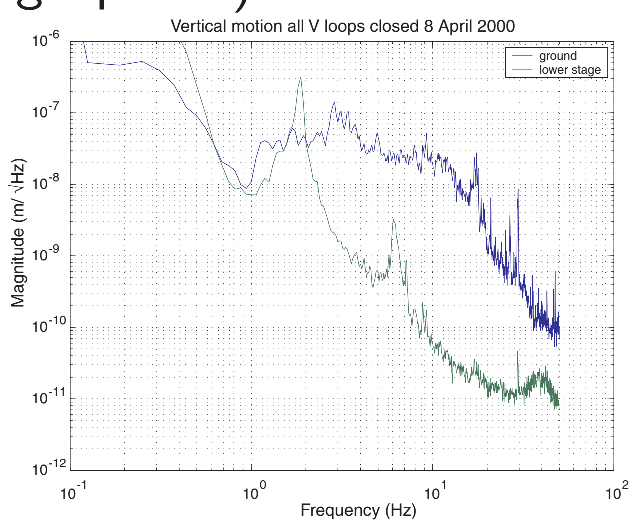
Two-layer active platform test:

- 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:



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



Vertical noise on floor and on inner stage, with geophones and position sensors in vertical loops. (6 DOF's closed, no STS-2 yet.)

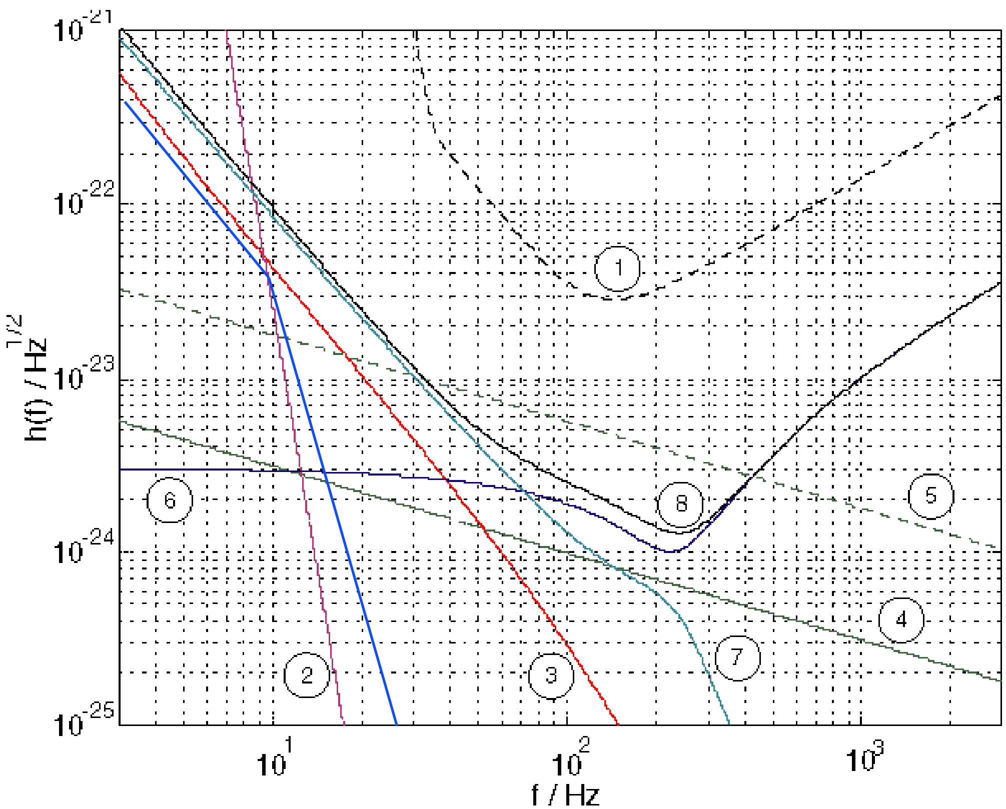
Stiff active SEI design advantages:

- 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.

Stiff Active Isolation approach

- **Update since these slides were prepared**:
  - » All transfer functions measured (each sensor to each actuator) with the objective of forming a complete multiple-input multiple-output control matrix; in analysis by Jonathan How
  - » Long-term drift information extracted from data: motion in horizontal and vertical less than 10 microns over 1.5 months, over ~3degC, and in air (thus with the potential for considerable temperature gradients)
  - » The manufacturer of the wideband seismometer has given 300,000 hours (34 years) for the MTBF in this application
- To note:
  - » Team is geographically distributed; both complicated and rich
    - – Richman, How: MIT; Giaime: LSU; Lantz: Stanford; Stebbins: JILA
  - » complete performance not yet demonstrated: true for any system

Noise Anatomy of LIGO II



1 LIGO I total
2 Filtered seismic noise
3 Suspension thermal noise
4 Internal thermal noise - sapphire
5 Internal thermal noise - fused silica (fallback)
6 Shot noise
7 Radiation pressure noise
8 LIGO II total