LIGO II SEISMIC ISOLATION SUBSYSTEM (SEI) DESIGN REQUIREMENTS REVIEW

January 24, 2001

Agenda:

1. Requirements, 30 min (Peter F)
2. Conceptual design, 1 hr (Joe G, Brian L)

COMMITTEE[1] CHARGE

- ❑ Evaluate requirements:
  - are they complete?
  - are the values appropriate?
- ❑ Evaluate conceptual design
  - is it consistent with the requirements?
  - practicality of design ... appropriate tradeoffs of performance and risk?
- ❑ Evaluate testing plan

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FUNCTIONS & CONSTRAINTS

- ❑ Vibration isolation (isolated platforms):
  - provides roughly 1/3 of the total isolation at 10 Hz
  - provides essentially all the isolation in the control band, f<10 Hz
- ❑ Payload support: adequate space, interfaces, load capability, counter-weights for balancing
- ❑ Coarse positioning of the isolated platforms
- ❑ External actuation for interferometer controls
- ❑ In-vacuum cabling: power & signals for
- ❑ Vacuum compatibility of materials
- ❑ Fit in existing chambers; reuse piers & tubes

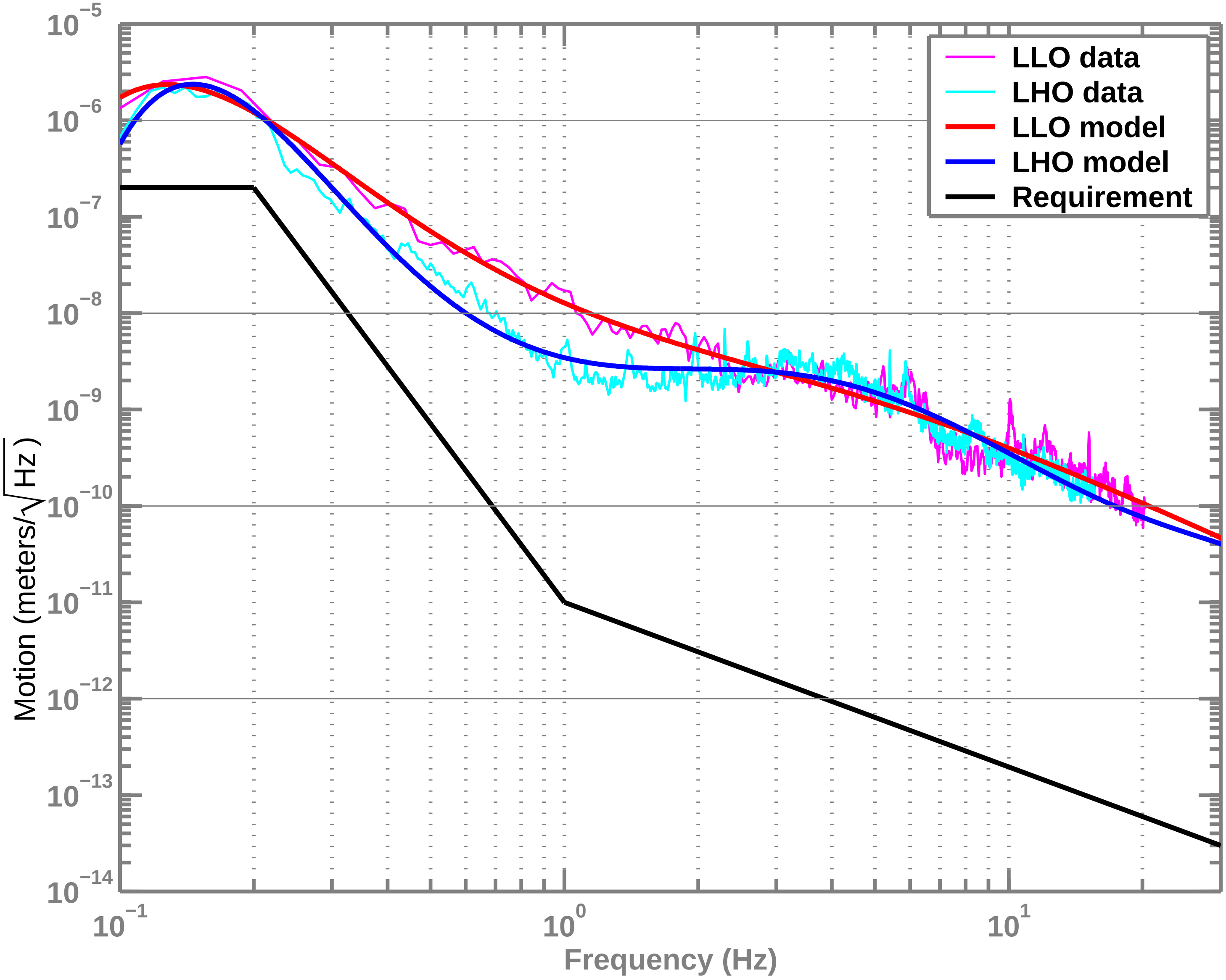
ISOLATED PLATFORM

- ❑ Payload: 800 kg
  - to be updated pending a detailed load study; quad pendulum w/ 40 kg TM and full reaction chain: 400 kg
- ❑ Platform size & height

SEI type	*Platform size*	*Platform height (LIGO global z-coordinate)*		*Comments*
		Nominal height	*Potential Range*	
BSC	1.5m diam.	1540 mm	1470–1800 mm	Minimum height for quad suspension w/ beam centerline on ITMs at -213 mm
HAM	1.9m × 1.7m	–315 mm	0	Must be low to accommodate triple suspension

- ❑ Initial positioning: within ±0.5 mm of nominal height

ISOLATION PERFORMANCE



ISOLATION PERFORMANCE

- ❏ Displacement input and requirement is the same in all 3 directions
  - vertical motion must be low to make up for weaker vertical isolation in the suspensions (could be relaxed below a few Hz)
  - transverse horizontal motion requirement could be relaxed if merited
- ❏ 10 Hz: 2×10^{-13} m/rHz
  - vs 10^{-19} m/rHz for BSC/test masses: need $>2\text{x}10^{6}$ isolation from quad suspension
    - ➢ $5\text{x}10^{6}$ along optic axis for long suspension
    - ➢ $3\text{x}10^{3}$ vertically, with 10^{-3} cross-coupling
  - vs $3\text{x}10^{-17}$ m/rHz for HAM optics: need $>7\text{x}10^{3}$ isolation from triple suspension
    - ➢ $3\text{x}10^{4}$ along optic axis; $3\text{x}10^{2}$ vertically

ISOLATION PERFORMANCE

- ☐ 1–10 Hz band: not a 'hard' requirement
  - want to enable ~1 Hz bandwidth loops for auxiliary degrees-of-freedom of the interferometer
  - SEI requirement corresponds to $\sim 10^{-11}$ m-rms
- ☐ Above 30 Hz: broadband noise: $<3\times10^{-14}$ m/rHz
  - internal resonances must be above 100 Hz
  - limits to {Q's, f's} to be developed with suspensions
- ☐ Angular degrees-of-freedom:
  - must not compromise 10^{-19} m/rHz requirement
  - should be less than suspension angular thermal noise above 10 Hz
  - rms angular fluctuations: $<10^{-8}$ rad in $1 < f < 30$ Hz band

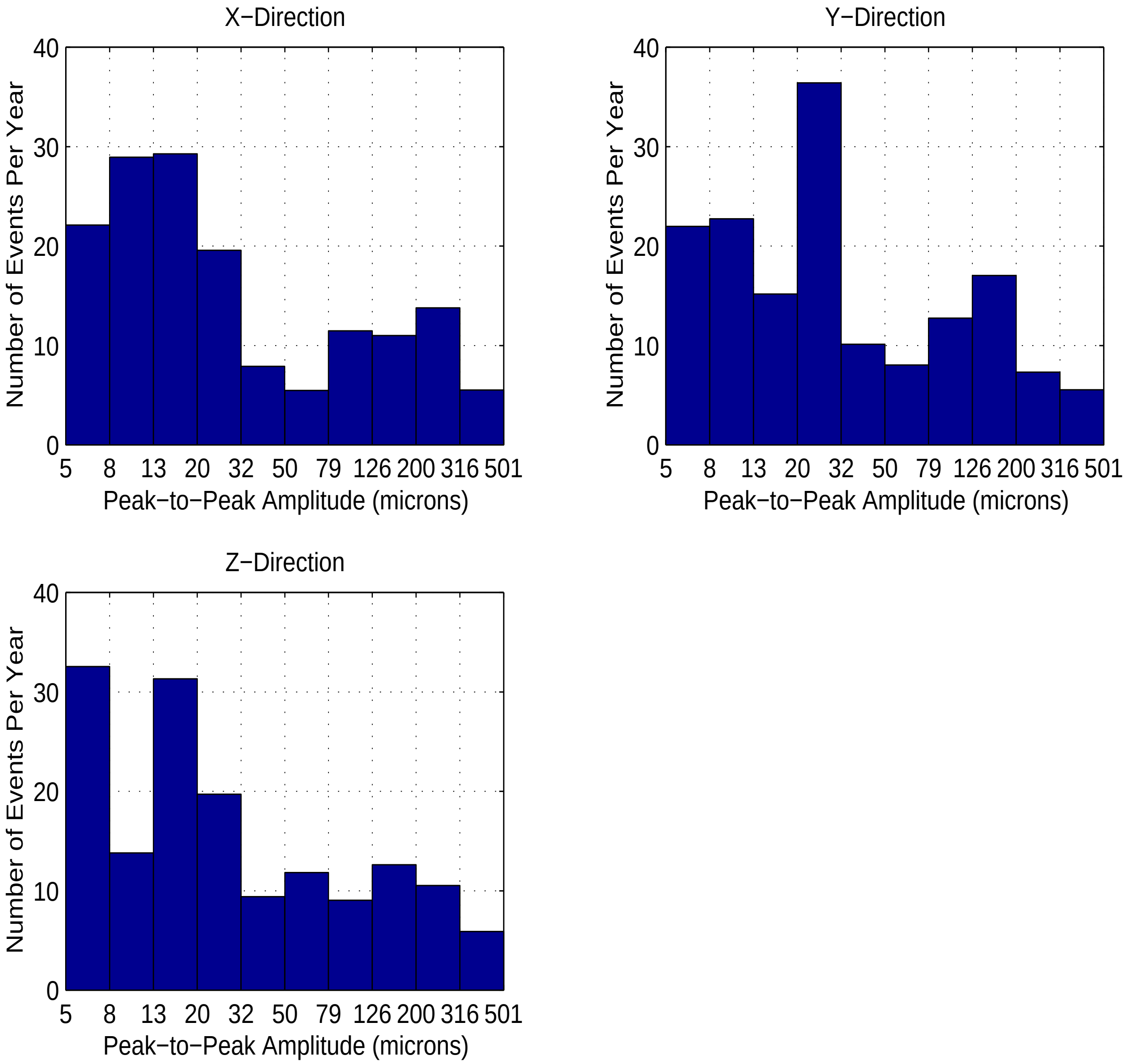
MICROSEISMIC BAND, 0.1-0.3 Hz

- ❑ Input
  - average level of microseismic peak expected to be ~1 micron-rms (models are 0.6-0.7 micron-rms)
  - variation over the year is under study at the two sites
  - maximum level the system must be able to handle (no saturation): 40 microns pk-pk
- ❑ Suppression required
  - factor of 5 – 10 suppression, to ~0.1 micron-rms
  - open issue: suppression of each chamber platform vs suppression of arm length only
    - ➢each chamber: leaves pieces of the interferometer not mounted on the isolated platforms (laser source; photodetectors; baffles) moving with respect to the rest ⇒ upconversion of scattered light; a 5 micron peak relative motion produces a maximum frequency of 10 Hz
    - ➢ arm length only: feedforward suppression only; probably more limited suppression than feedback

EARTHQUAKES

- ❑ Small, frequent (several times per week):
  - • don't significantly increase rms ground motion above the microseism
  - • increase noise in ~0.4 – 3 Hz band by a factor of 10-100
  - • SEI system should not saturate with such an input; response should be characterized with modeling & measurement
- ❑ Larger, rarer events (~1 per week)
  - • increase the rms above the microseism level
  - • typical motion timescale, 20-30 seconds, lasting for minutes
  - • SEI system should function without saturation for all but the rarest events
    - ➢ 500 micron pk-pk input at 20-30 second period

Estimated Yearly Rate of Earthquake-Induced Peak Ground Motions at Hanford



Averages of rates for 5 seismometers (LVEA, MX, MY, EX and EY) calculated from velocity-spectra. Rates were estimated from 47 earthquakes over 6 months using dead-time estimates for instrument and data acquisition down-time and for USGS email report fractions.

Ground motions for the 4 quakes that knocked us out of lock during E2 were less than 10 microns.

EXTERNAL ACTUATION

- ❑ Tidal arm stretching; estimates for 2001:

Tidal component	*Maximum pk-pk stretching, microns*		*Overall maximum, multiplied by 1.2, microns*
	LHO	*LLO*	
Differential mode	100–110		130
Common mode	180	200–210	250
Single arm		260	310

  - must be able to track differential component: ±90 μm range along optic axis; time constant less than 10 minutes; required for end/mid station systems only

- ❑ Microseismic correction:
  - ±10 μm range along optic axis; time constant, <0.1 sec; end/ mid station systems only

- ❑ Coarse positioning of isolated platform
  - ±1 mm in vert. & transverse horiz.; ±0.25 mrad about vert.
  - used only in ‘off-line’ mode; compensation of errors or drift

MISCELLANEOUS

- ❑ Operational modes & startup
  - design should be flexible to allow different modes of operation (trading off stability for isolation, eg)
  - initial startup less than a few hours; power down to operational less than ~30 minutes
- ❑ Field emission: interaction with suspension magnets must be addressed
- ❑ Drift & thermal expansion:
  - less than 0.1 mm in translation and 100 microrad in angle over any 30 day period

MISCELLANEOUS

❑ Power & signal transmission: supplied by SEI

- vacuum compatible
- stiffness and mounting so as to not compromise isolation performance and not introduce sources of transients
- specification of cabling types and number TBD

❑ Diagnostics

- must include capability of determining SEI performance
- internal diagnostics
- interface to Global Diagnostics Subsystem

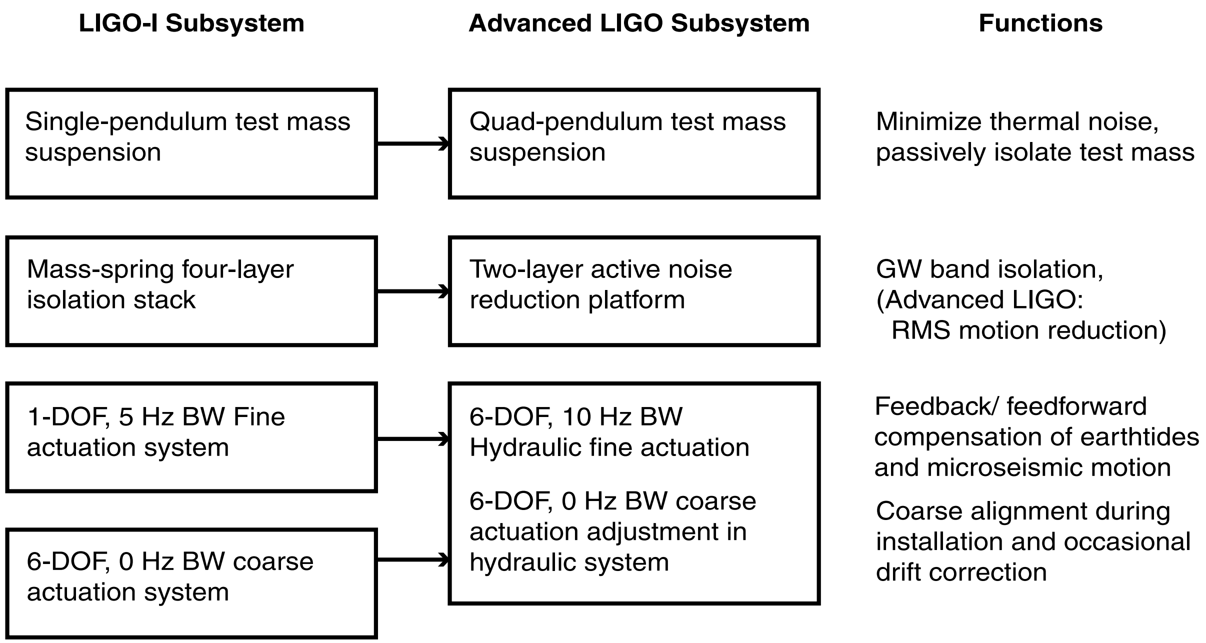
Advanced LIGO Seismic Isolation System Conceptual Design

By the Advanced LIGO Seismic Isolation Team members* at JILA, LLO, LSU, MIT, and Stanford

January 24, 2001 `LIGO-G010017-00-D`, part 2

*J. Giaime, B. Lantz, C. Hardham, W. Hua, R. Adhikari, G. Allen, S. Cowley, D. Debra, G. Hammond, J. Hammond, J. How, J. Nichol, S. Richman, J. Rollins, G. Stapfer, R. Stebbins,. . .

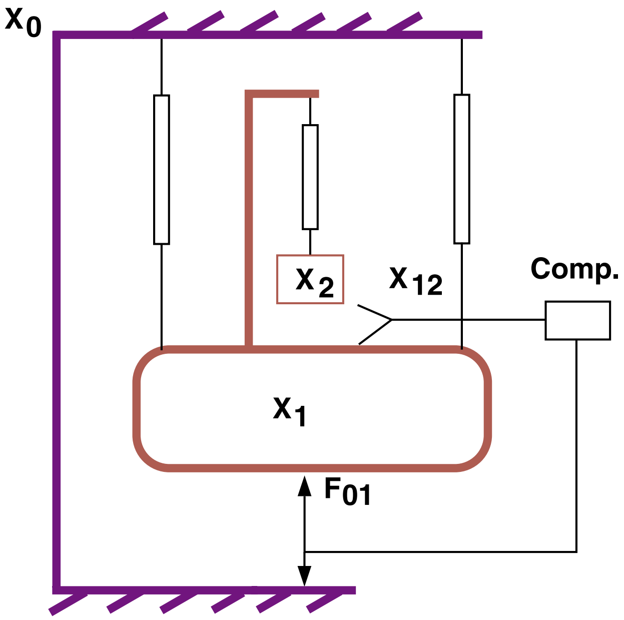
Functional Breakdown

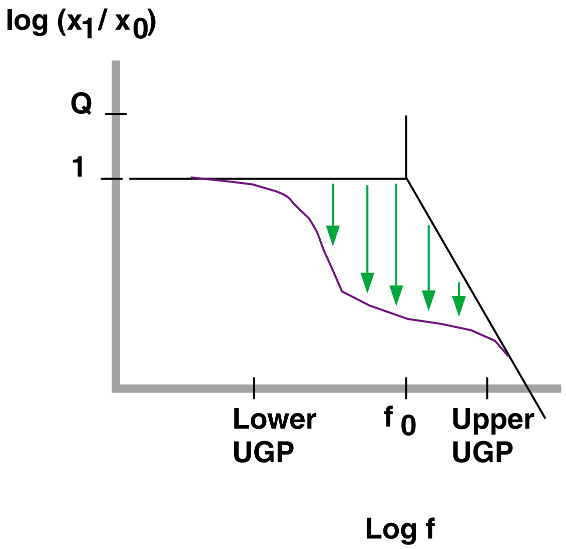


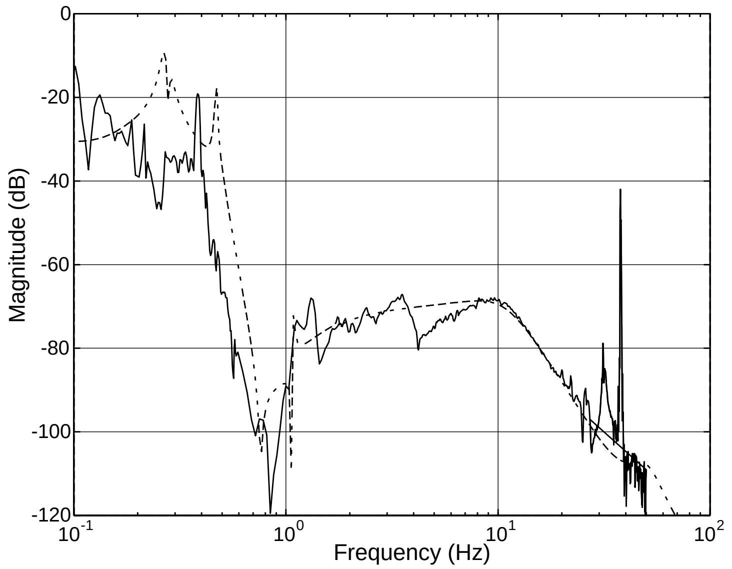
LIGO-I Subsystem	Advanced LIGO Subsystem	Functions
Single-pendulum test mass suspension	Quad-pendulum test mass suspension	Minimize thermal noise, passively isolate test mass
Mass-spring four-layer isolation stack	Two-layer active noise reduction platform	GW band isolation, (Advanced LIGO: RMS motion reduction)
1-DOF, 5 Hz BW Fine actuation system	6-DOF, 10 Hz BW Hydraulic fine actuation	Feedback/ feedforward compensation of earthtides and microseismic motion
6-DOF, 0 Hz BW coarse actuation system	6-DOF, 0 Hz BW coarse actuation adjustment in hydraulic system	Coarse alignment during installation and occasional drift correction

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

Active Seismic Isolation

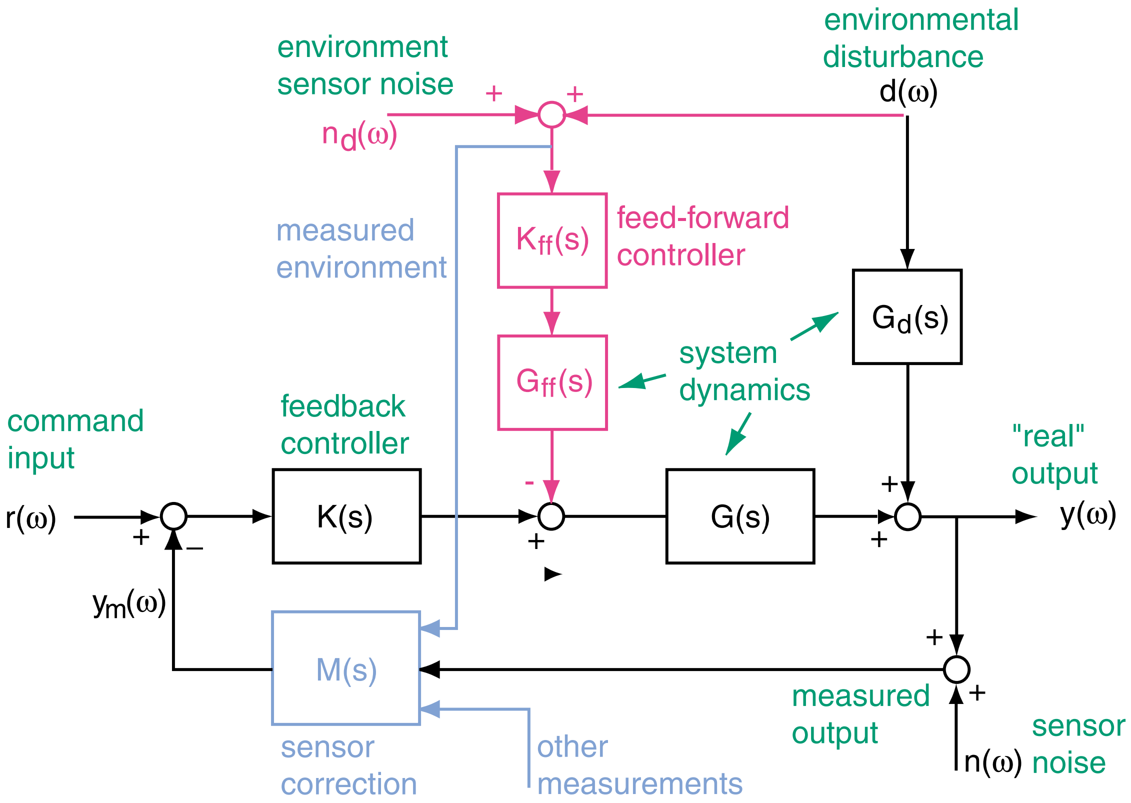






Active seismic isolation, with 1994 JILA results showing 70 dB of isolation.

Feedback, feed-forward, sensor correction

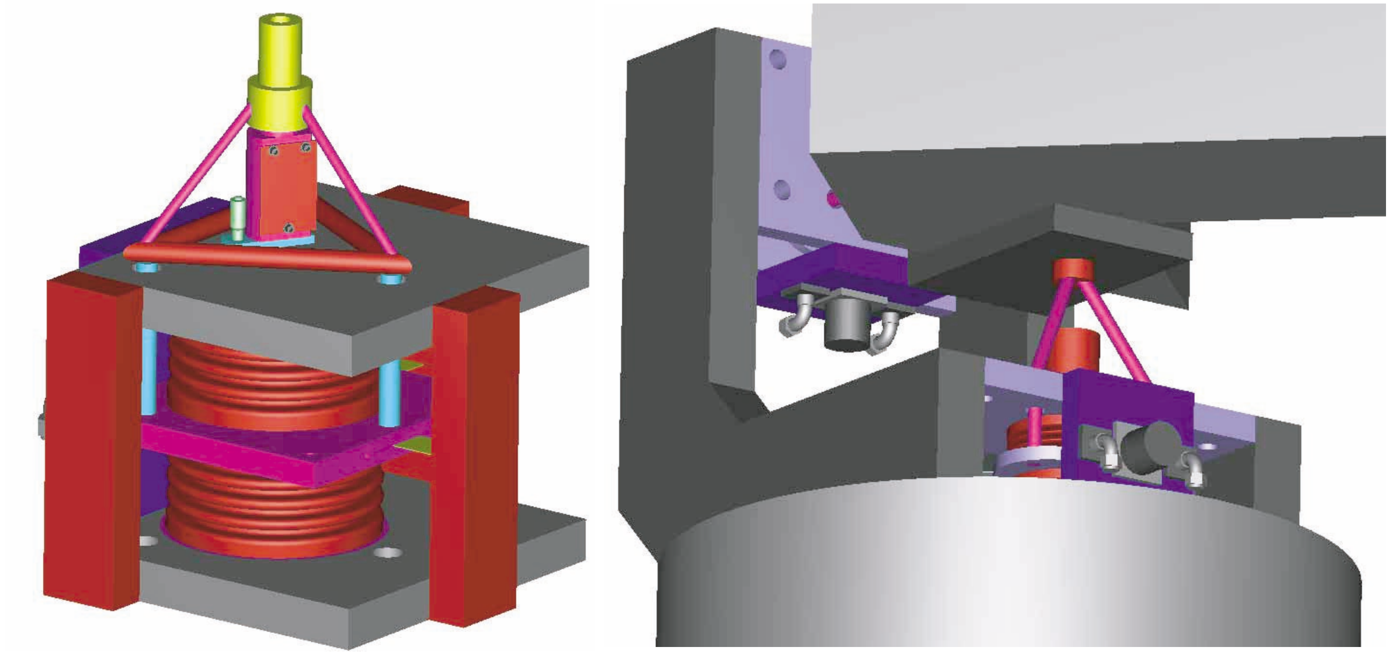


Feedback:

$$\begin{aligned} y \;=\; & (I+GK)^{-1}GK\,r && \text{command tracking} \\ & +(I+GK)^{-1}G_d\,d && \text{disturbance suppression} \\ & -(I+GK)^{-1}GK\,n. && \text{noise} \end{aligned}$$

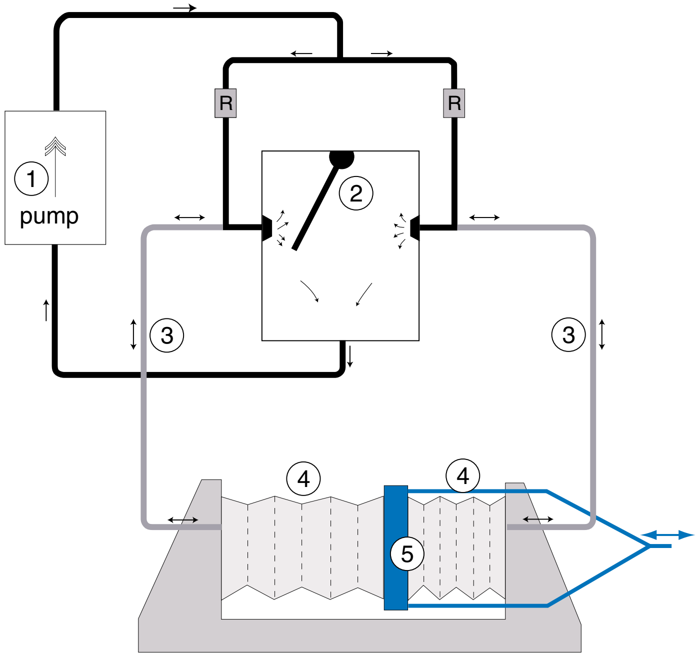
Feedforward: If $K_{ff}G_{ff}G = G_d$, environmental noise cancelled.

The Quiet Hydraulic Actuator.



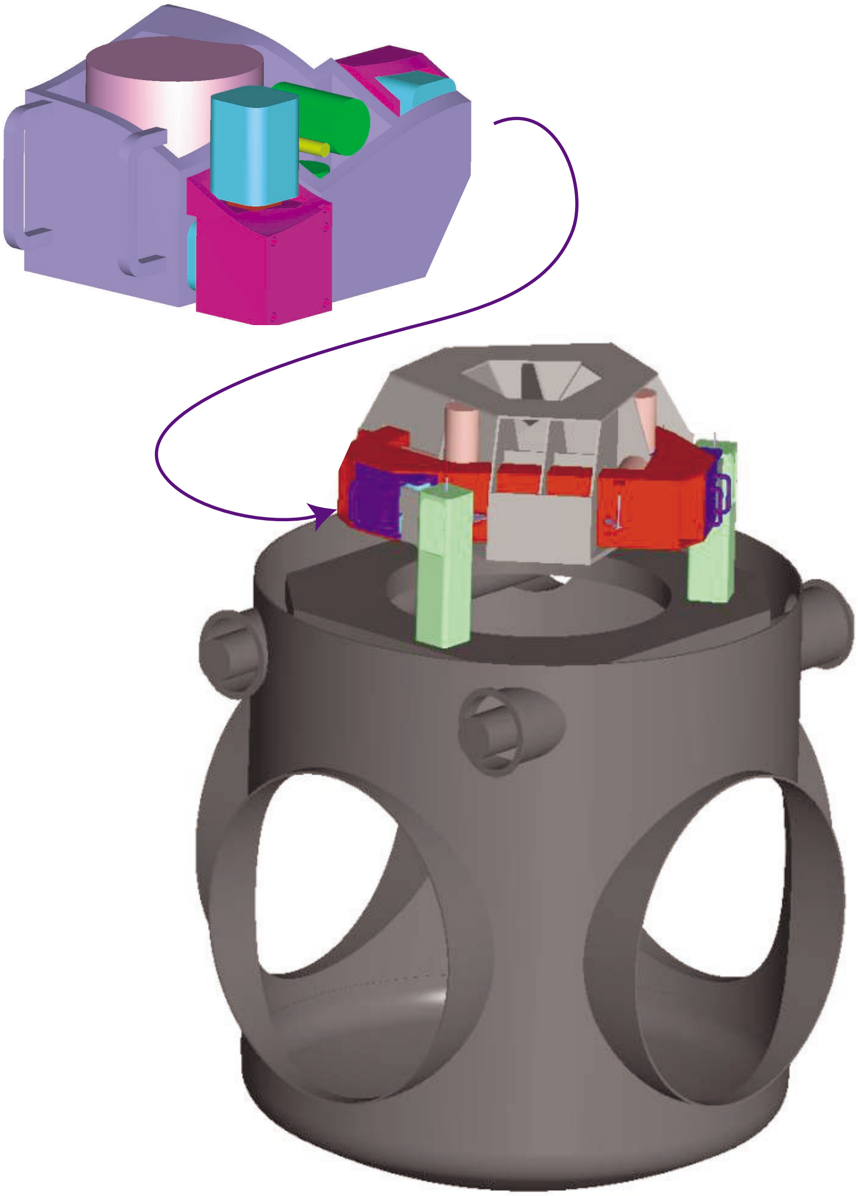
Hydraulic actuator will provide ±1 mm, 2 Hz BW continuous actuation in 6 DOF. Each bellows assembly acts in 1 DOF; two DOF at each corner. Viscous fluid and remote pump assure quiet operation.

Differential bellows:



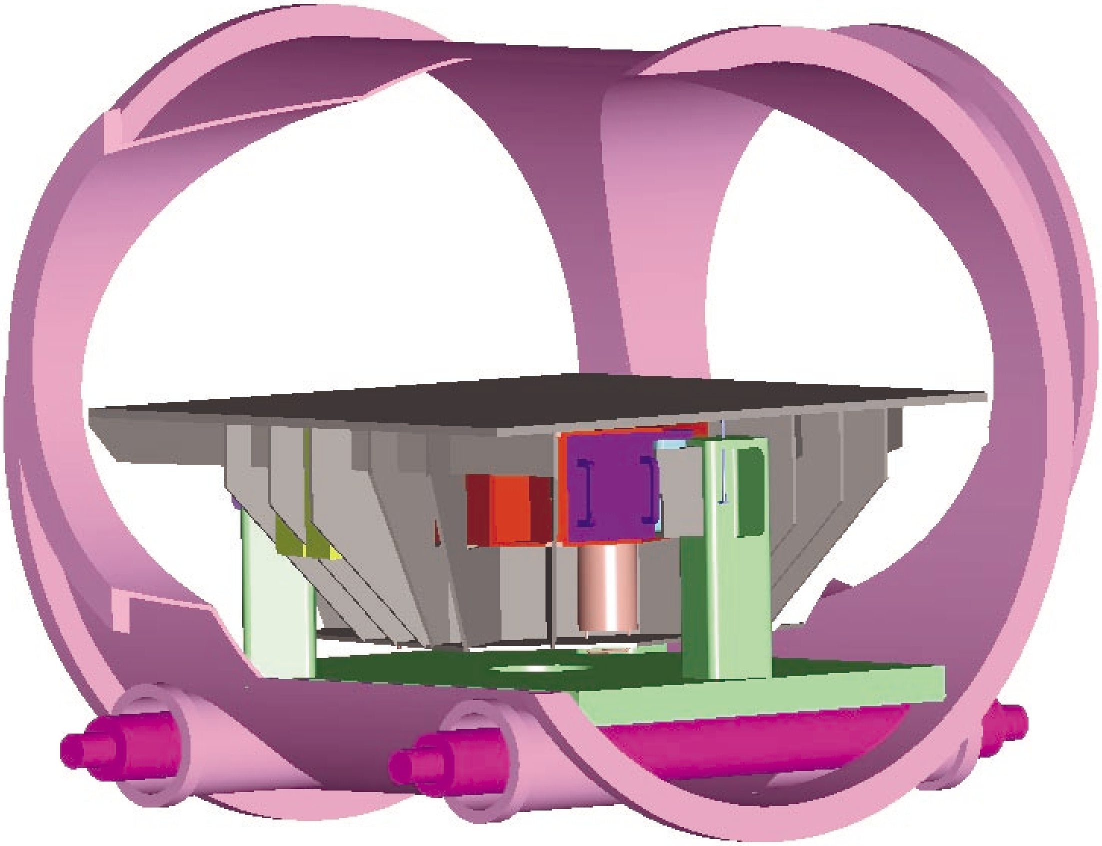
The control valve creates a pressure differential on the bellows. The middle plate is attached with flexures to both the base and the payload, only constraining motion in 1 DOF.

BSC Design



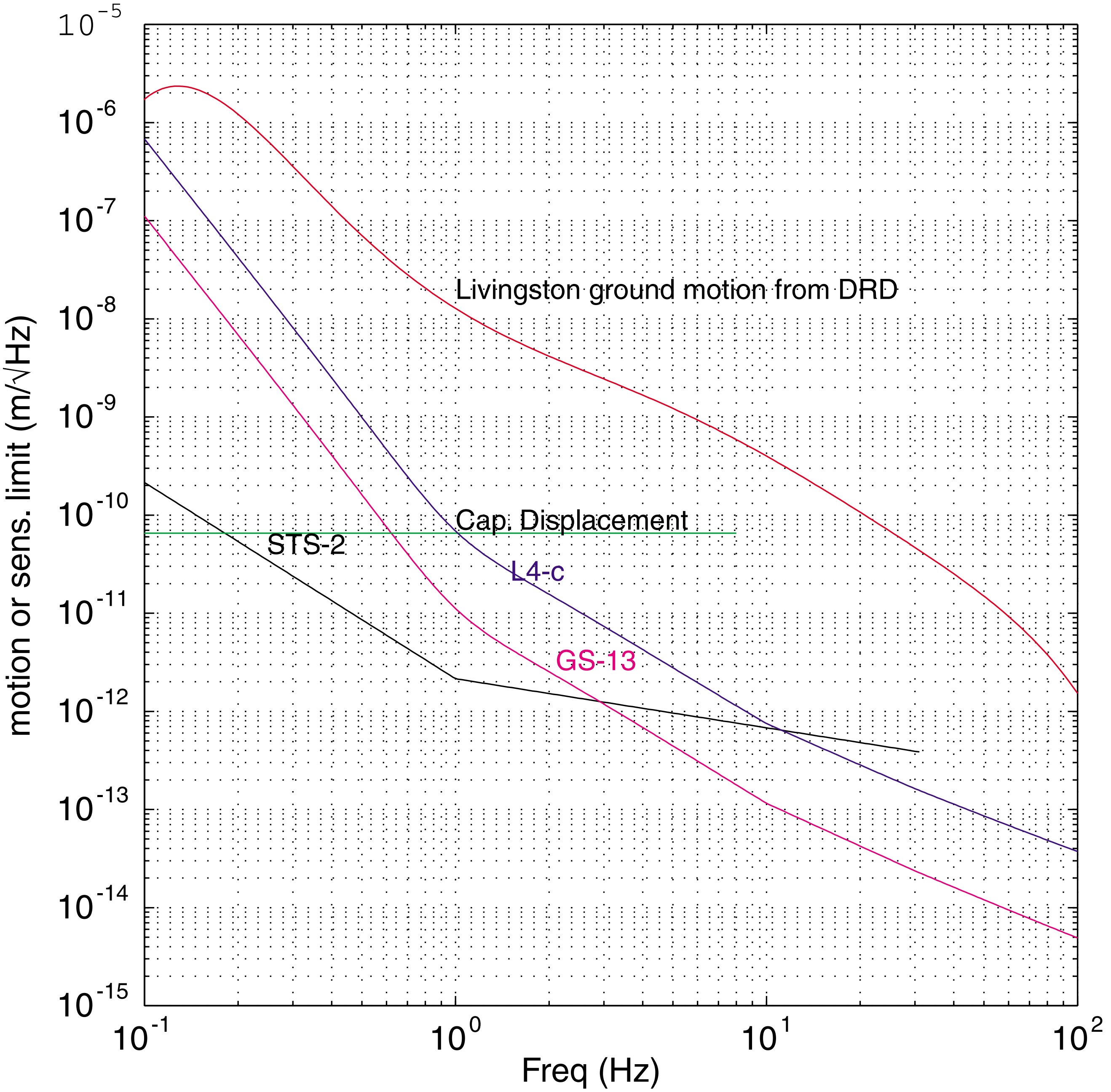
Rendering of BSC design of the two-stage active platform.

HAM Design



Rendering of the HAM design.

Sensor noise

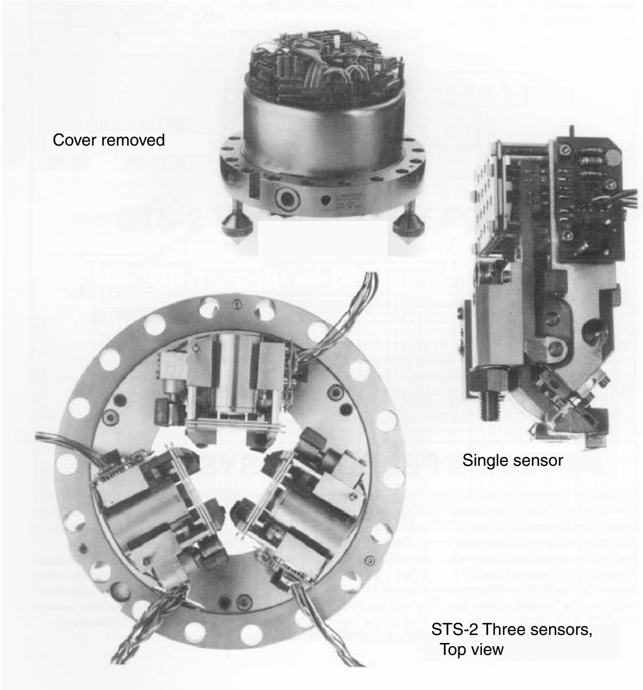


Sensors:

Capacitive Bridge Sensor: used to measure the relative displacement between adjacent SEI stages. Queensgate NXD or better.

Broadband Seismometer: used to measure velocity of the outer stage in the inertial frame, over 8 mHz - 50 Hz range. Streckeisen STS-2 is best choice.

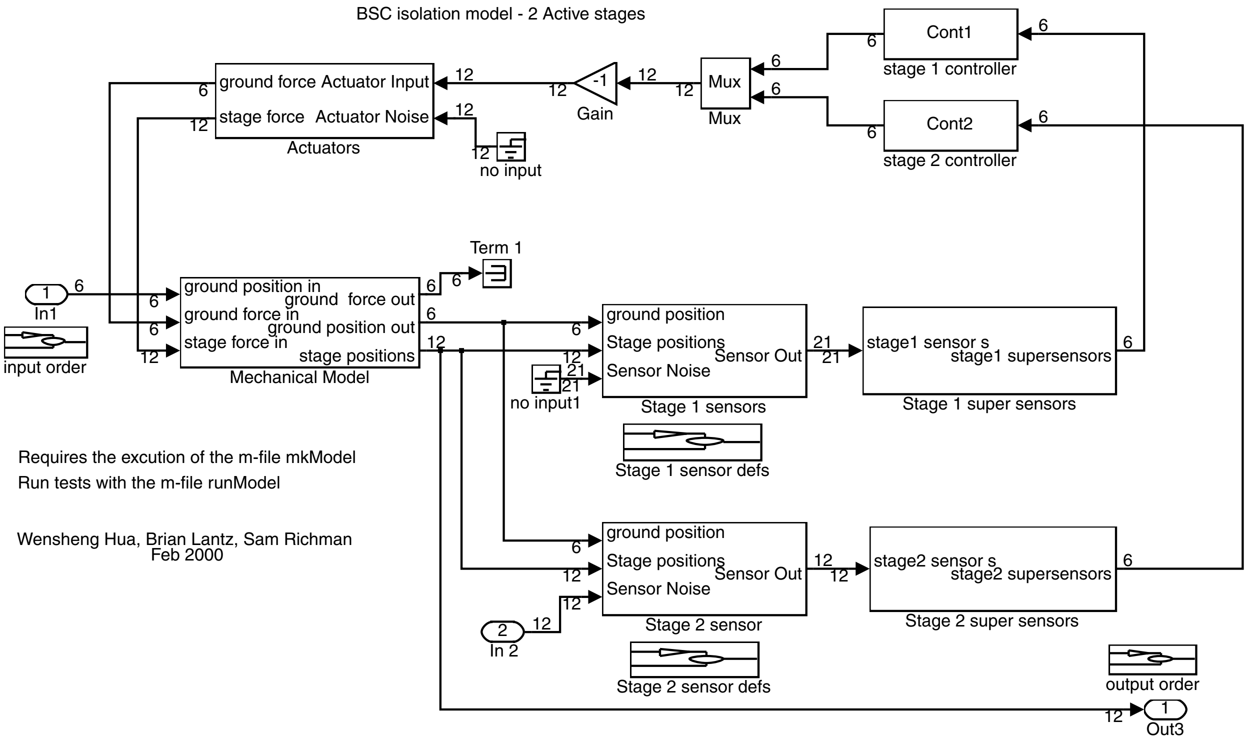
Geophone: used to measure velocity of the inner and outer stage in the inertial frame, over 1 Hz - 100 Hz range. Geotech GS-13 is best choice.



Actuators:

- voicecoil - permanent magnet non-contacting forcers
- rectangular coil in constant field on two sides, to minimize cross coupling.
- iron flux path, to minimize emission.
- good linearity.
- large (± 1 mm) gaps.
- Custom design, UHV compatibility under study at JILA.

Dynamic and noise model

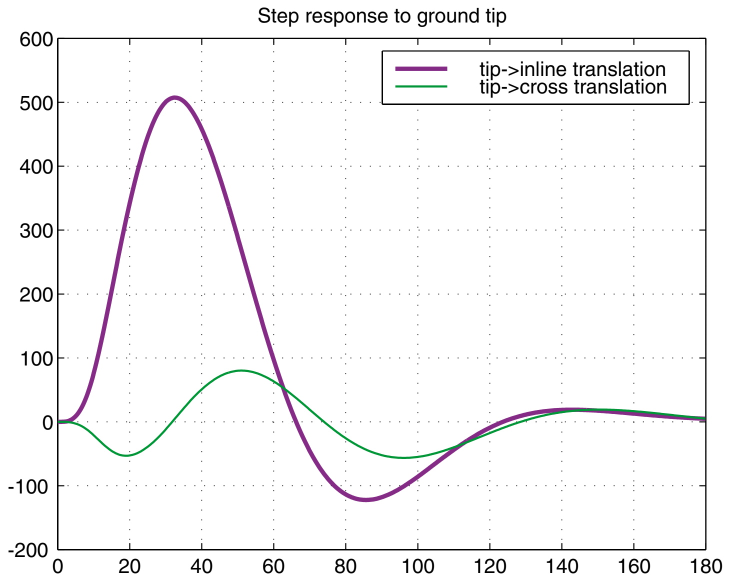


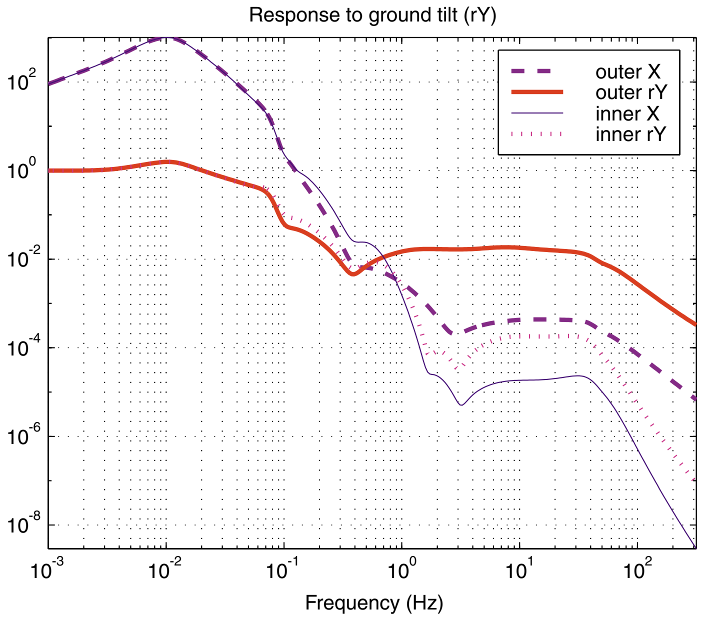
Simulink model used to calculate the dynamics, servo compensation, and noise propagation in the conceptual design two-stage active platform.

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.

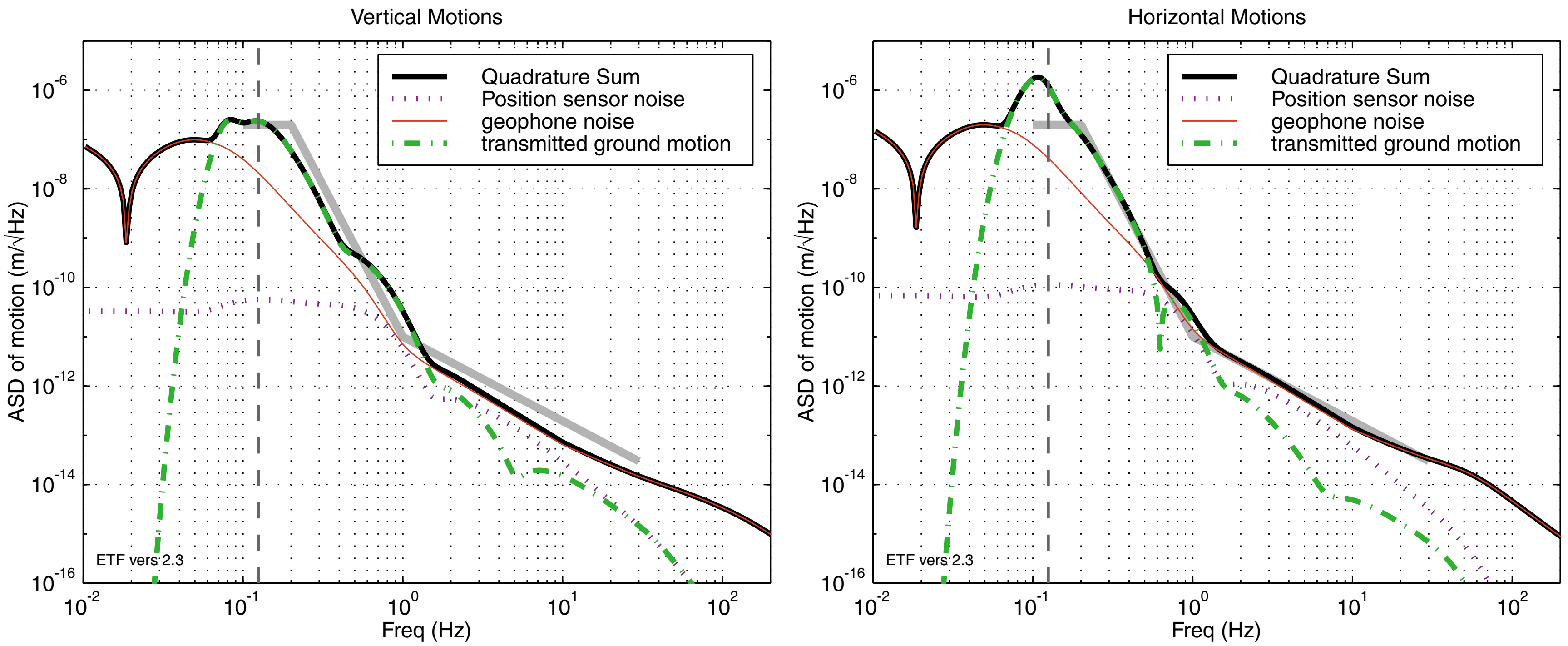
Tilt-horizontal coupling





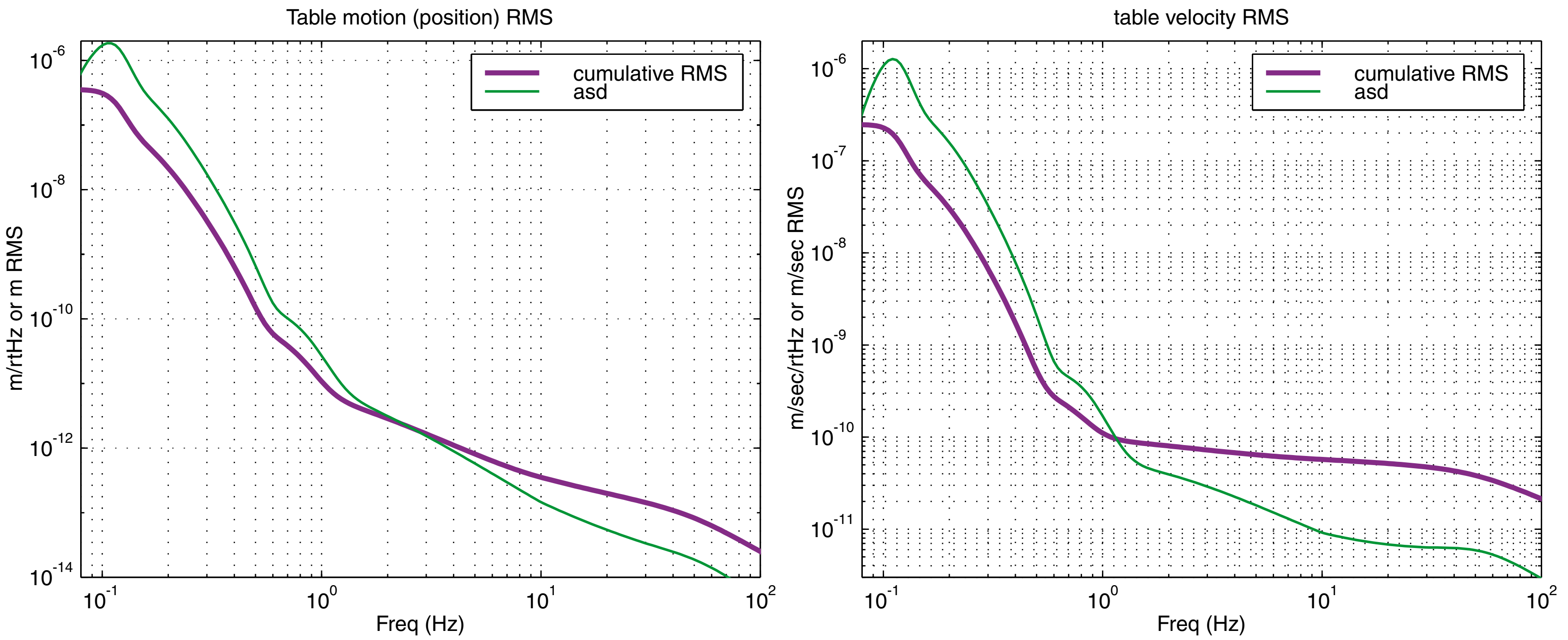
Tilt-horizontal coupling at very low frequencies: Tilt step function can cause slow horizontal excursion.

Displacement noise performance



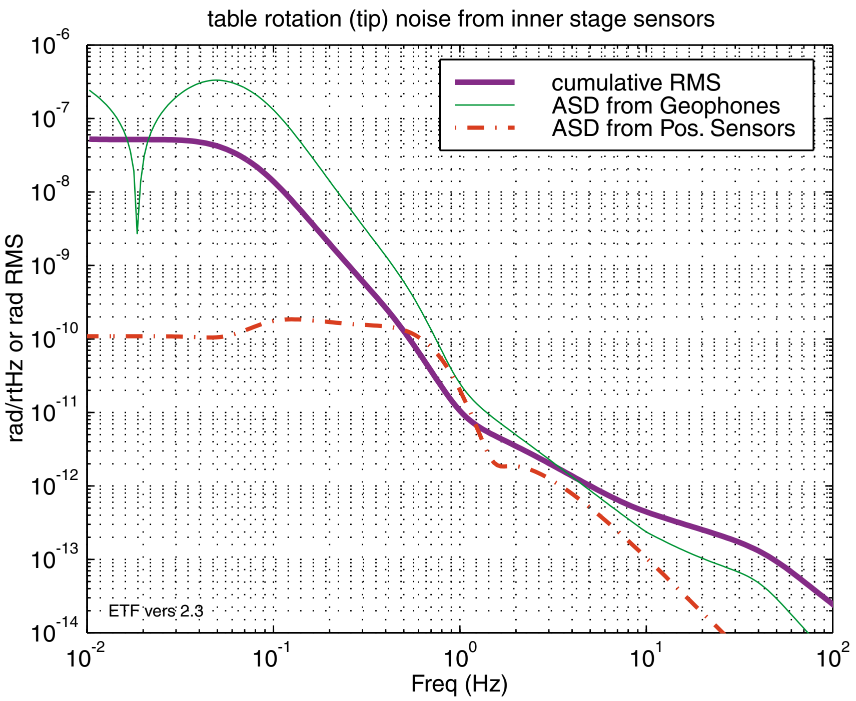
Displacement amplitude spectral density on the two-stage active platform.

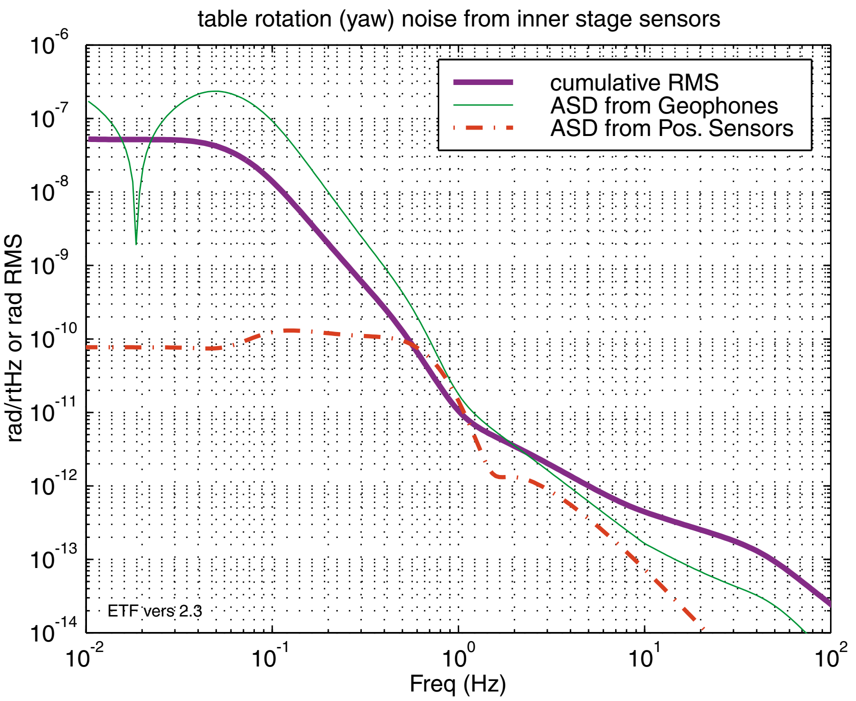
Root-mean-squared motion



Integral of RMS displacement noise of the SEI optics table.

Pitch and Yaw motion





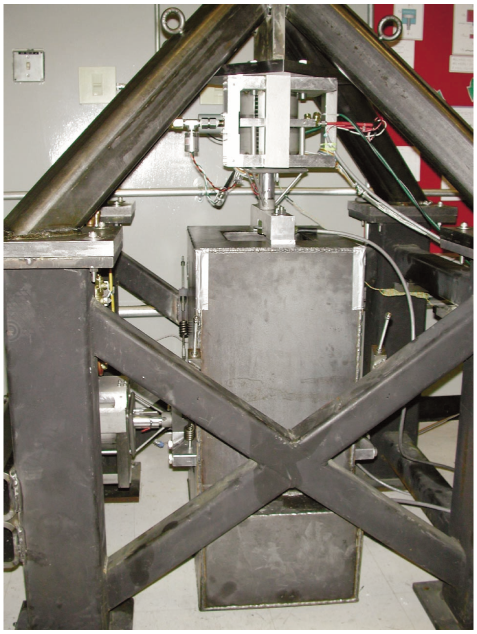
Integral of RMS pitch and yaw motion of the SEI optics table. Note that these curves assume zero ground excitation.

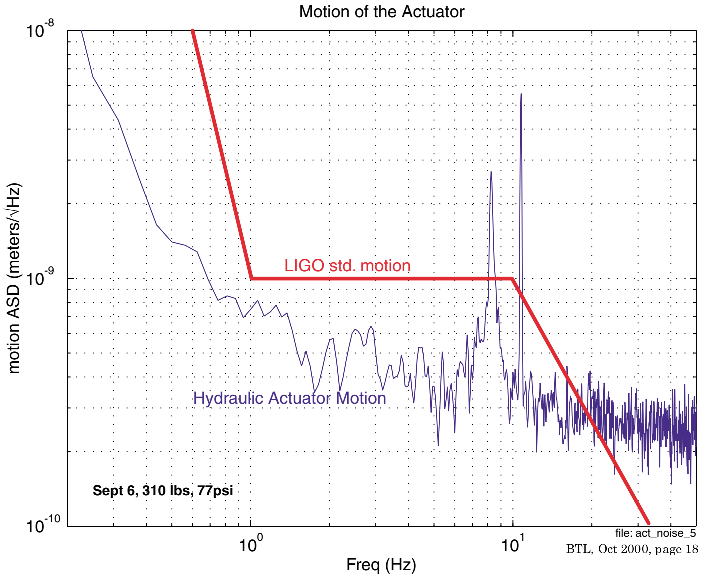
Model results summary

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

Key noise levels calculated for the two-stage active isolation platform, without the beneficial effects of the hydraulic stage and feedforward. The RMS noise is calculated by integrating the amplitude spectral density down to 1 Hz; See graphs in other figures for additional values.

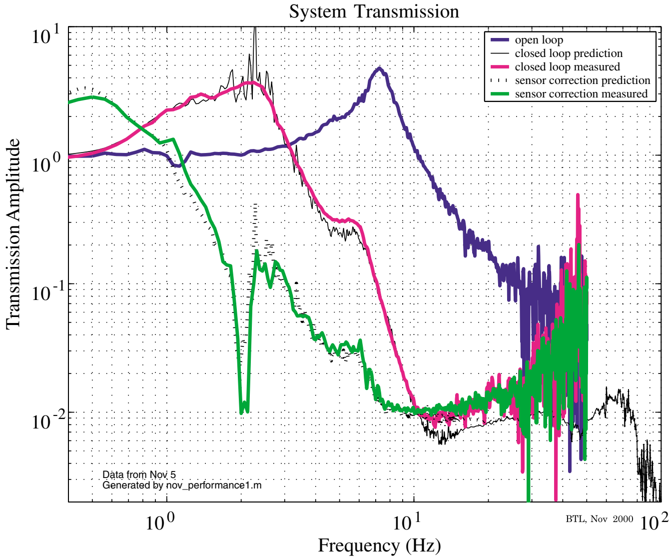
Prototype hydraulic actuator

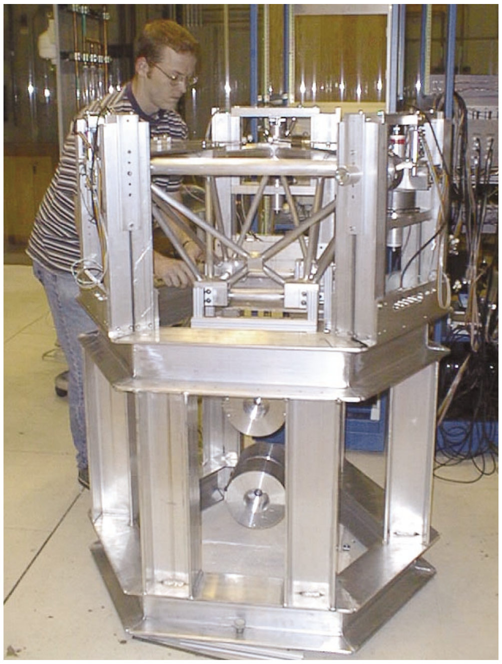




Test frame for hydraulic actuators, along with a plot of the maximum-force, open-loop noise.

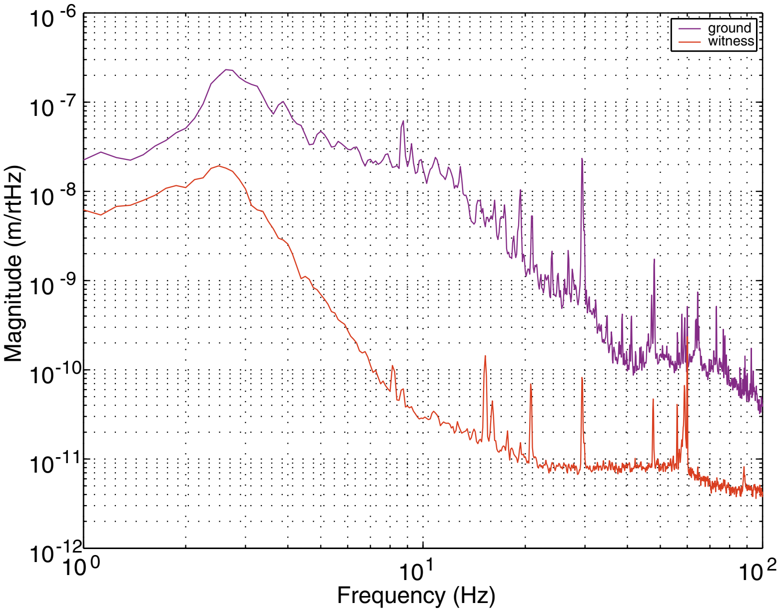
Active isolation stage with pendulums

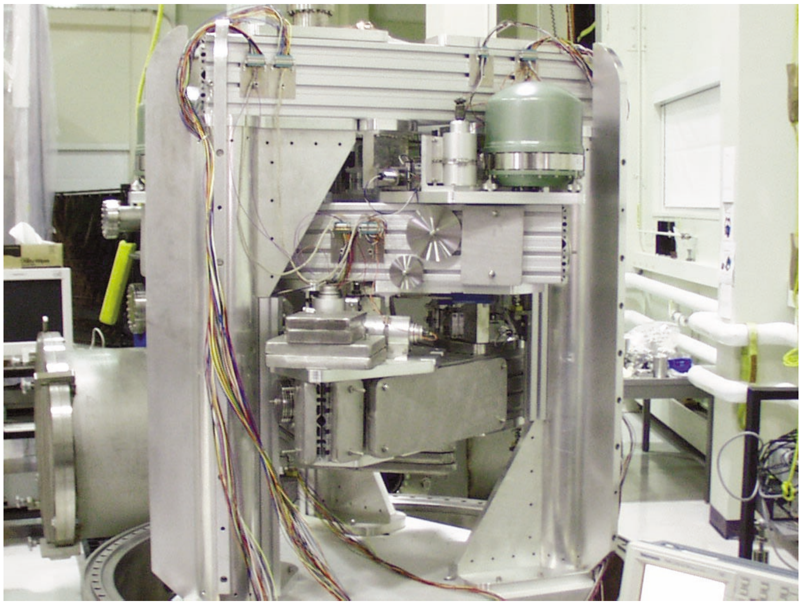




The Stanford single-stage active isolation platform and dual triple GEO600-like pendulum. of the design.

Two-stage pre-prototype





The two-stage active isolation experiment. Vertical ground noise (purple) and payload noise (red).

Operational modes

Normal Operation: Lowest noise, with or without global control or reallocation input

High-damping, minimum step/inpulse response: Used when environmental noise is high and low-noise operation not possible.

SEI Diagnostics: SEI commissioning or periodic sys ID.

SEI acquire lock: closes open servo loops in SEI.

Development plan

- UHV prep research.
- Electronics/DSP dSpace → LIGO-brand?
- Prototype HAM two-stage active isolation platform to be tested in ETF at Stanford, to be completed 2Q02 (preliminary results earlier).
- Pathfinder HAM and BSC to be installed in MIT LASTI, 2Q02. Hydraulic stage to provide extra attenuation for noisy MIT site.
- Final design. . .

Conclusions

- Requirements can be met or nearly met using only the two-stage active platform.

- Modelled isolation performance nearly meets goal, exceeding it slightly in horizontal microseism due to transmitted ground motion.

- Tilt-horizontal coupling may be an *operational concern,* but there are several promising techniques to be explored.

- Hydraulic stage pre-isolation and tilt stabilization needs study.