J. Giaime, LSU; B. Lantz, Stanford

LSC Seismic Isolation Progress

Work done by dozens of people at LIGO Lab (all locations), JILA, LSU, Stanford,. . .

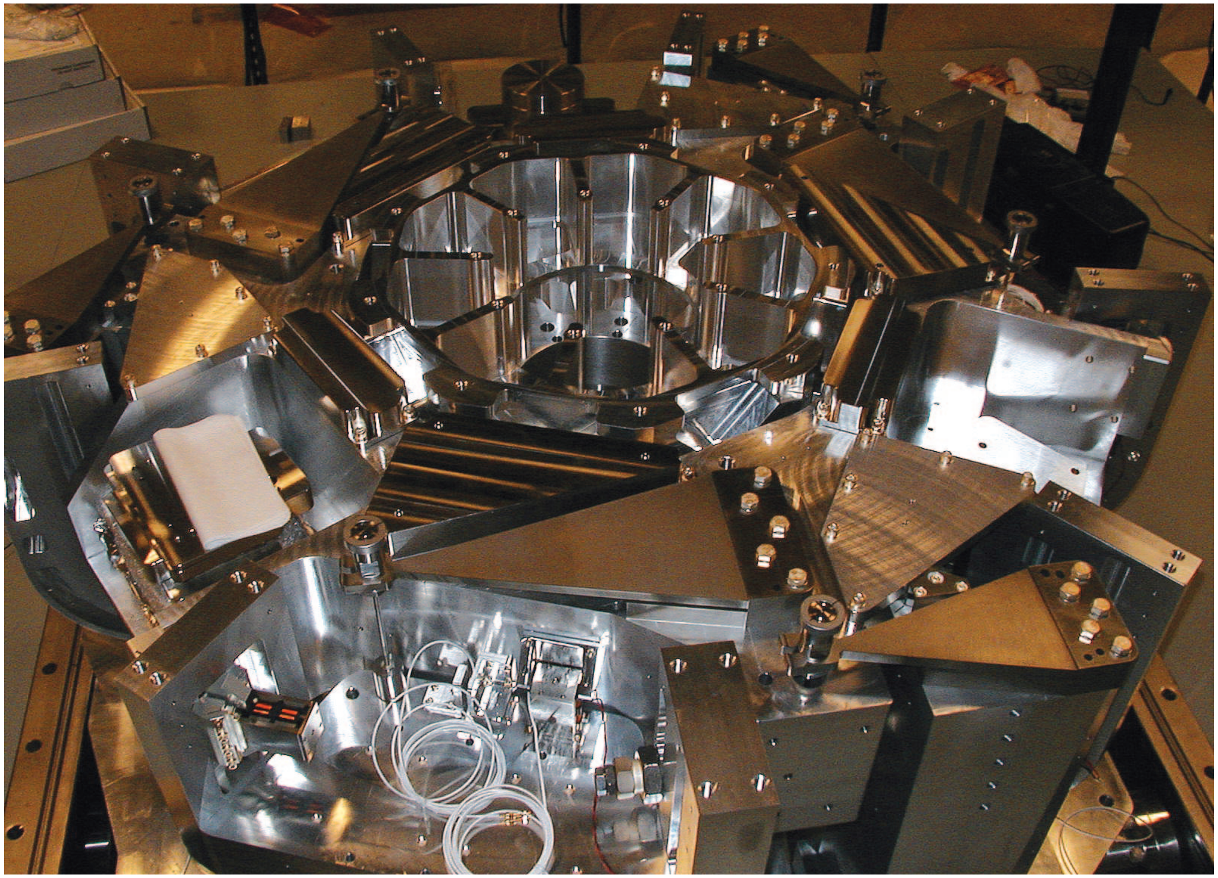
- Advanced LIGO system development.
- Initial LIGO system improvement/ retrofit.

The Advanced LIGO and LIGO 1 retrofit Seismic Isolation Collaboration

Stanford, Caltech, LSU, MIT, LLO

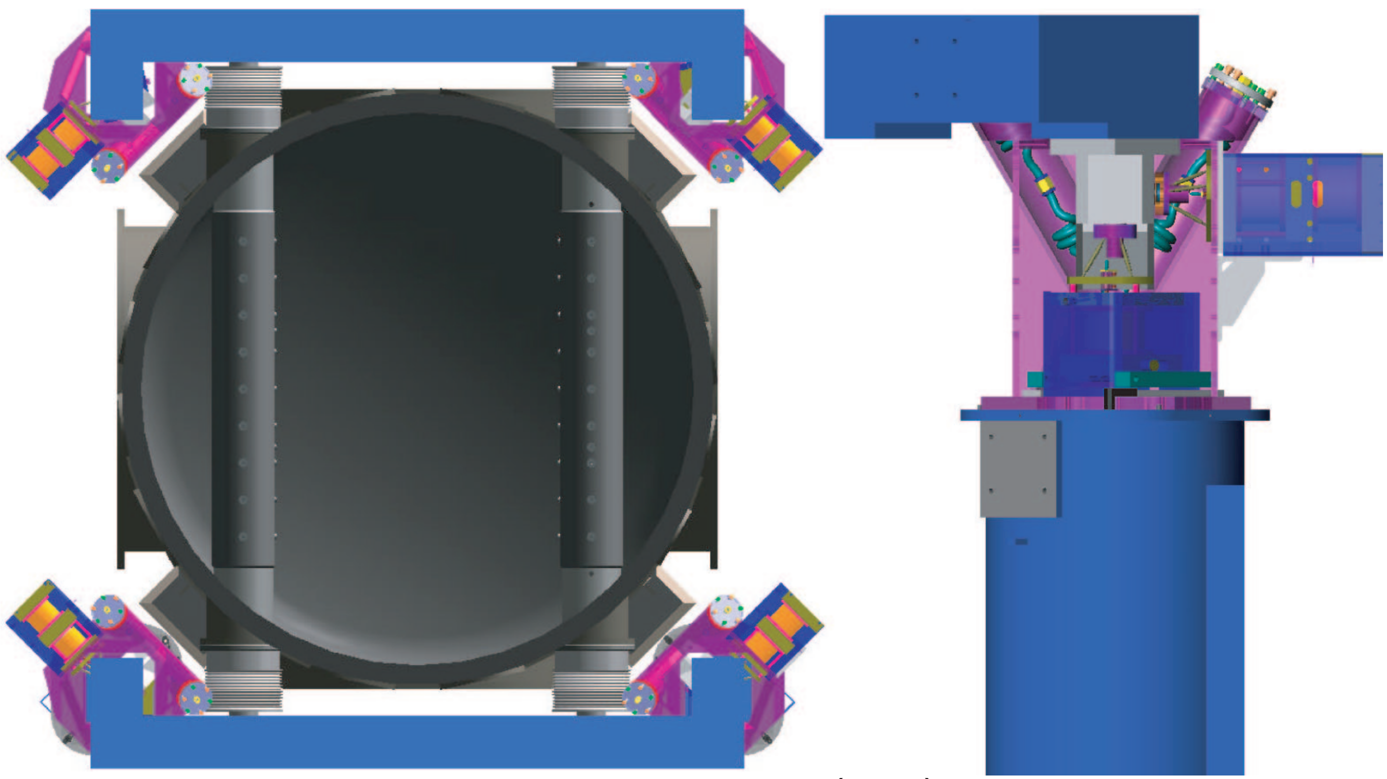
Rich Abbott, Graham Allen, Drew Baglino, Colin Campbell,
Daniel DeBra, Dennis Coyne, Jeremy Faludi, Peter Fritschel,
Amit Ganguli, Joe Giaime, Marcel Hammond, Corwin Hardham,
Gregg Harry, Wensheng Hua, Jonathan Kern, Brian Lantz,
Ken Mailand, Ken Mason, Rich Mittleman, Jamie Nichol,
David Ottoway, Joshua Phinney, Norna Robertson, Ray Scheffler,
David Shoemaker, Michael Smith, Gerry Stapfer,
and the Livingston Staff

Advanced LIGO System Development: In-vacuum



- 2-stage in-vacuum platform uses feedback from inertial sensors to reduce noise in ≈ 1–30 Hz band.
- Work currently focused on ETF prototype under assembly in Stanford ETF vacuum system. Loops should be closed within months.
- Pre-prototype being used to test low-noise capacitive sensors and control techniques.

Adv. LIGO System Development: External Pre-isolation



- External, mm-range, pre-isolation stage (**EPI**). Platform servoed with large gain to local sensors, corrected for coupled ground noise and global signals. Effective in 0.1–10 Hz band.

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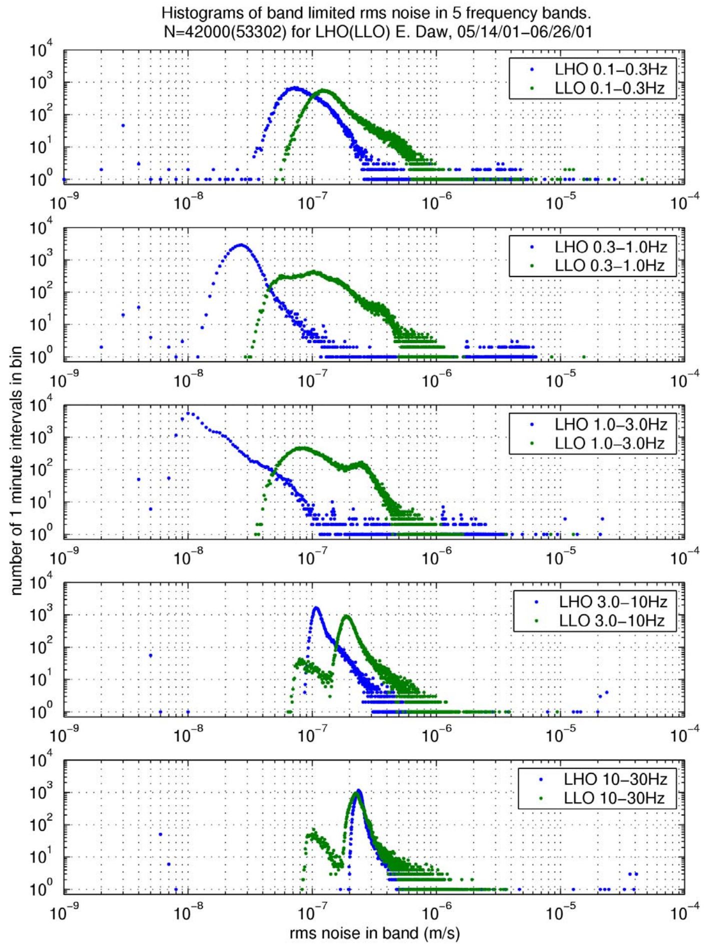
Initial LIGO improvement



- LIGO Livingston must contend with ground noise of order $\mu\mathrm{m/s}$ in all frequency bands.
- Noise in the 1–3 Hz band, often from timber harvesting, is enhanced by the stack resonances, making daytime operation difficult.
- (Noise in 0.1–0.3 Hz band now corrected with microseism feedforward system.)

LLO Seismic improvement

Group Strategy

- Accelerated development of EPI, with prototype tests at LASTI through this fall, and installation at LLO between S2 and S3.
- Installation of Piezoelectric pre-isolation (PEPI) as interim measure.
- Modelling and lab work in support of EPI

Key Technologies needed for EPI

- Linearized actuators, with of order 1 mm range, colocated with displacement and inertial sensors.
- Support springs free of low-frequency resonances, and stiff external mechanical structure.
- Installation procedure that avoids damage or misalignment to payload.
- Controller filters and topology that corrects ground noise problem without adding, for example, low-frequency drift or tilt.

External actuator development

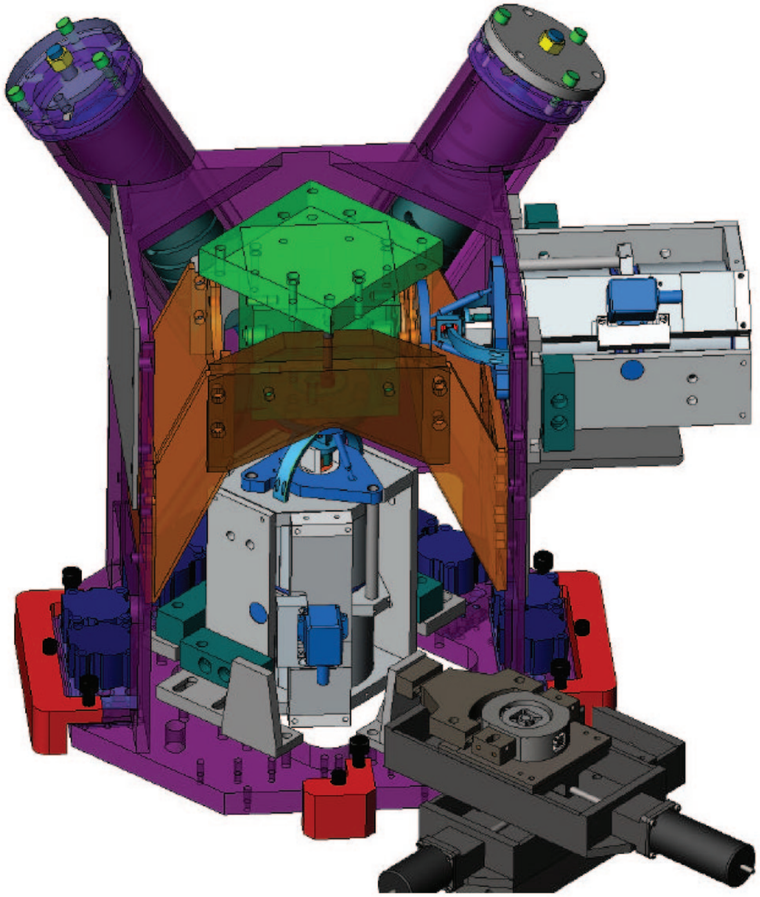
Hydraulic EPI:

- A 3rd generation hydraulic actuator design has been handed off from Stanford to LLO for prototype production, which is underway.
- Test to be carried on in LASTI BSC.
- Hydraulic pump station constructed at LIGO/Caltech.
- Hydraulic dynamics modelled at Stanford and MIT.
- Alternative fluid under study.

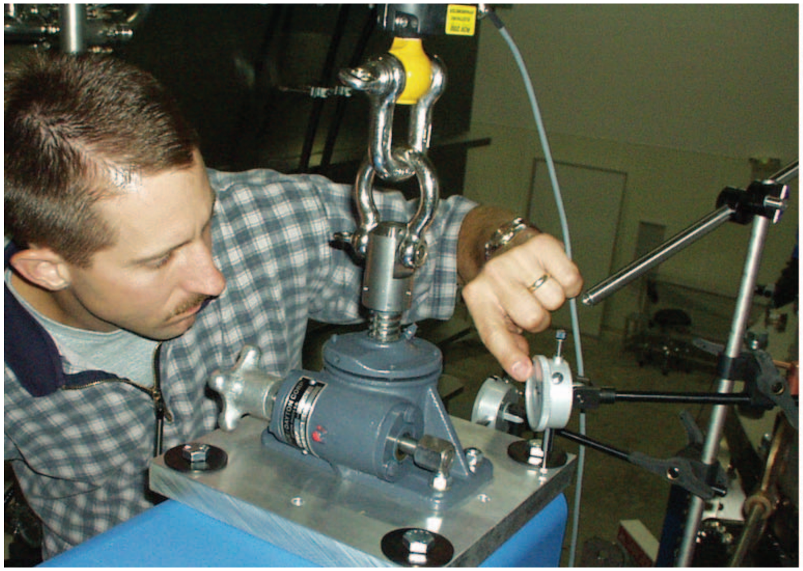
Electromagnetic EPI:

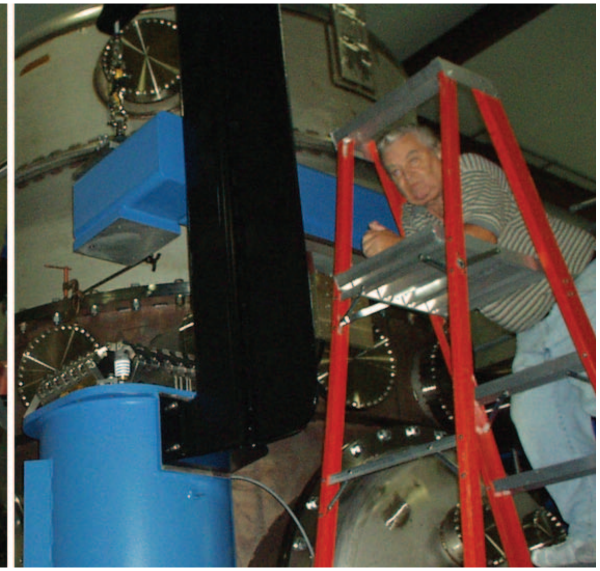
- E/M actuator taken from Adv. LIGO internal active stage.
- to be tested in LASTI HAM.
- E/M interference under study.

EPI Spring and structure design



EPI Installation method



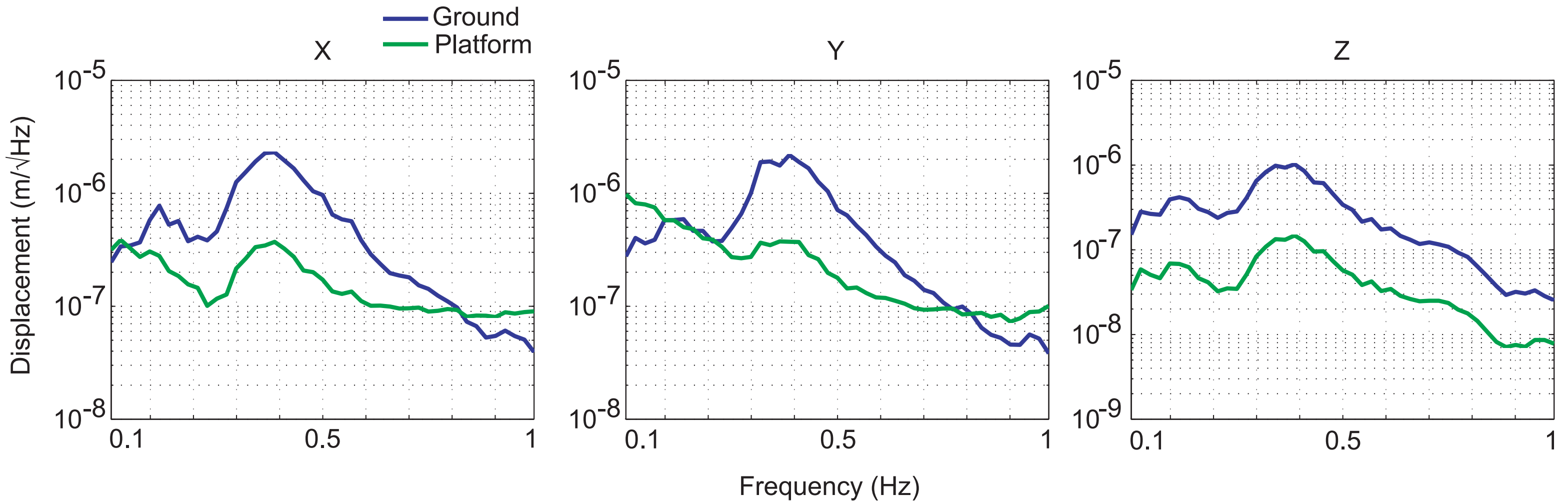


- Fine actuators installed at LLO's inner test mass tanks, for PEPI. A similar method is appropriate for EPI retrofit.
- Technique: offload and reload from above with precision screw, allowing position to vary over only ≈ 0.1 mm, ending to within ≈ 0.03 mm
- Optical levers monitored for angular deviation. Optical lever never went out of range, and end deviation was well within our control range.

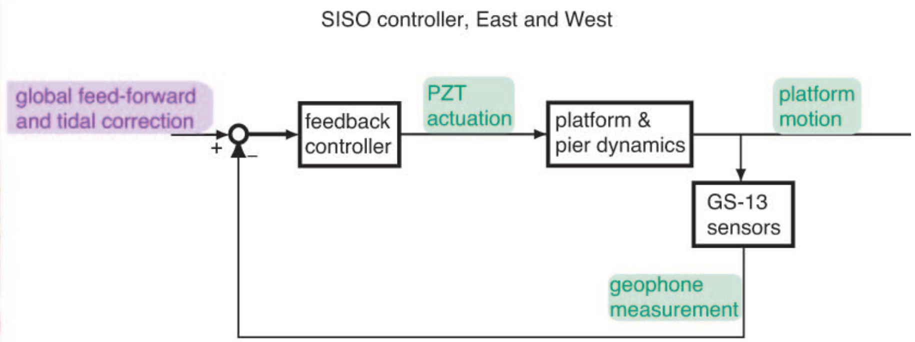
Controller techniques: developed on Adv. LIGO prototypes

"Rapid" pre-prototype:

- 6 DOF active control and reduction.
- 3 DOF sensor correction noise reduction in 0.1–1 Hz band, in 3-D.
- Digital transformation from 12 sensors, non-colocated, to 6 DOF well-understood "supersensor" signal. Similar transformation for actuators.
- very high bandwidth low-frequency control over position and tilt, to allow linear response to sensor correction. **Please come to W. Hua's talk tomorrow PM.**



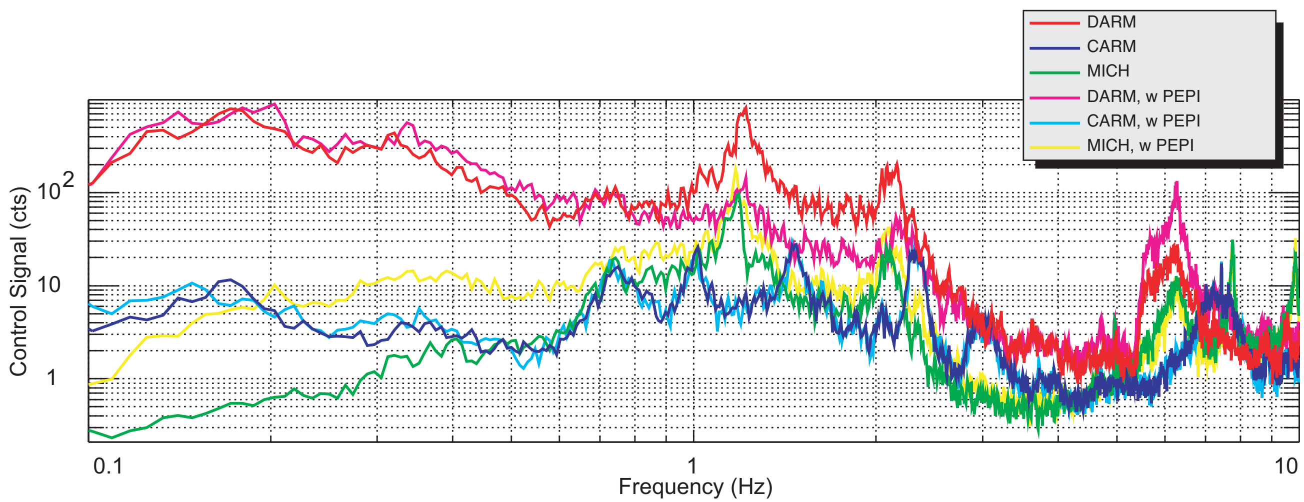
Controller techniques: PEPI at LLO.



- Geophone is mounted on each crossbeam filtered to make error signal for local active isolation loop.
- Loop gain shape set to enhance reduction at stack modes at 1.2 and 2.1 Hz.

Controller techniques: PEPI at LLO, cont'd.

- Factor of 5 reduction in arm length control signals seen in active band of about 1–3 Hz.
- Similar reduction of pitch excitation seen at test masses; yaw not affected much.
- No statistics yet on its effects on LLO duty cycle.
- Nice test on feasability of physical retrofit and pier-top active control.



Modelling

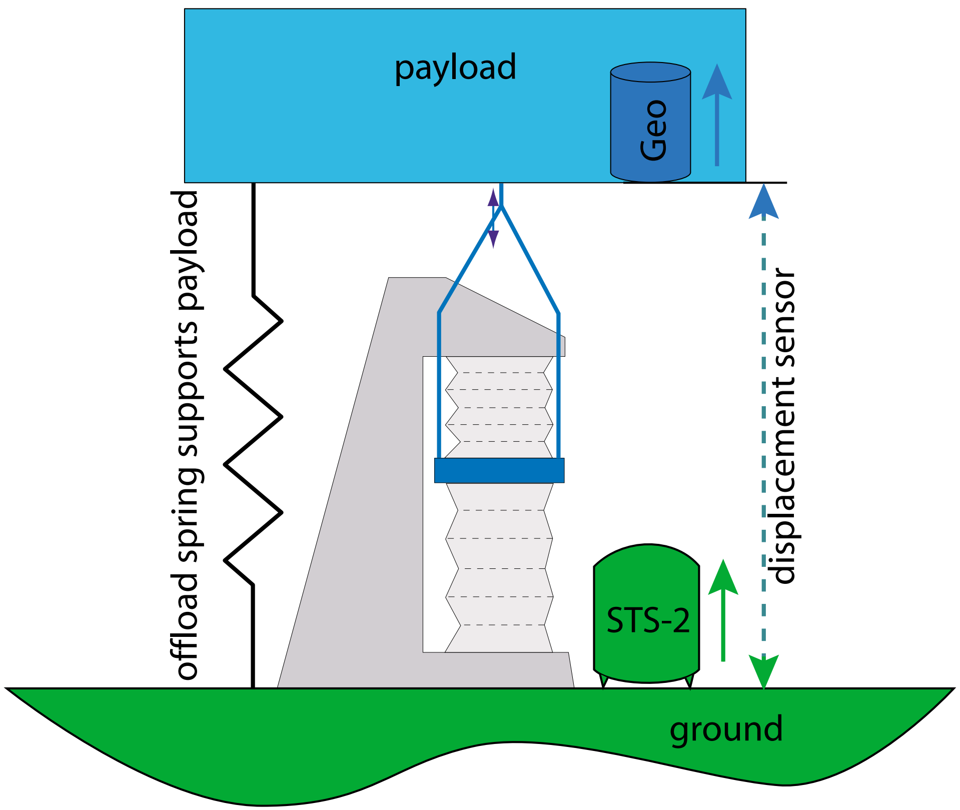
- Lantz/Hua model of 6 DOF external platform, with full stack model, is mature enough to begin considering control loop shapes.
- versions for hydraulic and magnetic systems under development.
- comparison with PEPI sys-id data looks encouraging.

Active Hydraulics for LIGO 1

Hydraulic actuator design and testing: Stanford
Hydraulic actuator manufacturing: LLO
Actuator Frame: MIT
Offload Springs design and testing: LLO
Pump Station and distribution system: Caltech and Stanford
Electronics: Caltech
Modeling: Stanford, MIT
Plant ID: MIT, LSU
Multi DOF low frequency control: Stanford, LSU

How to get
Isolation from the Ground

Wensheng Hua will give a separate talk on this topic, showing reduction of Stanford Microseism in all 3 translations



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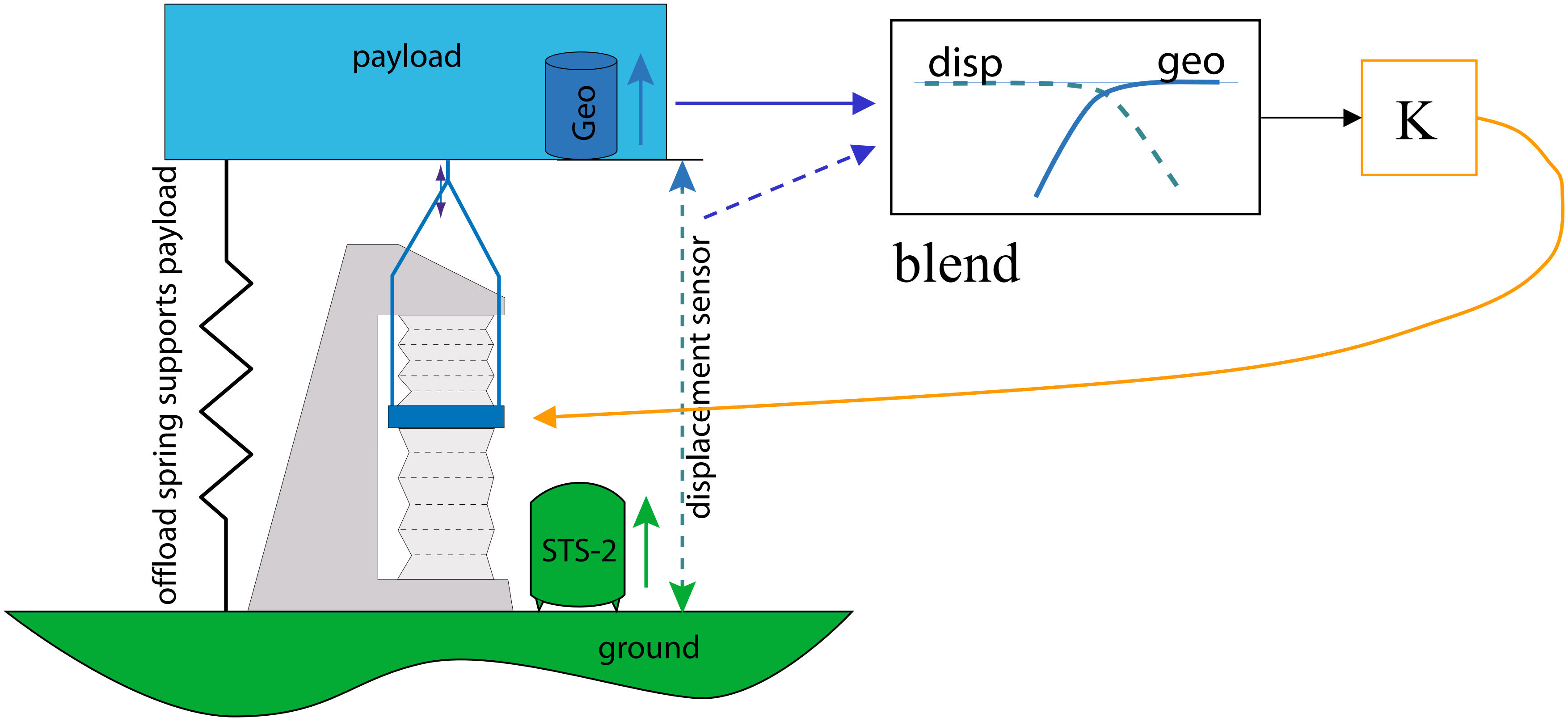

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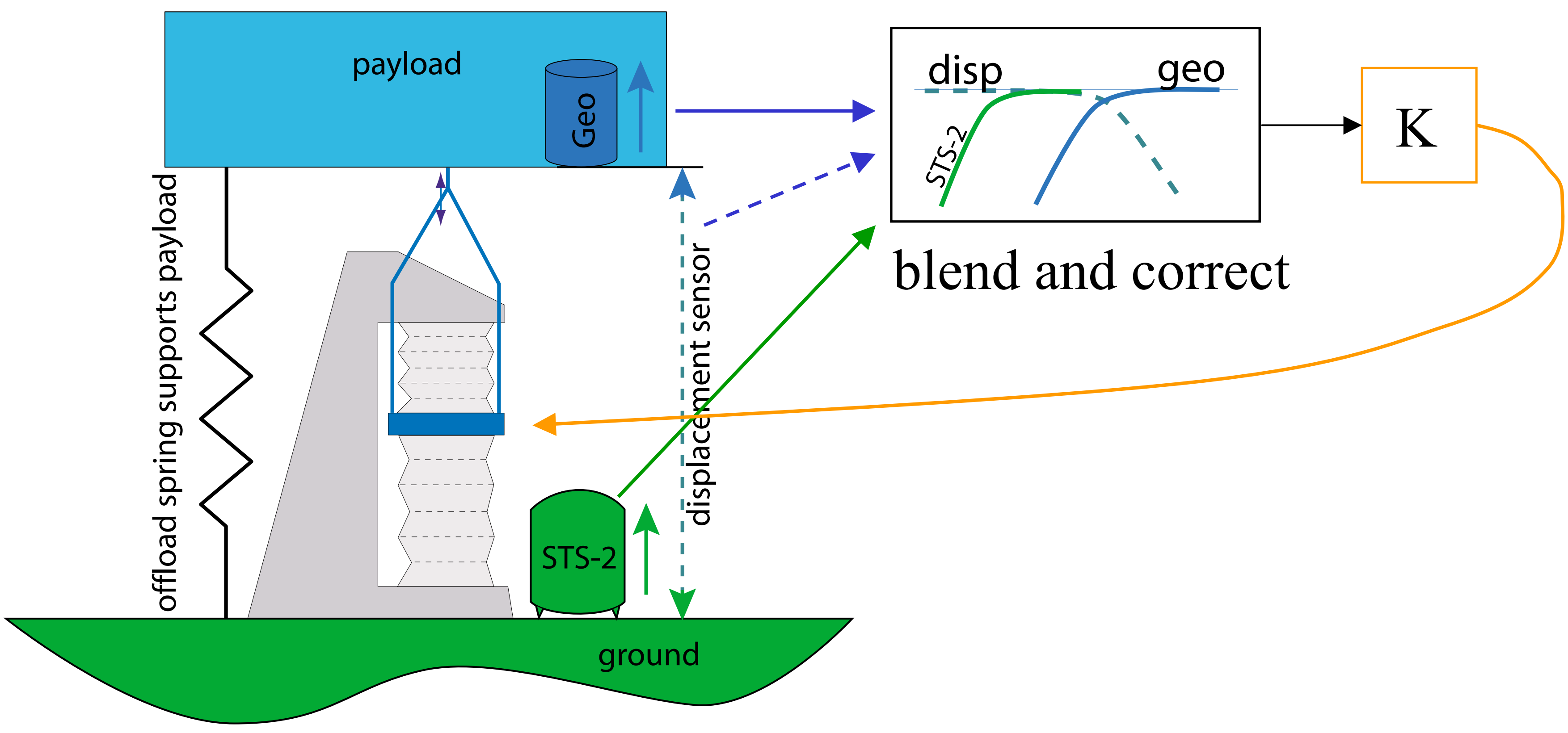


Design of LIGO 1 affords opportunity for Advanced LIGO techniques

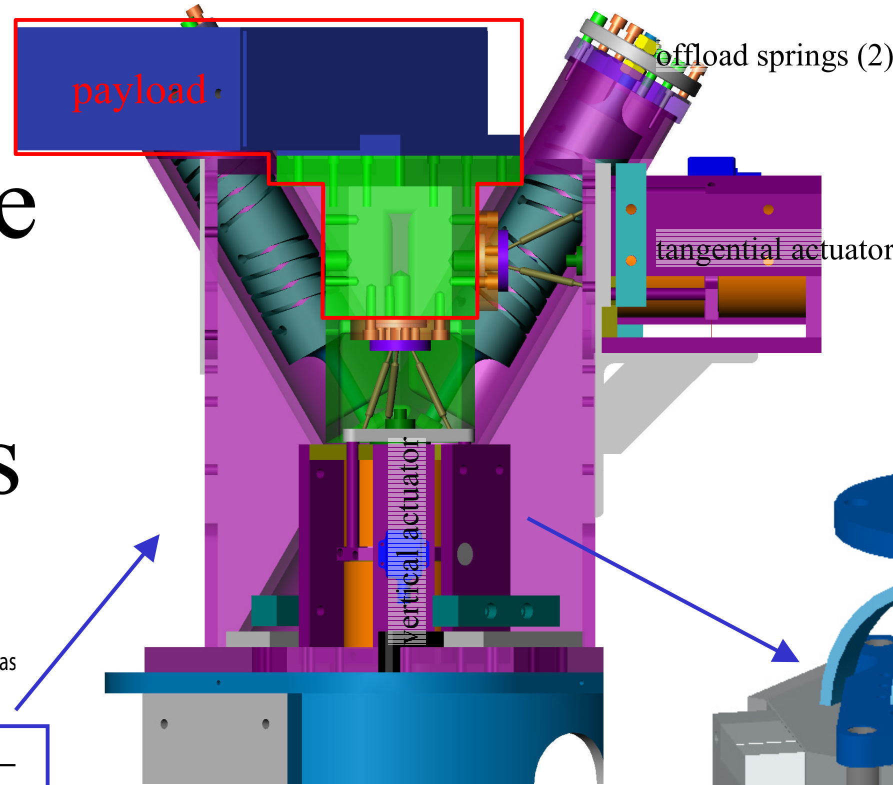
Hydraulic Actuators

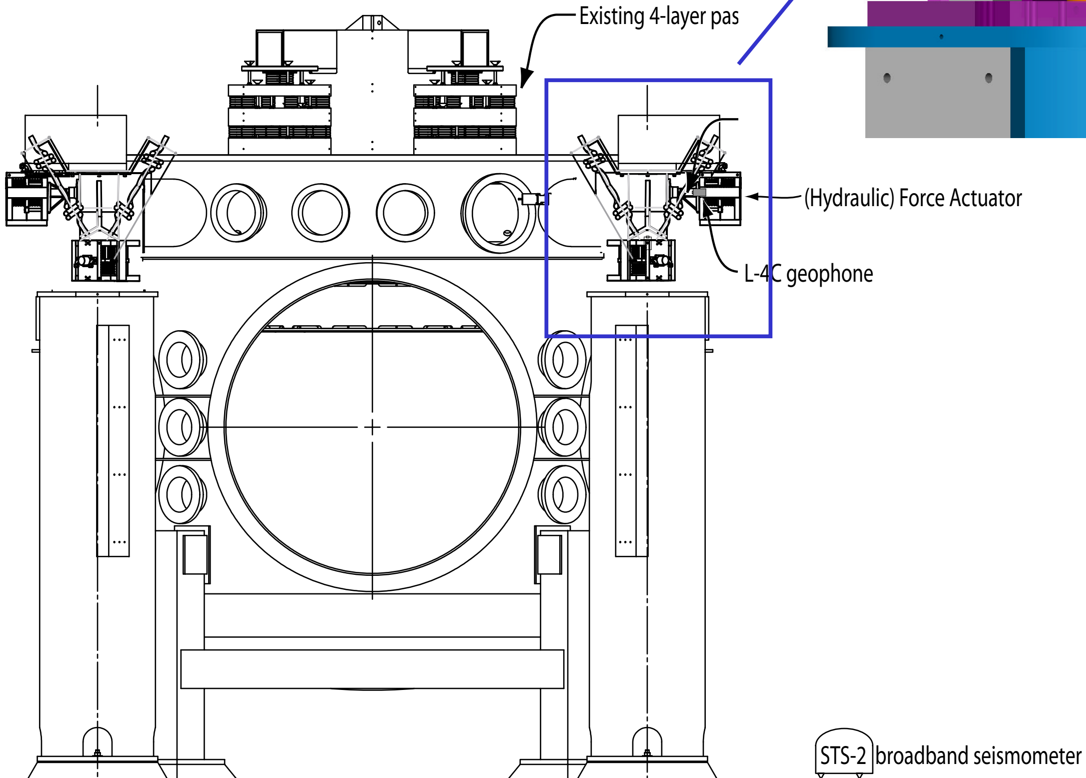
- Control the support platform of the stack in 6 degrees of freedom,
- Provide seismic isolation from 0.1 to 10 Hz, (BW ~30 Hz) and
- Have +/- 1 mm range for long term locking, and
  +/- 5 mm range for 'sweet spot' determination.
- Maximum velocity of 80 microns/ sec

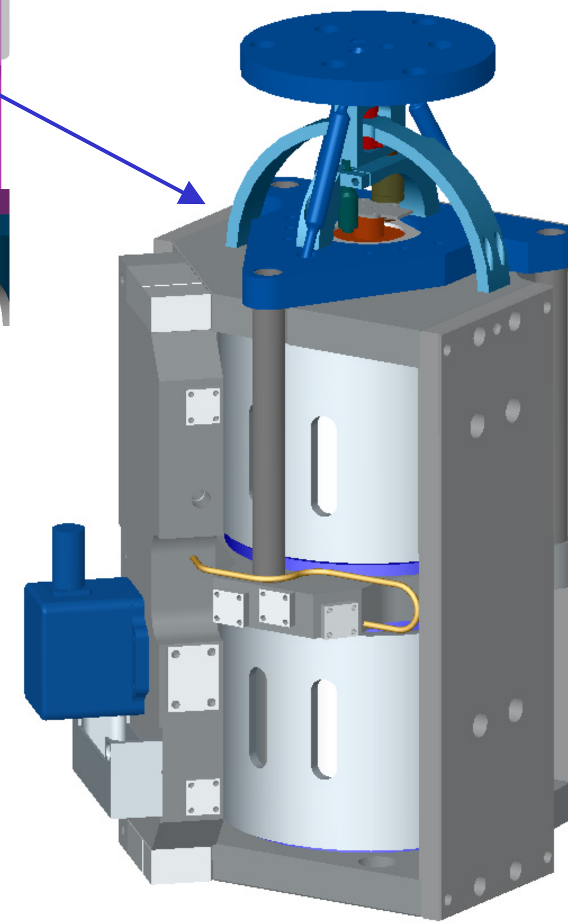
- Replace the LIGO 1 'fine actuators'

Location of External Actuators

Placement of the Actuators and Offload Springs

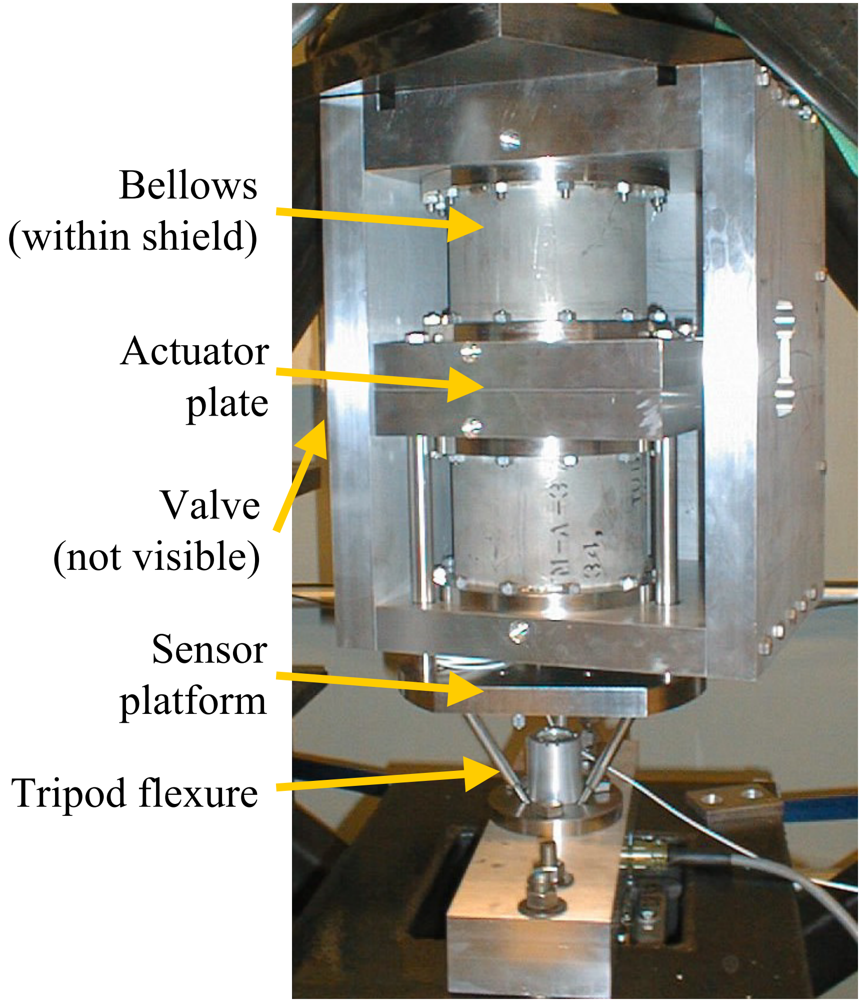




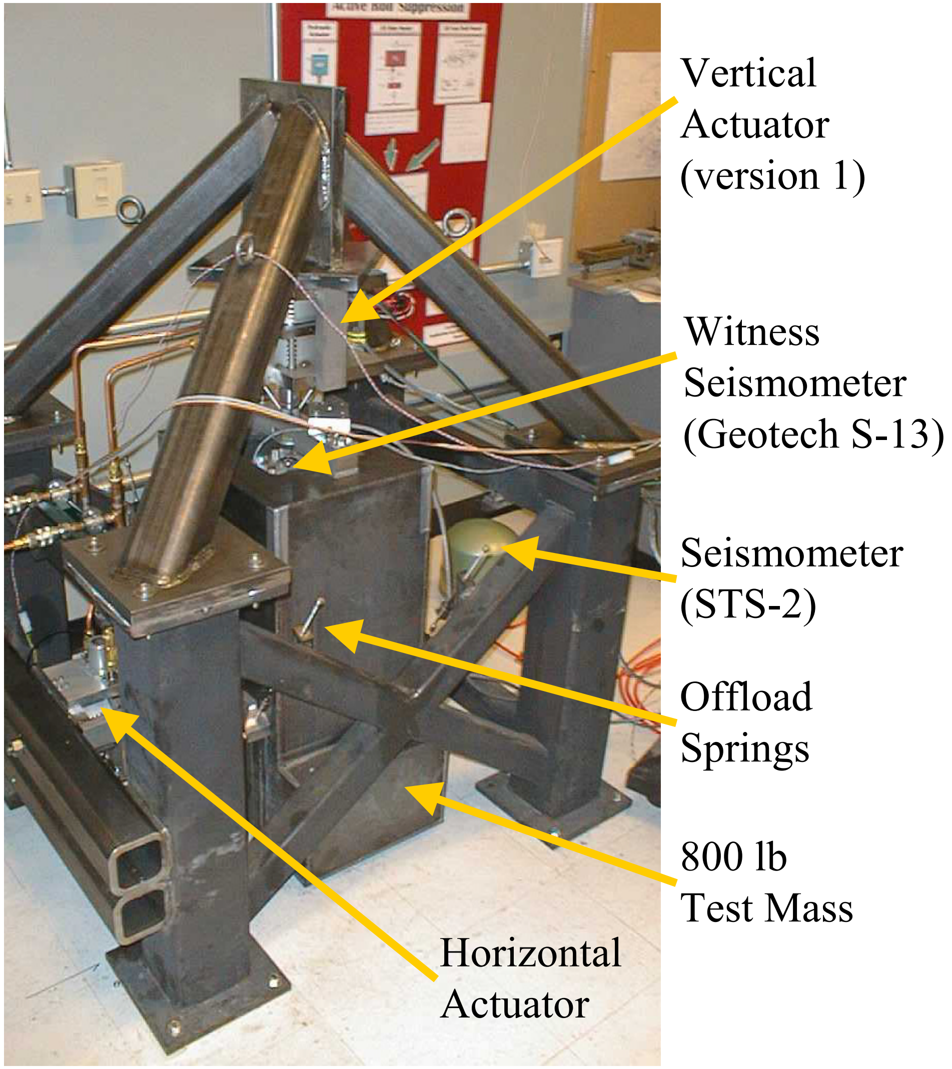


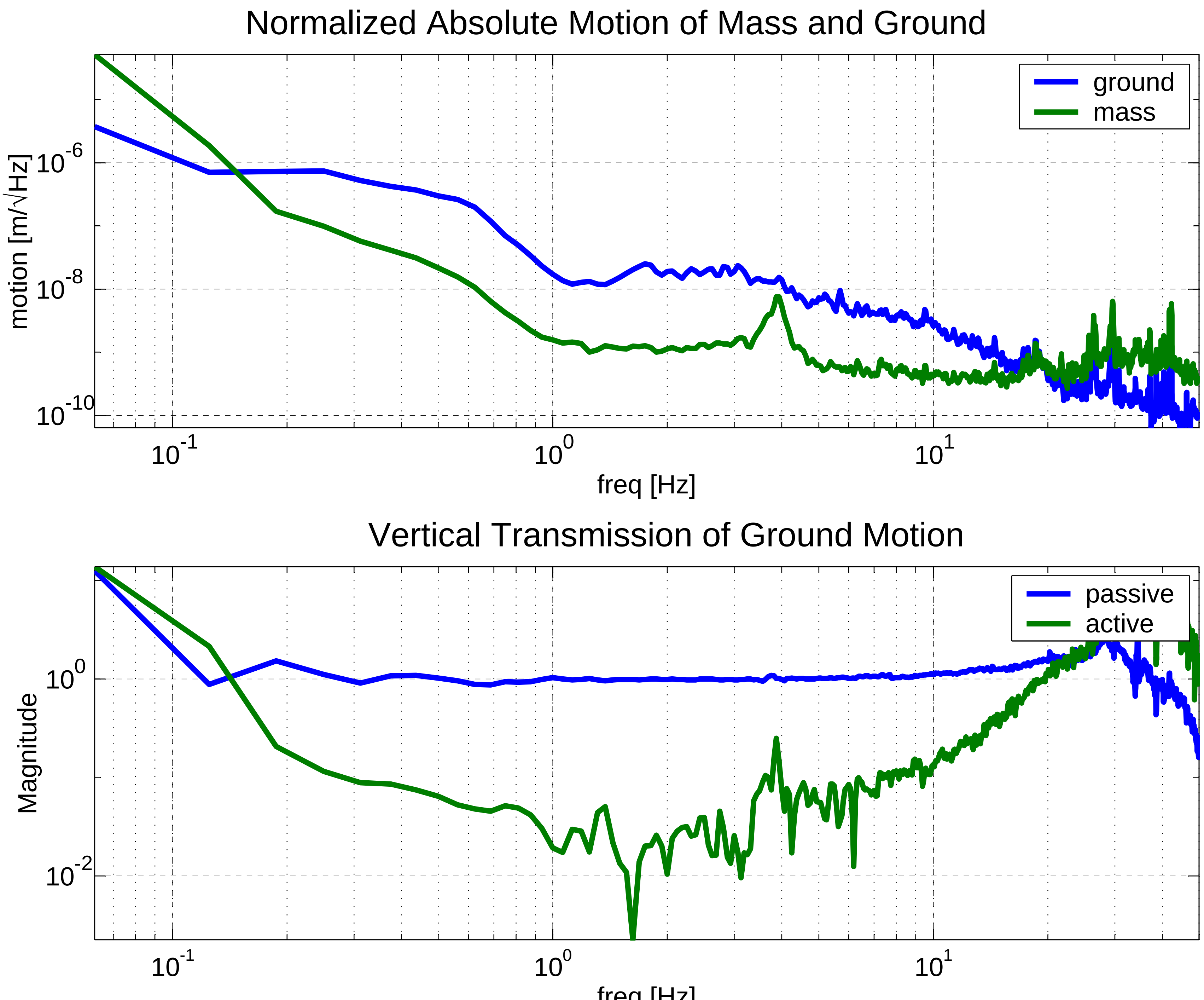
Graphics by J. Giaime, K. Mason, C. Hardham

The Test Platform at Stanford



Vertical Actuator –version 2

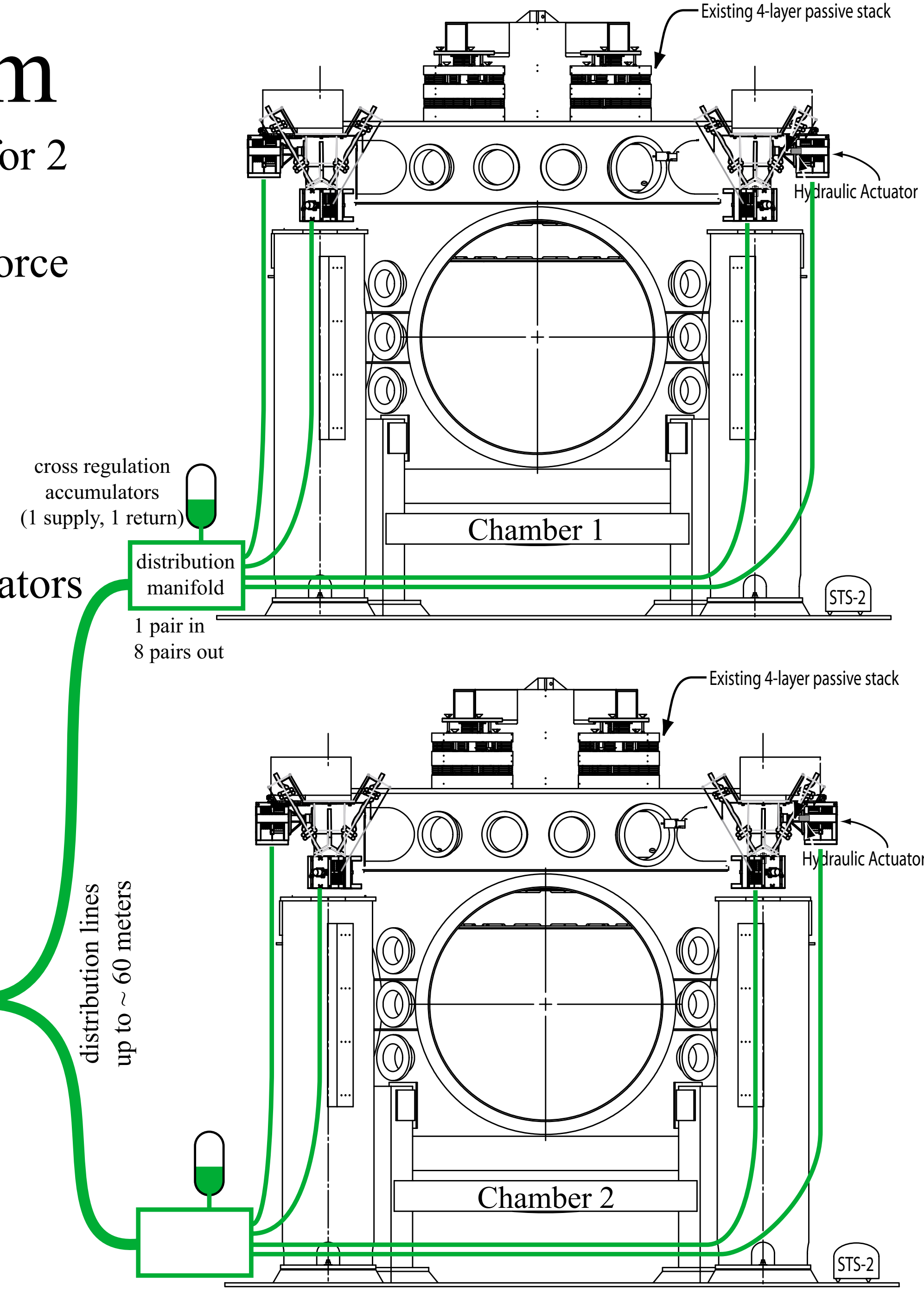


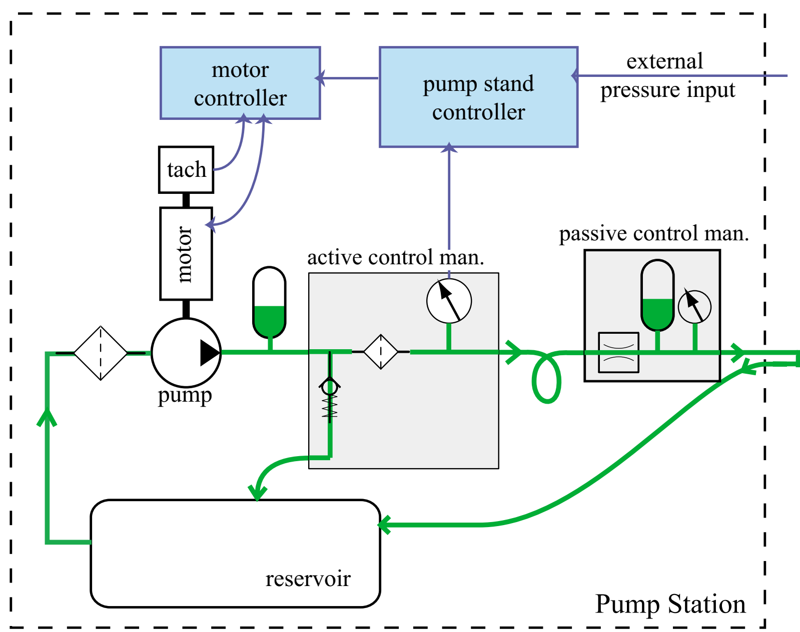


- Vertical Super Sensor
Controller: v hyd cont 1212

Distribution System

- Pump station provides source of quiet fluid for 2 vacuum chambers.
- Pump pressure fluctuations couple to drive force when the hydraulic bridge is unbalanced (lose common mode rejection.)
- Pump fluctuations are controlled both actively and passively.
- Accumulators at the distribution manifold attenuate the cross-modulation amongst actuators





Pump Station at Caltech

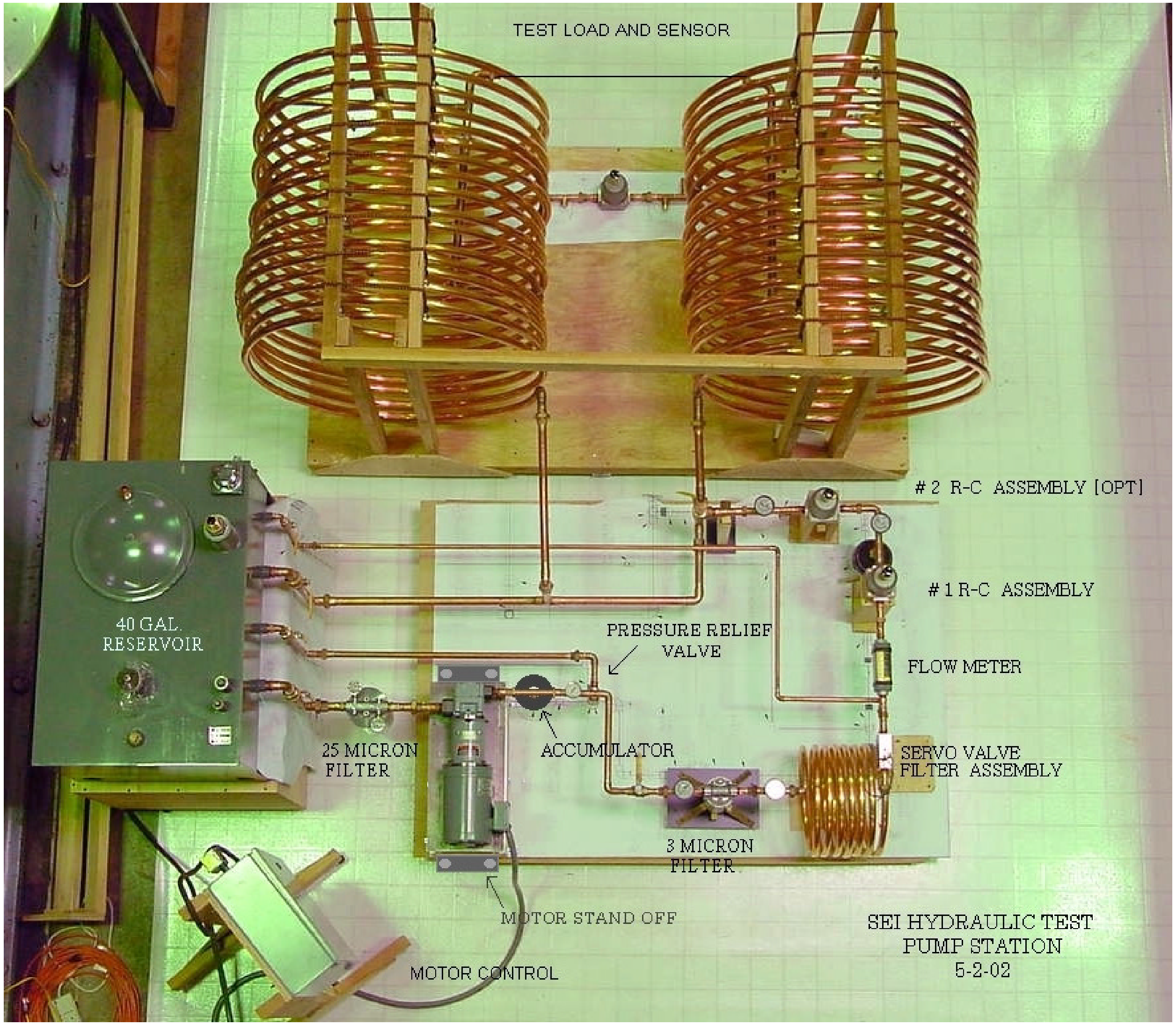
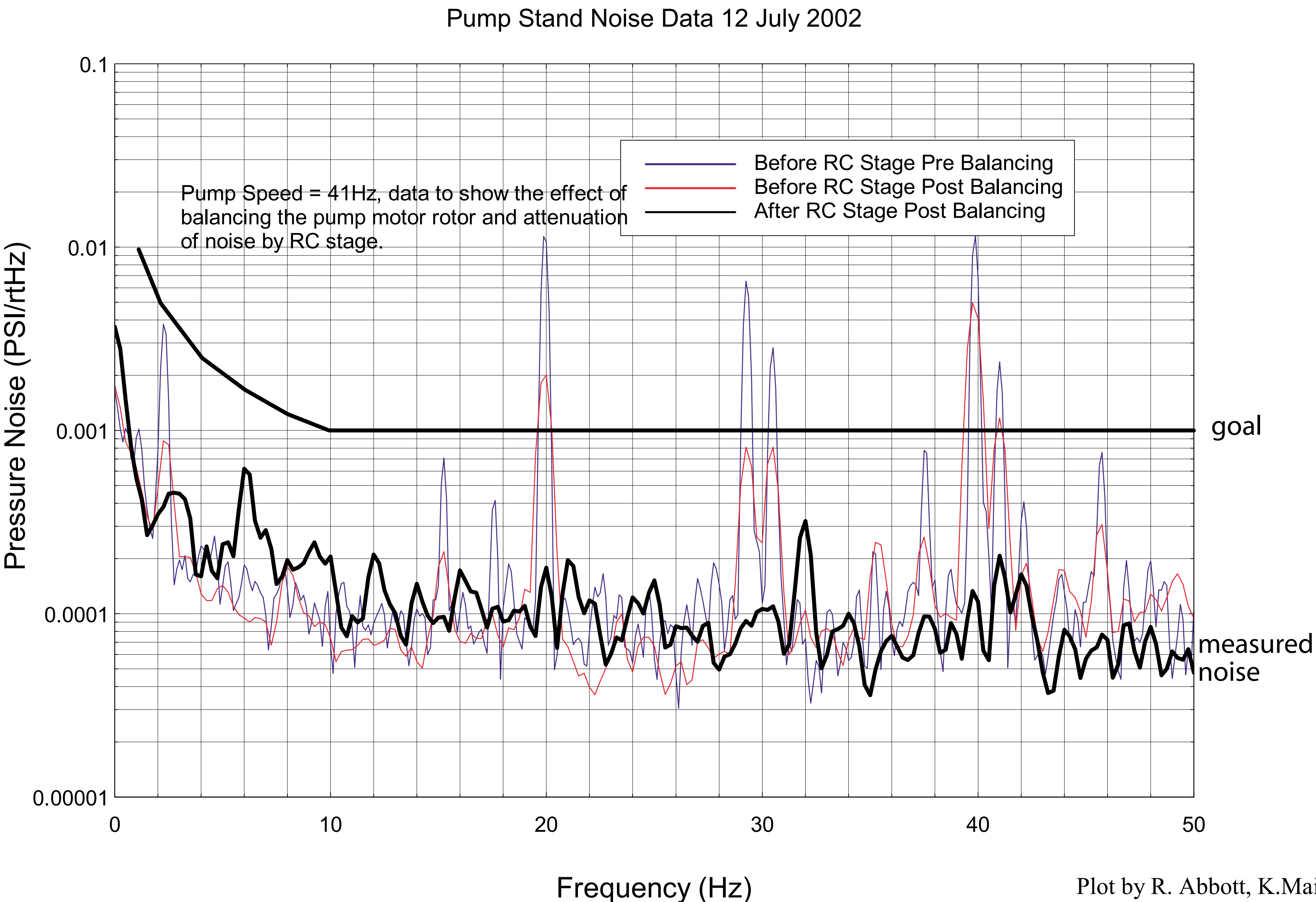


Photo by K. Mailand

Performance of the Pump Station

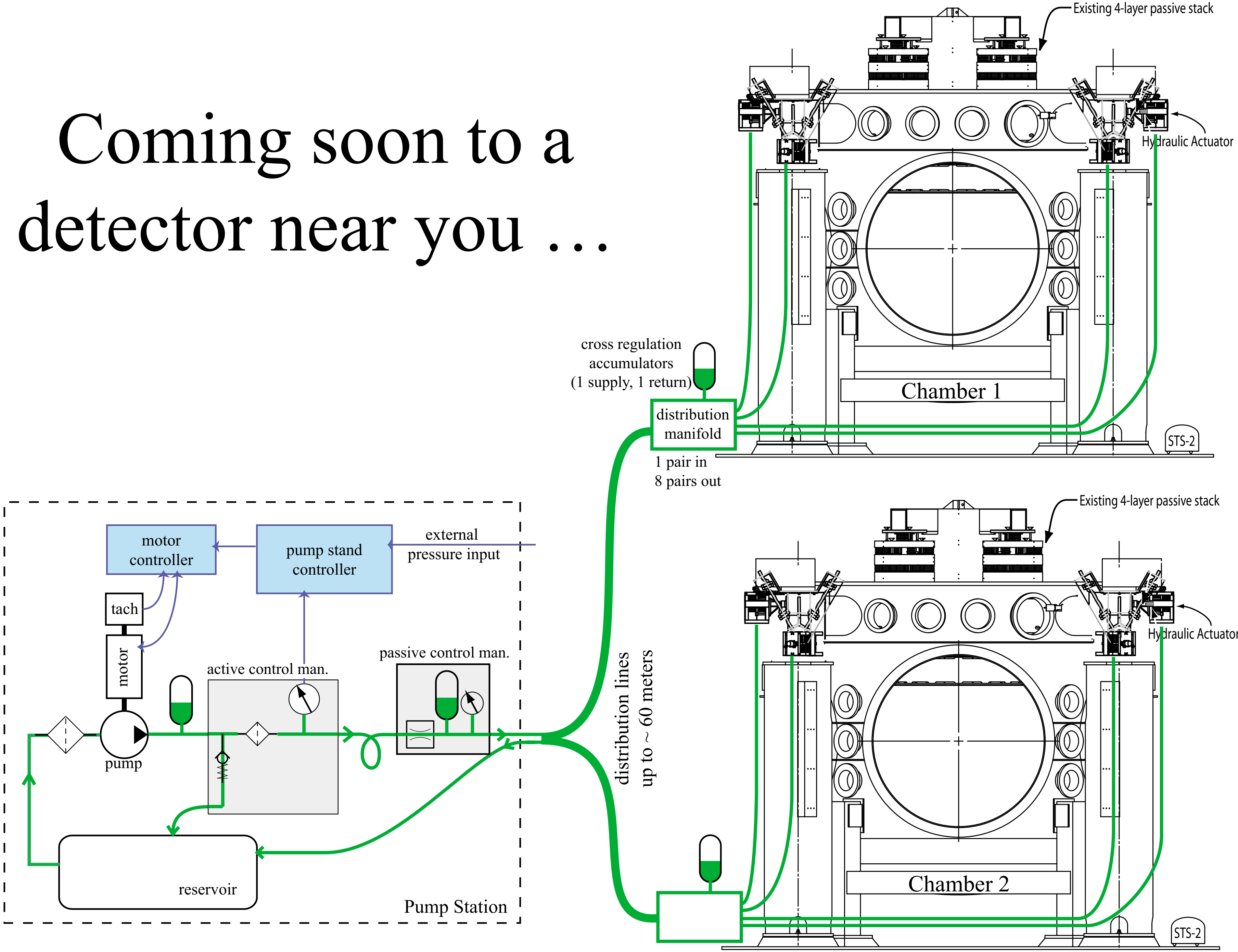


Plot by R. Abbott, K.Mailand

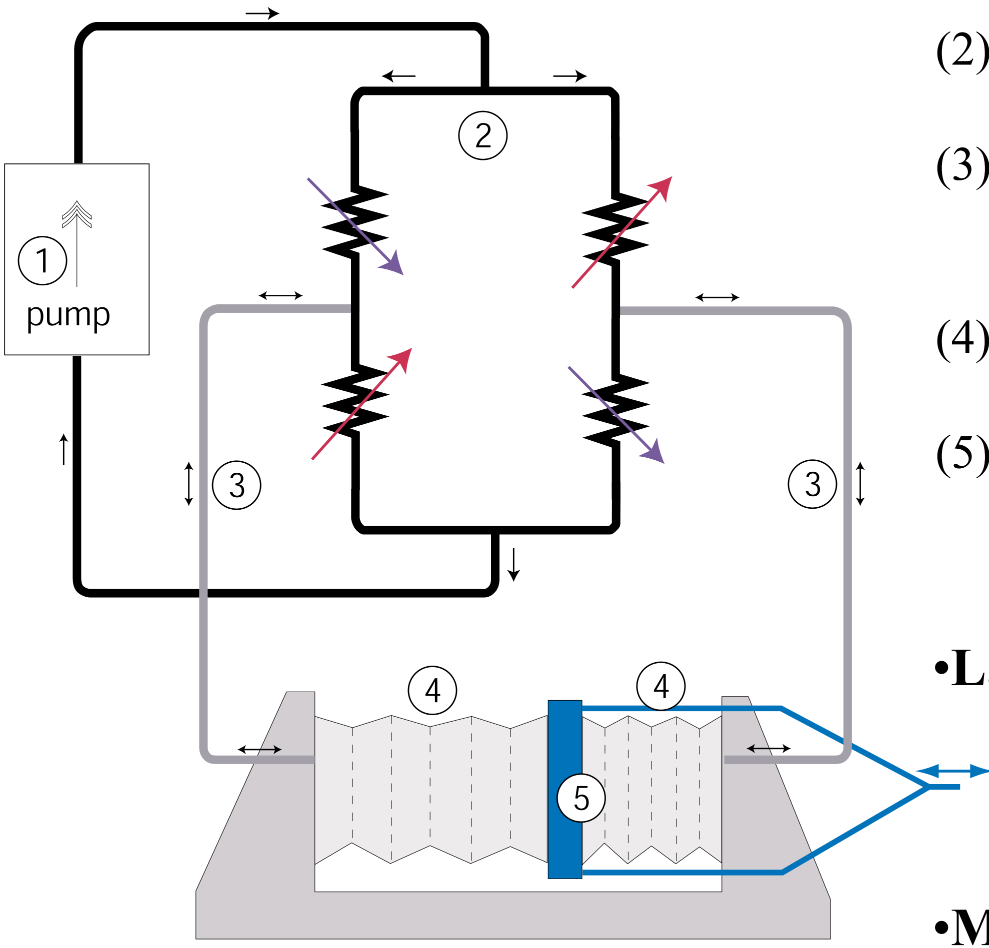
Seismic Retrofit Schedule

May ’02	Accept design of actuator
Aug ’02	Finish installation of MEPI at LASTI
Sept 9 ’02	Ship pump station to LASTI
Nov 6 ’02	Finish installation of hydraulic system in LASTI
Feb 14 ’03	Prove system in LASTI
April ’03	Begin installation in LLO

Coming soon to a detector near you …



Hydraulic Actuator Basics



(1) Pump supplies a constant flow of fluid to the actuator.
(2) Fluid flows continuously through a hydraulic Wheatstone bridge.
(3) By controlling the resistance, one generates differential pressure across the bridge, which are connected to
(4) Differential bellows which act as a stiction-free piston.
(5) The actuator plate is between the bellows, and is connected to the payload with a flexure stiff in 1 DOF

- **Laminar flow**
  - high viscosity (100 x water),
  - low velocity (80 microns/ sec.),
  - fluid path geometry.
- **Motion with flexures**
- **Offload springs to keep bridge balanced**
  - common mode rejection of pump noise

Performance Measures

Bandwidth = 20-30 Hz,

mass/ spring resonance of actuator against piers and payload.

Max range = +/- 1 mm, to accommodate long term locking,

set by bellows geometry.

Velocity = 80 microns/sec, well beyond typical peak velocity,

set by bellows area and bridge flow.

Three dominant noise sources:

- Ground motion coupling
  (limited by loop gain, sensor matching, low frequency tilt)
- Sensor noise
  (limited by cost, dynamic range, space)
- Pump noise
  (limited by line dynamics, acceptable power loss to filtering)