LASTI LIGO II Mechanical Subsystem Tests: Objectives and Approach

LIGO T000025-00-R
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1 Introduction

This document is designed to give an overview of the objectives and technical direction for the tests of the LIGO II mechanical systems to be performed on LASTI, the LIGO Advanced System Test Interferometer at MIT LIGO. It will evolve quickly as the program is better defined and will contain pointers to more detailed design information as appropriate.

2 Experiment Objective

The overall objective of LASTI for the next five years is to aid in the development of and perform tests on the LIGO II mechanical subsystems. A coordinated plan between the Caltech 40m and the LASTI, with the GEO 10m, Stanford ETF, and possibly other prototypes playing associated roles, should allow tests of all subsystems which can be successfully tested in a prototype environment.

The tasks projected for LASTI presently are

1. Full-scale tests (control, isolation, internally generated noise) of HAM and BSC seismic isolation systems
2. Full-scale tests (control, isolation, internally generated noise) of Test Mass and Mode Cleaner suspension systems
3. Tests of the coordinated controls systems for these two subsystems
4. Tests of the installation jigs and procedures for the mechanical subsystems
5. Tests of first-article isolation and suspension components.

These tasks may involve more or less development proceeding and parallel with the tests; the baseline plan is that the seismic isolation and suspension systems will be ‘delivered’ to LASTI (whether developed at MIT or not), but they may undergo their first full-scale testing (with the associated probability that things won’t work first time around) when installed in LASTI.

The Caltech 40m is the principal complement to the LASTI full-scale testing; at the 40m, the optical and sensing configuration, and the overall controls scheme, will be tested. For each subsystem there should be an appropriate testing program to allow release of designs to fabrication; the LASTI should perform those tests for the Seismic Isolation (SEI) and Suspension (SUS) subsystems.

3 Top-level Constraints

In the planning for the LASTI work, there are some top-level questions which will have a significant impact on the design and execution of the effort.

3.1 Displacement sensitivity

Ideally, the LASTI would test the suspensions and isolations in the LIGO site environment and to the level of sensitivity and at the frequencies required by the LIGO II design. There are technical reasons why this is especially difficult in a prototype setting:

- Seismic noise: The present estimate seismic noise at the MIT campus site is 100 greater at 10 Hz than the LIGO site (see Figure 1). The dynamic range requirements are similar for LASTI and the LIGO sites. However, the motion of the optics table may exceed LIGO II specifications up to ~15 Hz.
- Short arm lengths: In general, having a short arm length aids in the seismic and suspension testing by reducing the differential motion of components. However, the perceived thermal noise motion in the mirrors varies with the beam size with respect to the optic size, and it is an optics challenge to support large beams in short cavities. To get a sense of the problem, thermoelastic noise scales with the –3/2 power of the radius of the beam, and the beam size for a given cavity stability varies with the root of the cavity length. Larger (effective) beams can be handled, but at a cost of complexity and an increase in the distance from the LIGO configuration.

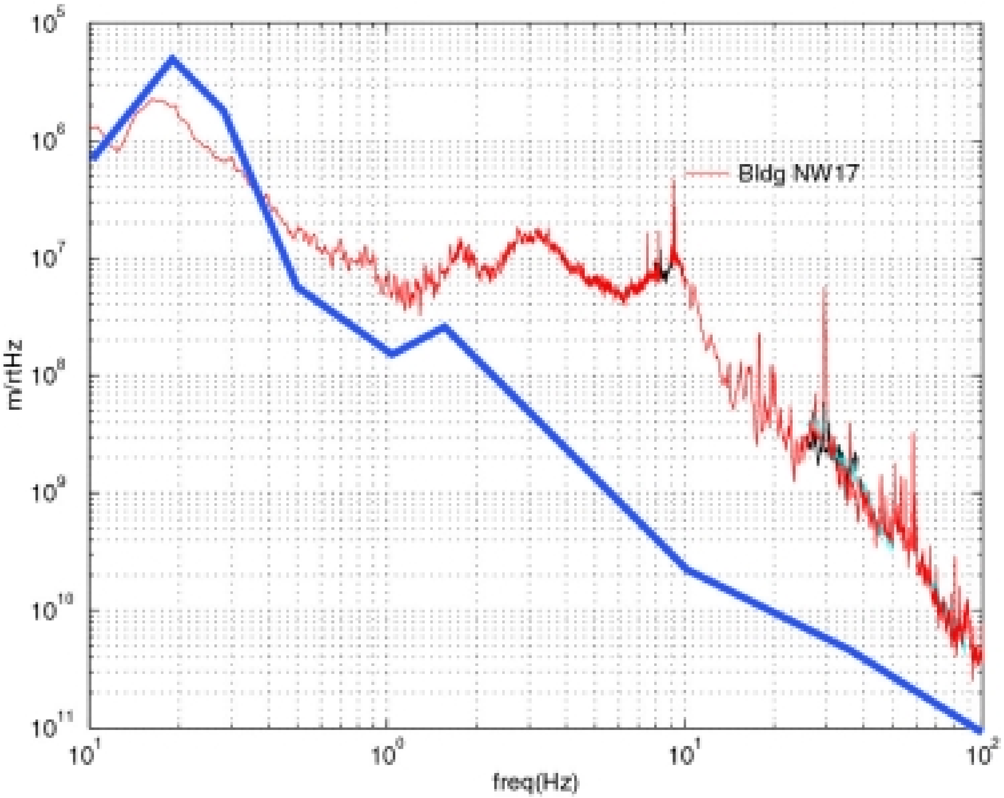

Figure 2: Noise measured in LASTI lab (before lab rebuild) and best-estimate LLO spectrum. Both subject to new measurements.

3.2 Control electronics testing vs. displacement noise testing

LIGO I integration has had difficulties which would have been mitigated by more integrated control electronics tests.In our experience, such problems are mostly oversights, unexpected interactions, and inadequate interface definition, and (once identified) have been readily addressed by re-engineering. As a result, tests of the suspension and seismic isolation control electronics interacting with the physical system have a high priority, and a good chance of a timely and productive outcome.

3.3 Controls interface to Interferometer Sensing and Controls (ISC)

An interface to the LIGO II ISC is needed which allows a complete but standalone test of the isolation and suspension controls. This may place modular constraints on the ISC design, and some compromise in either the LASTI configuration and test scope and/or of the ISC design may be needed. However, assuming a logical evolution of the LIGO I ISC and suspension control philosophy, the system will be primarily digital with analog conversion deferred to the latest possible stage (i.e., as close as possible to the suspension force drivers). This configuration is intrinsically flexible to adjustment of the controller interface, and lends itself easily to simulation of alternate interfaces.

4 Technical approach

The infrastructure of LASTI needs to be qualified before testing of the subsystems starts, and so our discussion starts with this. The isolation and the suspension subsystems have clear interfaces which allow testing to be designed somewhat independently (or more exactly sequentially).

The basic plan is to set up and test the seismic isolation systems 'stand-alone' using seismometers; then to measure relative displacement between the two seismic systems using interferometry; then to assemble a Mode Cleaner cavity between the two seismic isolation systems; and to finally form a short cavity on the BSC isolation system, illuminated with mode-cleaned light. This will be done first for 'controls prototypes' of the suspensions (possibly metal wire suspensions, aluminum masses, etc.); and then for final 'noise performance prototypes' of the suspensions.

Figure 5 shows the anticipated final layout for the complete system; one works toward this in a staged fashion.

Lastly (not 'lastli') a first-article installation test will be performed to test installation jigs and procedures, with a possible functional test if indicated.

4.1 The LASTI Infrastructure

The LASTI consists of a semi-clean laboratory (like the LVEA), clean rooms, the vacuum envelope and pumping system, interfaces to the seismic isolation system, an optical sensing system, and control and data systems.

4.1.1 LASTI Laboratory

The LASTI is in a high bay in the MIT LIGO Lab, NW17-161, 175 Albany St, Cambridge MA 02139. The space is 'L' shaped, with arms roughly 20 m in length. The ceiling height is approximately 24', and a pair of reconfigurable bridge cranes allows crane access over and around the vacuum system. The maximum hook height is 21'3". The two cranes are configured with variable-frequency drives and may be used in tandem to lift a domed object between them. For example the BSC cover as is may be lifted approximately 47" above its flange to clear internal components. To allow the full 74" of height in the BSC to be exploited, it would be necessary to segment the BSC dome.

The air in the laboratory is HEPA filtered by a dedicated air handling system, and with typical activity achieves less than 2000 particles per cubic foot (equivalent to ISO Class 2000). Portable clean rooms are used when working on an open vacuum system. There is currently no dry-air purge system for the vented vacuum system, although small HEPA-filtered air sources are available to create limited laminar flow in the desired direction.

Booties are required for access to the high bay. Wood, cardboard and other particulate-generating materials are excluded.

Laser safety provisions and procedures comply with with ANSI Z136 and MIT/CSR campus regulations, and generally parallel the analogous LIGO site policies. For example, provision is made for electrically interlocking lasers operated within the high bay and adjacent labs to dedicated laser warning signs at all entry points, and all operators are certified by a safety training course and eye exam.

4.1.2 Associated Laboratories

Laser and mechanical labs, cleaning facilities, a small but complete machine shop, and electronics labs are on the same floor and available for staging, part fabrication, and side experiments.

4.1.3 LASTI Vacuum envelope and pumping system

The LASTI consists of one BSC and three HAM chambers as shown in Fig 3. The connecting tube is 76 cm internal diameter, and the end chamber center-to-center distance is 16.0 m (the left arm midchamber is situated midway between the ends).

Vacuum pumps and instrumentation are described in LIGO- E990383-03. Briefly, high vacuum is achieved in the main volume using a 1600 l/s turbomolecular pump backed by a dry-type 80 m^3/h hook-and-claw pump, which is also used for roughing the main volume. As in LIGO site installations, major access ports are sealed with dual O-rings; the flange annuli between these seals are pumped by small 50 l/s turbopumps (backed by dry membrane pumps) and a 70 l/s ion pump dedicated to each chamber.

Once at high vacuum, provision will be made for “silent” pumping using a combination of ion pumps and liquid nitrogen cold traps. The exact deployment is currently TBD pending evaluation of the envelope and internal component outgassing budget.

To test the LIGO II seismic isolation and suspension systems, we are planning to use the left arm. The first article LIGO II HAM and BSC isolation stacks will be installed in the end HAM and corner BSC, respectively; the midpoint HAM will support input/output optics on a LIGO I type isolation. There is additional capability for isolating the other (right end) HAM for offline testing, if need be, by reconfiguring test covers and tubes.

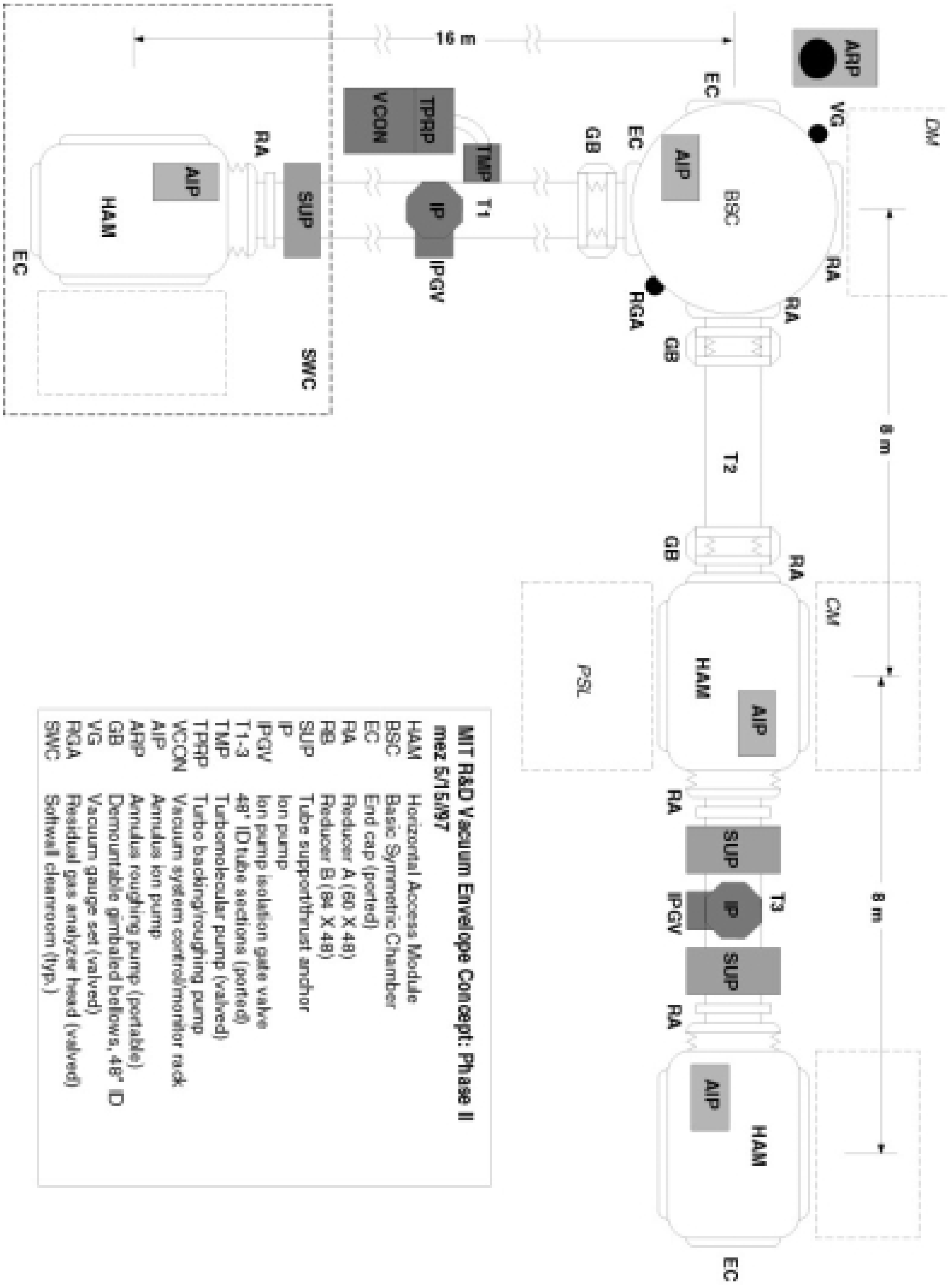

Figure 3: LASTI Vacuum system layout.

4.1.4 Seismic isolation interface

The external seismic isolation support structure consists of the LIGO I 'blue piers', and support tubes and bellows are also available in the (desirable) case that this remains part of the interface to the LIGO II isolation system. No LIGO I scissors tables or fine actuators are provided; this space may be used by LIGO II isolation systems for external actuation.

It has yet to be determined how external excitation will be provided; it may occupy some of the scissors table/fine actuator height/volume. It may be sufficient to act on the PEM plates on the ends of the support tubes for most tests.

4.1.5 Optical Sensing system & Control Topology

The sensing system must have a sufficiently small shot noise and associated noise terms to allow a significant test of the suspension system. Our target for the test-mass suspensions ideally should be 10^-19 m/rHz at 10 Hz, and 10^-20 at 100 Hz, to be modified as the final (thermal-noise limited) performance of the overall LIGO II system is firmed up.

The best sensing configuration to test suspensions appears to be a short high-finesse Fabry-Perot cavity formed of two mirrors suspended in the trial suspension system (sketched in Figure 4). The laser wavelength will be referenced to a longer suspended cavity, whose mirrors are permitted to have higher displacement noise in proportion to its greater baseline. The 16 m length of the LASTI vacuum envelope sets the scale of this cavity. This cavity also serves as a mode cleaner, being used in transmission (see below).

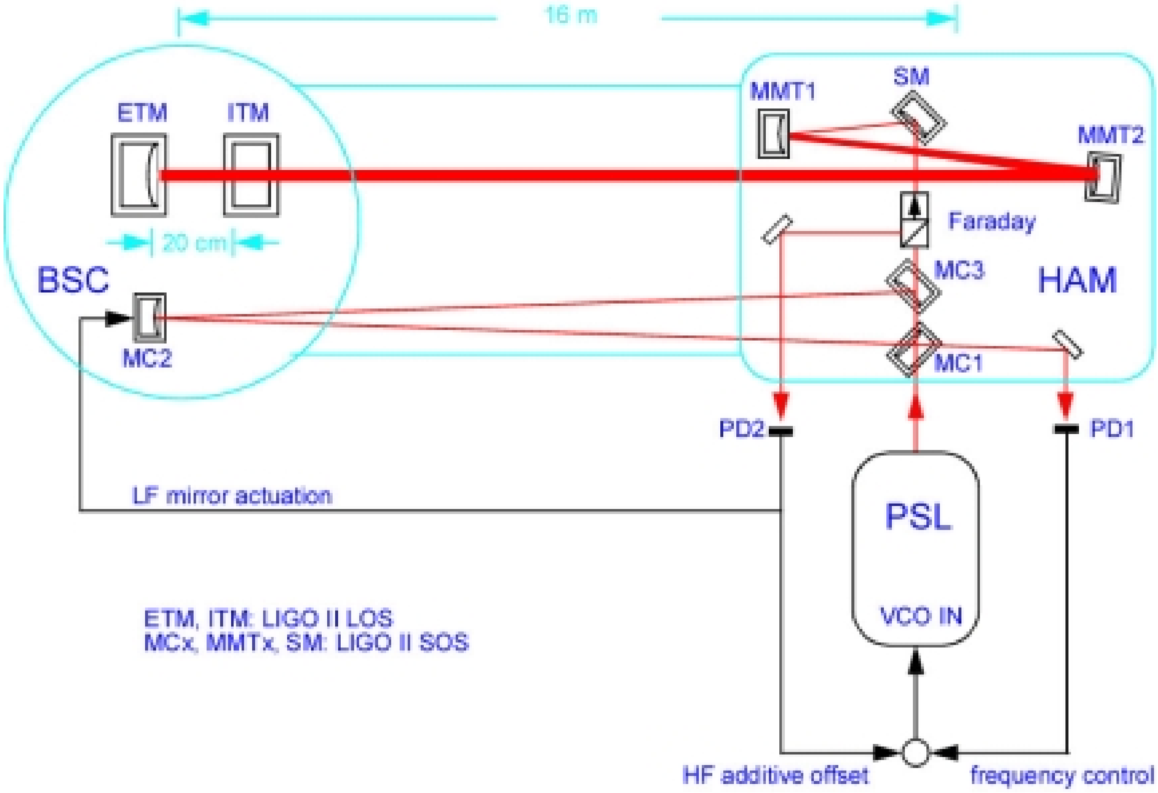

Figure 4: LASTI optical layout

This greater tolerance to displacement noise in principle permits greater control actuation bandwidth and dynamic reserve on the longer cavity's mirror actuators. The most promising topology has the laser locked tightly to this cavity (using an acoustooptic VCO between the laser and its fixed reference cavity). Moderate-bandwidth acquisition and control of the light wavelength to match the shorter, low-displacement-noise cavity is effected by the actuators on the longer cavity. This permits testing the low-noise suspensions without increasing the control authority or bandwidth of their actuators to compensate for the noisier environment at MIT.

Wavefront sensing will be employed for alignment of all suspended cavities.

4.1.6 Noise sources

Some estimates for the limitations of the sensing arrangement are as follows.

4.1.6.1 Shot noise

A first approximation to the displacement equivalent shot noise is given by $x \approx (\pi / 2F)(\lambda / 2\pi)\sqrt{2e/I}$. A finesse of 15,000 (mirror loss plus scatter comparable to 1/15000 or 66 ppm/bounce), wavelength of 1064 nm, and an incident photocurrent of 2 amperes leads to a shot-noise limited sensitivity of 1e-20 m/rHz. This will be degraded by the photodiode efficiency, and the modulation system, by a factor of ~2. The detected photocurrent can be much less, depending on the 'impedance match' to the cavity. The incident power would need to be 3-4 W to obtain this sensitivity.

4.1.6.2 Laser frequency noise

We take as the point of departure the relation $\delta x / x = \delta \nu / \nu$. We would like to make the cavity as short as practical; we take 20cm as a first guess. This leads to a requirement that the frequency noise be 1.4e-6 Hz/rHz at 10 Hz and roughly 10x better at 100 Hz, a very difficult requirement to meet. We propose to have a frequency stabilization cavity formed of LIGO II Mode Cleaner mirrors (2 or 3, TBD), over the baseline between the HAM and BSC isolation stacks. This gives a length of 15 m, which must show equivalent displacement noise of 7.5e-18 m/rHz at 10 Hz and have an equivalent shot-noise limited sensitivity (requiring ~200 mA of effective photocurrent).

4.1.6.3 Laser intensity noise

The technical and fundamental radiation pressure must not induce motion of the mirrors greater than the sensing requirement. As the circulating power is much lower than LIGO II, we can be assured that the fundamental radiation pressure noise is negligible. Similarly, if the laser can be intensity stabilized to roughly 18 (180W/10W) times more lax requirement than that for LIGO II, technical noise should be manageable. Needs numbers.

4.1.6.4 Laser beam pointing noise

The baseline design calls for using the Mode Cleaner as a cavity in transmission and to exploit its ability to suppress pointing noise. Needs numbers.

4.1.6.5 Thermal noise

The thermal noise in the short Test-Mass suspension cavity will be increased above the target for LIGO II if the laser spot size is not comparable to that in LIGO II. Both structural and thermoelastic damping become smaller with larger beam spots, with thermoelastic (probably dominant if we use Sapphire mirrors) falling as r^-3/2 in displacement. If a similar cavity 'g' factor were to be used for the LIGO II and LASTI cavities, we would expect a beam spot in the ratio of the square roots of the lengths, or sqrt(0.2/4e3)=7e-3, and a thermoelastic contribution 1.7e3 greater in LASTI than in LIGO II.

While this could provide an excellent opportunity for investigating thermoelastic (or other beam-scale-dependent) noise, it could prevent stringent tests for other technical noise. We will therefore plan for a cavity g-factor which affords an intermediate spot size, consistent with maintaining cavity stability against initial errors, thermal lensing, and spatial mode degeneracy. No evaluation has been made to date of the limits to this approach.

4.1.7 Suspension and seismic isolation controls

The controls for the combined seismic isolation and suspension systems will be as close as possible to the actual LIGO II article. The increased seismic activity at the MIT site may force some trades in selection of noise and dynamic range parameters, or alternatively, restrict the most sensitive tests to quiet times of day.

4.1.8 Frequency & length controls

The Controls for the PSL, MC (there may be an in-vacuum pre-mode cleaner in addition to the main 15 m cavity), and for the overall locking will be adapted from LIGO-I systems. A compatible interface and gain characteristics which complement the suspension controller characteristics will be developed in conjunction with simulation of the actual LIGO II operating environment.

We expect that testing the hierarchical allocation of gain and dynamic reserve to the various stages of suspension actuation will be significantly easier on this simplified optical system. A sketch of the controls layout and principal signal paths is shown in Figure 5.

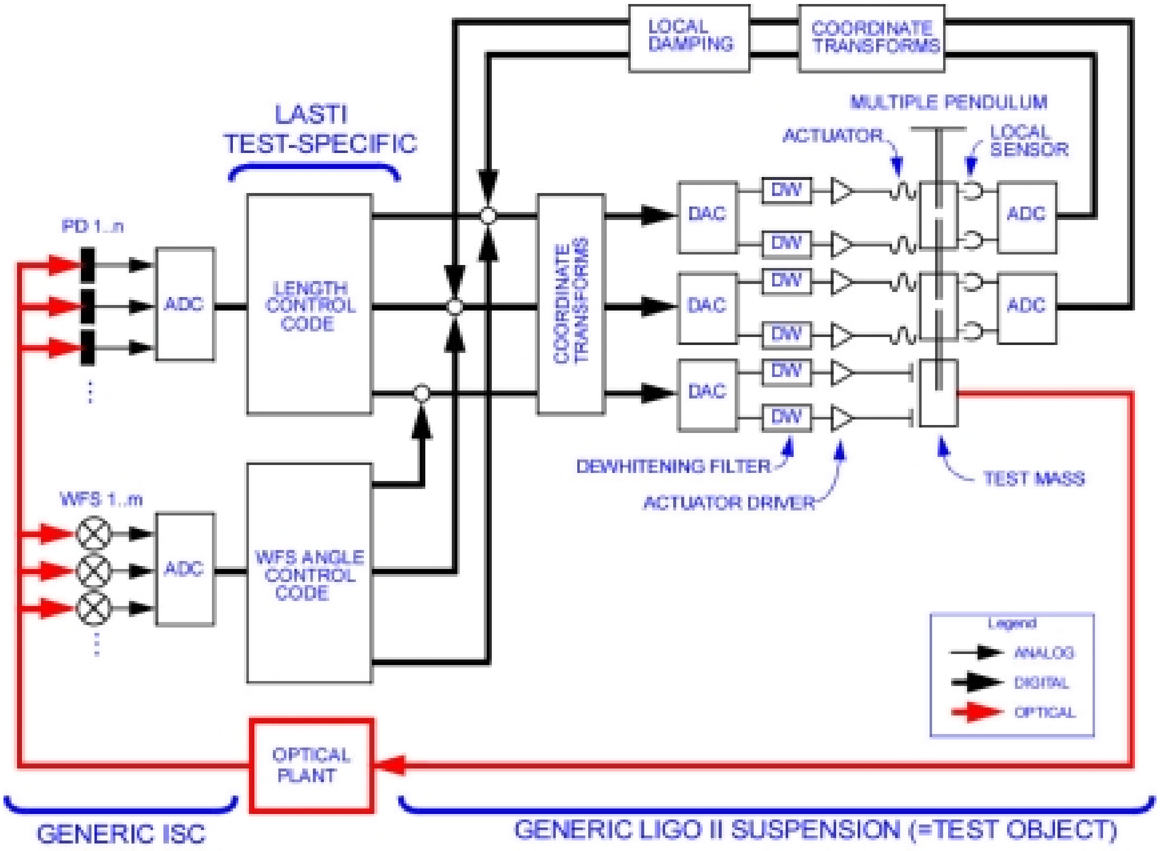

Figure 5: Controls and signal flow

4.1.9 Data system

We will want to acquire the full collection of diagnostic signals planned for LIGO II for the two isolation systems, two Test Mass suspensions, and two (or three) Mode Cleaner suspensions. In addition, we will want to be able to acquire (at least) 6 DOF of excitation and 12 DOF of auxiliary seismometer data. The normal suite of diagnostic signals associated with the PSL and IO/mode cleaner length/frequency and alignment controls will also be required.

No extended data collection is anticipated, so that ‘spinning media’ and ordinary backup tapes should be sufficient for storage.

4.1.10 Tests of the infrastructure

4.1.10.1 PSL

The PSL will be assembled and tested stand-alone.

4.1.10.2 Trial cavity

A LIGO I HAM isolation system will be assembled (in the ‘Y-midstation’ HAM) and a cavity formed of PNI (earlier LIGO I Phase Noise Interferometer) components as a test of the integration of the PSL and to get people and systems up to speed. This cavity can/will also serve as a suspended pre-mode cleaner for the remainder of the tests.

Control and Data systems will be exercised at this opportunity.

4.2 Stand-alone Seismic Isolation testing

Once the infrastructure is ‘qualified’, we move on to the SEI and SUS testing per se. Ideally, each significant requirement for each subsystem will be tested, and the test list below is organized by requirement. For the seismic isolation, the principal requirements are the isolation in all degrees of freedom, and the actuation performance.

Both the BSC and the HAM isolation systems will be tested similarly. The discussion below refers to BSC isolation requirements for some examples but the test program is the same. At the present time, the purpose of the list is to help define the scope of the LASTI effort. As the SUS and SEI subsystem designs advance, there will be more complete test programs developed there which will drive the LASTI program.

4.2.1 Mechanical characteristics

4.2.1.1 Dimensional interface

Measurements of the dimensions of the isolation system, interfaces to the seismic support and the vacuum envelope. Because the LASTI Laboratory has a lower hook height than the LIGO Site VEAs, it may be necessary to modify the LASTI BSC top cover (by segmenting) to allow installation of a seismic isolation system.

4.2.1.2 Payload and Payload geometry

A set of dummy payloads will be installed to ensure compliance with the requirement and to establish the correct operating point for further tests.

4.2.1.3 Suspension interface

The dynamic interfaces to the suspension will be checked: ability to handle dynamic forces and torques correctly.

4.2.2 Isolation performance

The isolation will be tested using seismometers and geophones as sensors, and electromagnetic shakers external to the vacuum system as actuators. Sensitivities of commercial instruments are just sufficient to test that requirements are met.

4.2.2.1 Start-up and Acquisition mode

Performance without additional interferometer signals. This is a test of time to reach operational specifications, and a test of velocity during the interferometer locking process. Due to the larger seismic input, an attenuation will be measured as opposed to a simple velocity along with auxiliary measurements to ensure internal noise (active/passive) to be consistent with requirements.

The velocity and displacement with respect to inertial space must be characterized. The BSC requirement at present calls for a velocity of 10^-9 m/sec and displacement of 10^-14 mRMS, integration down to 0.01 secs.

4.2.2.2 Operation mode

Performance as for operational mode. Interferometer signals will not be available in the first stand-alone tests of the isolation system, but will be in the later integrated suspension-isolation test. The isolation will be tested with external excitation to form transfer functions of all DOF.

The GEO suspension design of Jan 00 (LIGO-T000012-00-D) delivers greater than 10^6 isolation at 10 Hz and above. The overall performance requirement of the BSC isolation and the suspension is 10^-19 m/rHz at 10 Hz. The seismic input best estimate at present at 10 Hz is 10^-9 m/rHz. Thus the isolation system must deliver at least 10^4 isolation in the horizontal axis at 10 Hz and may remain constant above 10 Hz (the suspension delivers adequate additional isolation at higher frequencies).

4.2.3 Actuation

4.2.3.1 Coarse alignment mode

Response to control signals measured using seismometers, optical levers, and position detectors (with respect to the facility floor).

4.2.3.2 Operation mode

Response to control signals measured using seismometers and geophones.

4.2.4 Internal resonances

The Q of internal resonances will be measured; their appearance in transfer functions characterized.

4.2.5 Internally generated noise

Due to the higher seismic background in LASTI, the lowest frequency at which meaningful tests can be performed is XX. Need a Figure X showing the LIGO II noise curve, and the various limits to LASTI testing: Seismic noise at LF, Seismometer and geophone noise nearby, thermoelastic due to small spot size at intermediate frequencies, shot noise above.

Seismometers and geophones will be able to make a significant excess-noise measurement up to XX Hz. Higher frequencies must use interferometric sensing in the integrated test described below.

4.2.6 Drift and Thermal expansion

signals measured using seismometers, optical levers, and position detectors (with respect to the facility floor).

4.2.7 Signal and power delivery

Checked against requirements.

4.2.8 Installation procedures

The initial installation may be ad-hoc and used to help develop installation procedures to be tested during the First-Article test, described below.

4.3 Differential Seismic Isolation testing

Once both the BSC and the HAM seismic isolation systems have been individually tested, a measurement will be made of the differential motion between the HAM and BSC over the 15m LASTI baseline. Mirrors will be placed in fixed mounts on the optics tables of the isolation systems, and brought into rough alignment in air. Coarse actuation will be used to complete the coarse alignment, with fine alignment provided by the injection optics.

The differential motion will be the final test of the isolation system actuation, stability, and isolation.

4.4 Stand-alone Suspension Testing

The outline for suspension testing resembles that for the isolations systems. The suspensions are first tested stand-alone insofar as possible; final control, isolation, and noise performance is tested interferometrically.

Here is a guess at the significant tests and how they are addressed.

4.4.1 Mechanical characteristics

4.4.1.1 Dimensional interface

Measurements of the dimensions of the suspension system, interfaces to the isolation system and the vacuum envelope.

4.4.1.2 Isolation interface

The dynamic interfaces to the isolation will be checked: dynamic forces and torques delivered, response of the isolation system.

4.4.2 Suspension performance

The basic damping and modal control will be tested using the seismic isolation system as an actuator and the internal suspension sensors as sensors.

4.4.3 Actuation

4.4.3.1 Coarse 'Safe' alignment mode

Response to control signals measured using optical levers, and position detectors (with respect to the facility floor).

4.4.4 Internal resonances

The Q of solid-body resonances will be measured; their appearance in transfer functions characterized.

4.4.5 Drift and Thermal expansion

signals measured using optical levers, and position detectors (with respect to the facility floor).

4.4.6 Signal and power delivery

Checked against requirements.

4.4.7 Installation procedures

The initial installation may be ad-hoc and used to help develop installation procedures to be tested during the First-Article test, described below.

4.5 Differential Suspension Testing

This is the point in the program where the noise performance is tested interferometrically. The following is a guess at the significant tests and how they are accomplished. Tests will be performed first on the Mode

Cleaner suspensions, and then that characterized cavity will provide light for the characterization of the Test Mass suspensions.

4.5.1 Suspension performance

The basic damping and modal control will be tested using the seismic isolation system as an excitation and the cavity length and alignment controls as sensors.

4.5.1.1 Start-up and Acquisition mode

Performance with interferometer control signals. Fringe counting of cavity signals, reconstruction of the velocity. Acquisition of lock, tests of the coordinated actuation on the various intermediate masses and isolation system

4.5.1.2 Operation mode

Performance as for operational mode. The isolation will be tested with external excitation to form transfer functions of all DOF for the combined isolation-suspension system; relative displacement between the two suspensions on the BSC optical table will be used to check similarity of suspensions.

4.5.2 Actuation

4.5.2.1 Coarse alignment mode

Response to control signals measured using, optical levers, and position detectors (with respect to the facility floor. Cross check that the interferometer alignment signals agree with the commanded coarse actuation.

4.5.2.2 Operation mode

Response to control signals measured using the cavity signals (alignment, length).

4.5.3 Internal resonances

The Q of internal resonances will be measured; their appearance in transfer functions characterized.

4.5.4 Internally generated noise

Short and long-term deviations from anticipated noise performance. Refer to Figure X showing the LIGO II noise curve, and the various limits to LASTI testing.

4.5.5 Drift and Thermal expansion

Differential signals measured using seismometers, optical levers, position detectors (with respect to the facility floor), and the interferometer length and angle controls.

5 Schedule

The schedule is laid out in the LSC Sept 99 White Paper, and is reproduced here with annotation. We would like to reconsider internal readiness milestones as the LASTI program becomes better defined and feedback is received on the overall plan.

5.1 4Qq99: LASTI envelope commissioned

The vacuum envelope is installed and aligned; the vacuum pumping system is commissioned, and the system is pumped down for the first time.

5.2 1Q00: LASTI external structures installed

The seismic piers are erected around the HAMs and BSC. We may choose to delay this milestone until a firmer baseline for the seismic isolation is established to avoid any backtracking. However, one of the present requirements is that the seismic isolation system use these support piers, and it is anticipated that they will be installed exactly as for LIGO I (so that this will be the interface at the LIGO sites). Delaying this milestone would not have any impact on progress until prototype isolation systems are available, anticipated in the 4Q01.

5.3 2Q00: LASTI infrastructure design review

This review should have noise sources detailed, models for the performance of the system, complete costing and manpower estimates. It is not a review of the isolation or the suspension subsystems, but rather a review of the optical sensing system, control and data, mechanical interfaces to LASTI, and of the experimental program.

5.4 3Q01: LASTI infrastructure complete

The LASTI sensing system, control and data, and a trial cavity test of the complete system function should be complete and reviewed at this point.

5.5 1Q02: LASTI prototype installation complete

There should be high-quality prototypes of the HAM and BSC isolation systems, and ‘controls prototypes’ of the suspensions, installed and ready for tests to start for this milestone.

5.6 3Q02: LASTI locked

The optical sensing system for the Mode Cleaner and the Test Mass Suspensions should be functioning and the cavities locked. No performance requirement.

5.7 1Q03: LASTI controls test review

An understanding of the controls performance of the seismic isolation systems and of the suspensions should have been achieved, possibly with some work to do to feel comfortable with the measurements and the designs.

5.8 2Q03: LASTI noise prototype installed

The ‘controls prototypes’ for suspensions should be changed out and fused silica fiber, sapphire test mass Test Mass suspensions should be installed.

5.9 3Q03: LASTI noise performance test review

This milestone should be renamed to ‘how many suspension fibers were broken and what is not working’ review.

5.10 1Q04: LASTI final test review

This milestone should indicate the status of tests to meet the noise performance verification. The duration of time from the installation to the final review is far too short to have comfort that we will have finished, and as this time approaches we may choose to adjust our goals and/or milestones.

5.11 1Q04: LASTI first article installation starts

Installation, using the planned installation jigs and procedures, of seismic isolation and suspensions.

5.12 3Q04: LASTI first article tests complete

After some number of reworks, the completed systems will undergo whatever testing we mandate. This may or may not include performance testing.

6 Manpower

The success of this endeavor will require significant contributions from LSC members in and out of the Lab for success.

In March 00, there is presently a technician and bits and pieces of Zucker and Shoemaker working on the vacuum system and experimental design.

This number will ramp up this year to perform the design and to procure and start to install the infrastructure. This is anticipated to require principally in-Lab personnel (at both MIT and Caltech, the latter for fabrication of PSL and CDS components).

We anticipate that there will be roughly 6 FTEs in the MIT Lab working on this effort in the latter stages: 1 technician, 1 net FTE engineer, 2 students, 1 postdoc, 1+ scientist.

A crude estimate is that we need roughly again as many people in moderate-term visits to MIT or thinking hard about the data and making frequent visits; this must be LSC folk (in and out of the Lab).

These manpower guesses do not include the staff associated with specific subsystems, although there will clearly be overlap in effort in the likely event that a mechanical subsystem is centered at MIT.