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Overview for the Advanced LIGO
HAM ISI Preliminary Design Review

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1 Introduction

This is an overview document for the Preliminary Design Review for the Advanced LIGO HAM Internal Seismic Isolation (ISI) system. This is a single stage isolation system to be installed in 5 of the 6 HAM chambers for each interferometer in Advanced LIGO. This system is part of the total isolation and alignment system for Advanced LIGO. It will be supported by a HEPI system (not part of this review) and is designed to support a total payload (including balancing masses) of 510 kg. The payload is also not part of this review, although we are concerned about the interaction of the HAM ISI control system and the mechanical vibrations of the payload, and we present some information about that interaction. The support structure for the HAM will be modified to accept HEPI, and the gullwing will be replaced by a new, stiffer crossbeam. Information about the crossbeam is included as related material for this review (including [E080356] 'Technical Justification' and [E080328] - documentation and discussion of the FEA for the crossbeam design). The procurement of the new crossbeams is part of the HEPI system. The decision to go forward with the new crossbeams has already been approved as part of the HEPI fabrication readiness review.

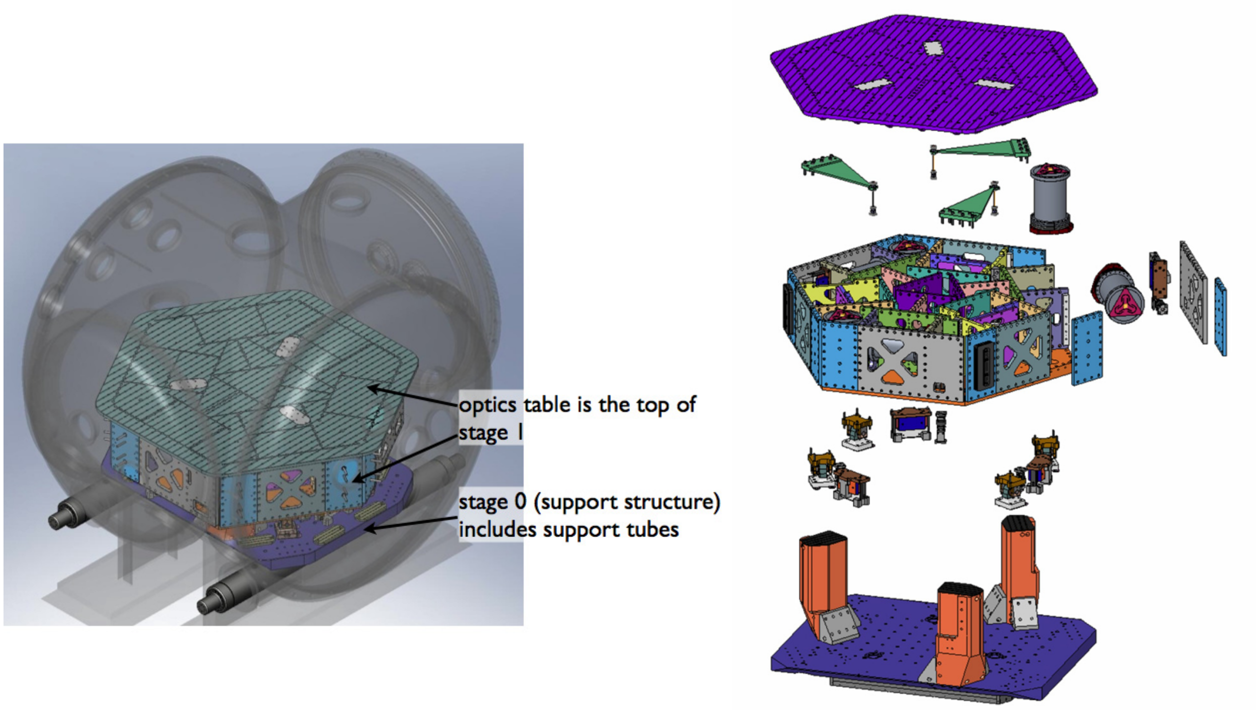

Figure 1. Left: CAD drawing of the HAM-ISI in a semi-transparent HAM chamber. Stage 0 will be mounted to the new crossbeams, and mounted on HEPI. Stage 1 is the isolated stage, and the optics table is the top plate of stage 1. Right: Exploded view showing various key components.

The development of the HAM-ISI system was accelerated so that units could be installed into HAM6 of LLO and LHO to support the output mode cleaner for Enhanced LIGO. Two units have been fabricated and installed. Commissioning work on these units is well underway, but not complete. Results so far indicate that only very minor changes are desired to the design before we go into full scale production for Advanced LIGO. We do not anticipate any changes to the installed HAM6 ISI mechanical hardware now at the observatories, i.e. the units now in L1 HAM6 and H1 HAM6 are the units to be used by Advanced LIGO. The external systems will be modified to install the new crossbeams and HEPI.

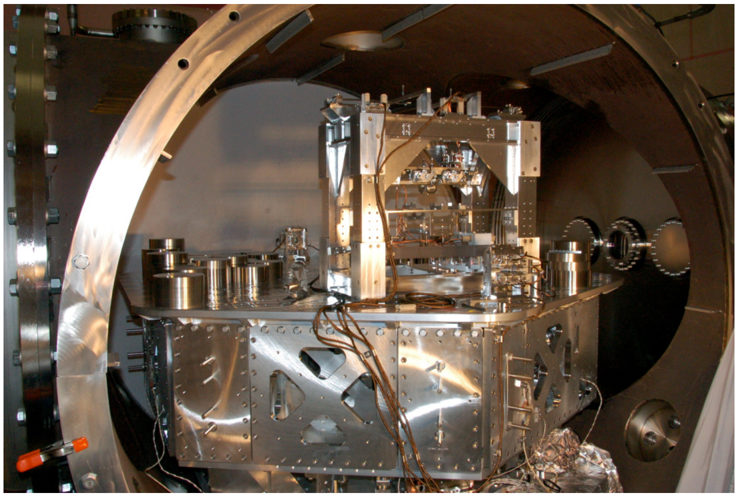

Figure 2. HAM ISI installed in L1 HAM6. The Enhanced LIGO output mode cleaner is installed on top of the platform. (S. Waldman, LLO log, March 14, 2008)

Even though we are pleased with our progress to date, we are anxious to take this review opportunity to explain the system capabilities, explore the weaknesses in the designs and implementation, and prepare to move forward in the best way possible. There are a few changes we intend to make in the mechanical design and also a few changes we plan to make in the electronics. These are described in referenced documents in the following sections. These changes are all minor. A major change to HAM6 in Advanced LIGO will be the installation of HEPI, which will be important for two reasons. First, the damping network in the HEPI actuators should substantially reduce the Q of the 11-15 Hz peaks now present in the support structure. Second, the low frequency motions will be performed by the HEPI actuators, which will greatly ease the steady-state in-vacuum power requirements for the HAM actuators. Several questions remain about the allocation of authority for the low frequency control, however. These questions are raised in the controls and performance section of the documents.

The review documents are arranged into several categories. The first major part of this review document describes the system mechanics, including the mechanical design, cleaning, assembly, testing, and installation of the platform. We discuss the sensors and actuators, including their preparation, cleaning, and testing. We also discuss the electronics required to run the system. We describe a large number of test procedures which have been developed, which range in scale from parts, to sub-assemblies, to end-to-end checks of system function.

The second major part of this review document is devoted to the isolation performance of the HAM ISI system. A detailed model was used in April 2006 to predict the isolation performance of a single stage HAM system mounted on HEPI. That modeling effort demonstrated that the HAM ISI would meet its performance goals above 0.6 Hz if: 1) the passive isolation were at a certain level, so that most of the 10 Hz isolation performance was passive, and 2) the system used good sensors and was able to run with control loops whose upper unity gain frequencies were about 23 Hz (or higher). We have demonstrated good active performance with the Tech Demo system at the Stanford Engineering Test Facility. Experience with the Tech Demo set the parameters for the design which affect the ability to do active control, and the performance modeling then set the level of passive isolation needed to reach our performance requirements. ~~The modeled active performance informed a set of requirements that the mechanical system be designed for control.~~ If we have a system with good passive performance which is also designed for good active control, our models and experience indicate that system will have good performance above 0.6 Hz. Below 0.6 Hz, the tilt-horizontal coupling of the existing HEPI system poses challenges to the whole SEI sub-system. These issues are only tangentially related to the ISI design, but further discussion is included in the related performance documents.

To date, we have shown that the passive isolation meets all of our expectations, and that our efforts to build a system which is easy to control have been successful. At this time, the implementation of high performance controls on the installed platforms is still underway, and so we have not yet been able to demonstrate all of the performance of which we believe these systems are capable. The performance data to date is promising, but does raise concerns about the external structures now in place. We are still working to understand the noise performance below 0.2 Hz. Since we have not yet commissioned the sensor correction performance, there is also uncertainty in that area.

The final part of this review document describes our plans to-date for moving into full-scale production for Advanced LIGO. Considerable planning has gone into this area, but it is not yet complete.

2 Mechanical System and Electronics

2.1 Mechanical Design - requirements

The detailed mechanical design of the HAM-ISI was done by High Precision Devices (HPD) in Boulder, CO. The design was done to a detailed set of specifications [E030180-02] which can be grouped into four basic technical areas: Interfaces to other subsystems, passive isolation performance, design for active control, and UHV compatibility. Considerable attention was also devoted to assembly and safety. LIGO conducted a Final Design Review of HPD's work on the mechanical design for the Enhanced LIGO system in March 2007. HPD created an extensive presentation [E070156-00] about the system and what was done to meet the design requirements. In April 2007, we created a status report [T070088-00] based on that review and concurrent lab work with discussion about many of the key elements of the design, including predicted performance, installation, ease of use, balancing, locks and limits, and access. A summary of the requirements are given below.

Interface: The system interfaces to the existing HAM support tubes. The major interface is the optical table surface. The table is aluminum, with a 2" on-center grid of ¼-20 tapped holes. The table height is either at (LIGO global coordinates) z = -200 mm or z = -325 mm [T070076-02]. The Initial LIGO tables are at z = -200 mm. Because the first installation is set for the Initial LIGO table height, a spacer was designed which fits between the support tubes and the base (stage 0) of the system. This spacer will not be present in some of the Advanced LIGO tables, which allows us to set the different heights. The system is designed to support 510 kg of payload. This payload includes the optics, detectors, wiring, etc., and also all of the counter-weights necessary to balance the table so that the cg is at the horizontal center of the table. This is similar to the balancing for Initial LIGO.

Passive Isolation: In order to meet the performance goals, the isolation platform is suspended and designed to give substantial passive isolation at 10 Hz. The system was designed to have natural frequencies between 0.8 and 1.8 Hz, depending on the DOF. Discussion of the various modes is described in the measurements sections.

Readers who have been following the evolution of the platform designs should note that the rX and rY natural frequencies are now comparable with the X and Y frequencies. This should help prevent 10 Hz tilt motion generated by deformations of the support structure from violating our motion requirements (c.f. the Tech Demo at Stanford). This was accomplished by keeping the free end of the springs close to the center of the table (reducing the tilt stiffness) and having major elements of the mechanical structure near the edge. Having the 'close-out plates' around the perimeter also helps keep the bending modes quite high.

Design for Active Control: The alignment of the system for ISC control and the isolation at performance between 0.1 Hz and 1 Hz comes entirely from active control. The system was designed to make the use of active control as simple as possible so that we could meet our performance requirements using only simple SISO controls. (Although we note that having a simple, well-behaved plant will also ease the implementation of more elaborate modern control techniques.) The design attempts to minimize tilt-horizontal coupling by carefully aligning the horizontal actuators with the 'Lower zero-moment points' of the flexures, and by aligning the ‘upper zero-moment points’ of the flexures with the neutral axis of its blade. This way, horizontal forces by the actuators result only in horizontal restoring forces from the suspension elements, and the torque-moments are very close to zero, so the stage has only minimal tilt resulting from horizontal drives.

The design also attempts to keep the bending modes of the table above 250 Hz, and is designed to keep the local inertial sensors very tightly coupled to their respective actuators. Bending modes complicate the control design, so by keeping the bending modes well above the upper unity gain frequency (25- 30 Hz), we both enable better active isolation at 10 Hz, and simplify the overall isolation design.

Close examination of the mechanical design will reveal many places where extra care has been taken, or access has been compromised, in order to create a system which is easier to control and has better performance. These include the precision of the actuator mountings, close-out plates all around the perimeter, a thick platform structure with many stiffening ribs, etc.

UHV compatibility: The system is designed for LIGO UHV compatibility. The inertial sensors are all contained in UHV ‘pods’, and the actuators are made from UHV materials and undergo several cleaning steps in their production. There are no greases used in the final parts.

2.2 Mechanical Design – The design

Based on these requirements, the system was designed, reviewed and built. The system is mostly composed of machined aluminum plates bolted together in closed, box-like ways. The design is stiffness driven, with the intent of driving the bending modes of stage 1 above 250 Hz, and making stage 0 so stiff that variations in the mounting of the ends of the support tubes do not deform the stage 0 structure enough to create interesting misalignments of the systems which span the two stages (actuators, displacement sensors, and locker/ limiters). The assembly drawing of the mechanical design for the two systems currently installed in L1 and H1 HAM6 can be seen in [D071400-C]. A Solidworks e-drawing of the system ‘Single Stage HAM Model’ is available at the Advanced LIGO wiki for the HAM ISI PDR .

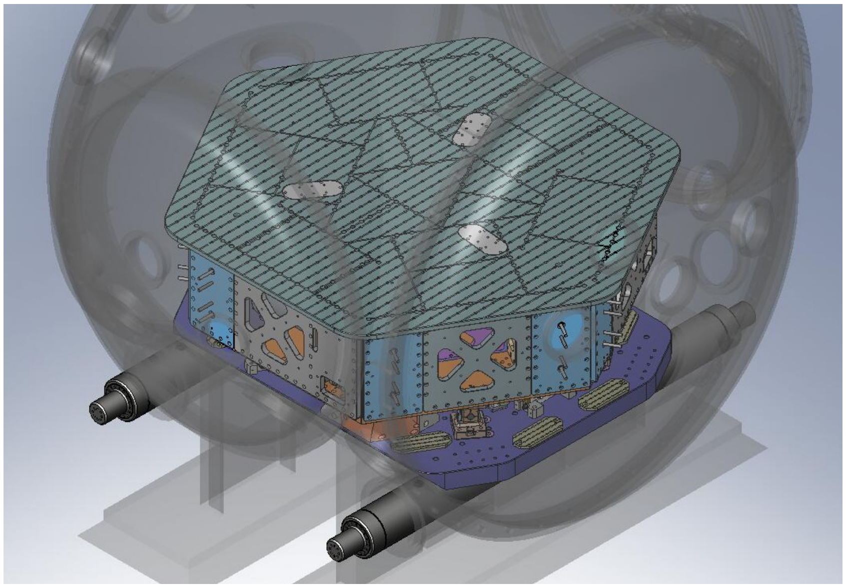

Figure 3. View of the HAM ISI in a semitransparent HAM chamber.

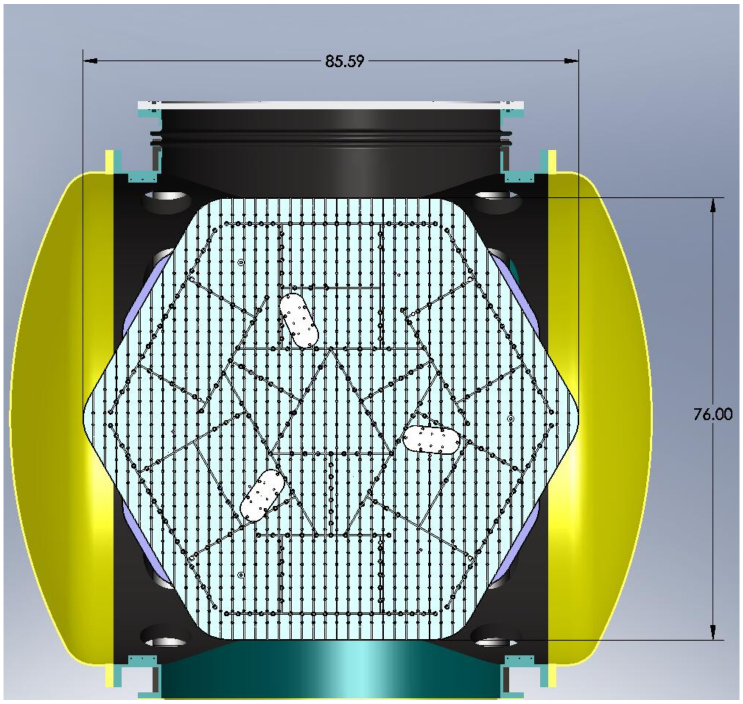

Figure 4. Dimensions of the table top, in inches.

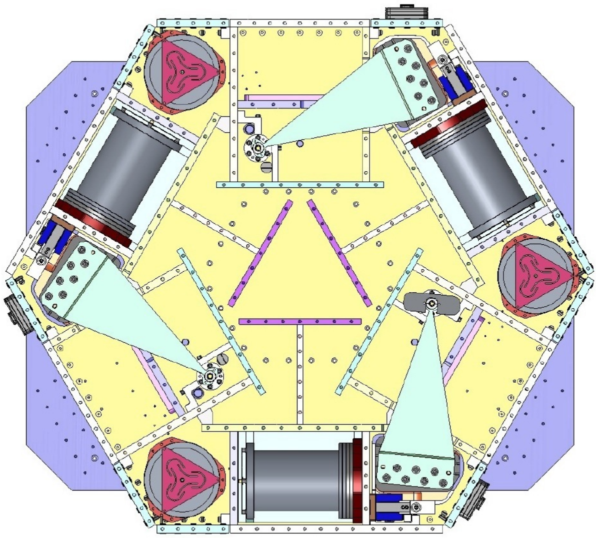

Figure 5. Top view of the isolation stage, with the table top removed to show the placement of major components such as the triangular blade springs and the GS-13 inertial sensors (in the 3 horizontal grey cylinders, and the 3 vertical cylinders, which here appear as circles). The 3 horizontal actuators can be seen in blue adjacent to the horizontal GS-13s. The vertical actuators are below the vertical GS-13s. The displacement sensors are below the horizontal actuators.

A few key parameters of the design are given here. An extensive discussion of the design can be found in the FDR document which HPD prepared [E070156]. Additional discussion about the table balancing, access to the lockers and instruments when the table is installed, table balancing, and ease of use can be found in our HAM status report for April 2007 [T070088].

In the fall of 2007, we did a ‘dirty assembly’ of the LHO system at the HPD facility in Boulder CO as a test run of the assembly and to measure the basic mechanical properties of the system. The assembly went smoothly, and the measurements we made of the system indicated that the system met or exceeded its requirements. A report of the tests can be found at [T080001]. A summary of those tests follows:

Basic mechanical function

1) Make sure it goes together: A few small things needed fixing and were fixed.

2) Measure table flatness: The requirement was 27 mils peak-to-valley. The goal was 10 mils peak-to-valley. We measured – inside the close-out plates, typical p-v <= 2 mils, a few spots at 3 mils. The worst we saw was at one edge of the table near a corner: 5 mils.

3) Test locker/ limiters: vigorous pushing by staff members did no damage to any parts. The alignment we achieved with the limiters prevented any contact by actuators, displacement sensors, or anything else. The lockers held the table location to about 12 microns when we sat on the table. The repeatability of the locked location of the table was good to about 12 microns.

4) Demonstrate table balancing: Goal was 200 microradians. We set the vertical location to about 1.5 microns, and the tip/ tilt to about 6 microradians.

5) Demonstrate free motion: We were not able to measure any effects of rubbing.

Design for isolation performance

6) Measure the natural frequencies and spring rates: these were all within specification, and close to the FEA predictions

The natural frequencies are:

DOF	Design range	FEA est	HPD	LLO	LHO
X	1.0 – 1.4 Hz	1.32 Hz	1.28 Hz	1.28 Hz	1.25 Hz
Y	1.0 – 1.4 Hz	1.32 Hz	1.29 Hz	1.29 Hz	1.25 Hz
Z	1.3 – 1.9 Hz	1.80 Hz	1.78 Hz	1.80 Hz	1.85 Hz
rX	0.8 – 1.1 Hz	1.07 Hz	1.00 Hz	0.98 Hz	1.05 Hz
rY	0.8 – 1.1 Hz	1.07 Hz	1.00 Hz	1.05 Hz	1.10 Hz
rZ	0.8 – 1.2 Hz	0.9 Hz	0.80 Hz	0.80 Hz	0.85 Hz

Total vertical stiffness: FEA=2.42e5 N/m, LLO = 2.67e5 N/m, LHO = 2.76 N/m.

The springs seem to be slightly stiffer than expected, but within our tolerances. We do not plan on making any changes to the springs.

7) Measure the tilt-horizontal coupling of the mechanical system, and other cross-couplings: There are many sources of tilt-horizontal coupling in structures. We did not set an overall requirement on the tilt-horizontal coupling. We did set a requirement on the most obvious source of the coupling, which is the misalignment of the horizontal actuators with the Lower Zero-Moment Plane of the flexures. This requirement was set at 1 mm. We measured the tilt-horizontal coupling to be 3.3e-3 radians/meter for X to rY, and 2.5e-3 radians per meter for Y to rX. This small level of coupling is excellent, and is equivalent to a misalignment of 0.61 mm and 0.46 mm, respectively. Further tests of this on the systems after installation at the observatories have yielded numbers which are not as good, but are still acceptable. LHO X = 0.98 mm, LHO Y = 2.04 mm, LLO X = 0.47 mm, LLO Y = 0.93 mm. One major source of error seems to be poor dressing of cables, which is discussed in the list of design changes (for ISI and for the suspensions).

Cross coupling to other modes is pretty small until we get into the bending mode frequencies.

8) First major bending mode frequency to be above 250 Hz: There are some narrow modes below 250 Hz, associated with specific items (e.g. the blade spring has a mode at 156 Hz). The first major bending mode

was at about 260 Hz. We are pleased with this performance, although if we think of easy ways to damp some of the narrow features, we will try to do so.

With this level of passive isolation and system performance, we are confident that the HAM ISI system can meet its performance goals.

Outstanding Issues with the Mechanical Design

The two systems were then cleaned (section 2.3), assembled (section 2.4) and installed (section 2.8). Based on the clean assembly, some minor modifications were required, and several additional minor modifications were suggested for future builds.

A number of items were discovered in the assembly which require attention. Most of these have been addressed in redlines to the procedure. The issue which caused the greatest delay in the assemblies was that we have several cases of stainless-on-stainless bolt galling. These bolts were replaced by silver plated versions, and the drawings and assembly documents have been (or are in the process of being) updated accordingly.

A list of suggested design changes has been assembled by Jeff Kissel and Joe Hanson [T080253]. This change list is on the PDR wiki. These are minor changes, and will make the system easier to build. The changes include making some access holes larger; improving the cable routing and clamping; improved marking for some parts and cables; several improvements to the tooling and jigging for some cables and instruments and lifting; and rounding off some sharp edges to improve the work environment. The changes which we decide to accept will all be in place in the designs by the final design review.

Helicoils in barrel nuts: The main outstand issue with the design is worth mentioning here. The aluminum barrel nuts in LLO have helicoils inserted, while the barrel nuts at LHO do not. Putting helicoils into the barrel nuts has several advantages. The nitronic-60 steel used for the helicoil insert sheds fewer particulates than the aluminum threads. This means that: 1) there is less chance for particulates to be created. However, these bolts are all below the optical table, and the particulates are probably only free to escape the nut when the bolt is removed, so we judge the risk from particulates to be small. 2) When the aluminum sheds, the particles are not the soft aluminum of the bulk, but seem to be quite hard alumina. This has been shown to cause bolt galling if the threads are used repeatedly. To combat this, we only tighten bolts into helicoil-free barrel nuts once. It things need to be taken apart, new barrel nuts should be used to help prevent galling. This is much easier to say than it is to do, and so we need clear instructions and a ready supply of clean barrel nuts if this is going to succeed. 3) Perhaps most serious issue is that the helicoils should provide a tighter bolted connection. Analysis is underway to see if major differences appear in the bending modes of the two installed systems.

The benefits of the helicoils are clear. The drawback is that they are extremely time consuming to install. At LLO, we were able to do about 1 nut per minute on a sustained basis. There are about 1000 barrel nuts per unit, making it an expensive and mind-numbing task. If we can show that the use of helicoiled barrel nuts in LLO did not make an appreciable difference to the system performance, they will be abandoned. We will be comparing the performance of the two platforms between 200 and 300 Hz in order to make a decision. This issue will be resolved for the FRD.

Note that there are also many places where bolts attach directly to tapped holes in other parts. These tapped holes (on stage 1) will all have helicoils, because the risk associated with wrecking those holes is too great to be accepted.

2.3 Cleaning

The parts are all cleaned to LIGO specifications. The large parts (big plates, support tubes) are cleaned commercially (Astropak did the HAM6 units) according to [E960022]. The large parts are airbaked at LLO.

Facilities modifications are ongoing to prepare the LLO spaces to airbake the parts for Advanced LIGO Facilities Modification Plan [T070122-00, new draft in progress]. The small parts are cleaned and vacuum baked according to standard LIGO procedure [E960022]. Special procedures have been added for the capacitive sensor heads (~~are these in E960022 yet?~~ This needs to be added to E960022 – see traveler E070328-00-X for the processing of the Enhanced LIGO heads). The clean assembly for the GS-13 pods is described in the GS-13 assembly instructions [T080086]. This includes cleaning and baking the pods, modifying the instruments, and inserting them into the clean pods. The pods are backfilled with neon tracer gas. The sealed pods are then check for instrument function, and then the sealed pods are leak-checked. [Leak check procedure needs to be submitted].

2.4 Clean Assembly.

The units are assembled according to the 'Single Stage Assembly Procedure' [E070154] by Andy Stein et. al. This document continues to evolve, but is currently in reasonably good condition, having been used and updated for 3 assemblies. Since that document is designed as a detailed guide and is 156 pages long, a précis of the assembly is given below to help understand the task. The hazard analysis for the assembly can be found at [E070330-B]. There is also a 'Gotcha' list [T080254] which has been assembled with some of the lessons learned and to help avoid easy mistakes. Much of this will be incorporated into the assembly instructions.

The system is primarily a bolted aluminum structure. Some of the bolts engage tapped holes with helicoil inserts, and many of the bolts engage 'barrel nuts'. The system at LLO was assembled with barrel nuts with helicoil inserts. The system at LHO was assembled using barrel nuts without the helicoil inserts. We are still evaluating which method is best, see previous discussion. Critical alignments are done with pins. Since we seek high bending mode frequencies, we use many bolts to insure good clamping pressure between the various parts.

Assembly begins with inserting helicoils into many of the clean parts, and assembly of various bits into subassemblies. These subassemblies get built up into small and medium sized parts. For example, two of the 'box-work' subassemblies are shown below in figure 6. These pieces go together to build up two large assemblies. One is the stage 0 assembly, which is put together on the 'test stand' which is a pair of HAM support tubes on stands anchored to the floor. The other is stage 1, minus the top, which is put together on the 'assembly stand'.

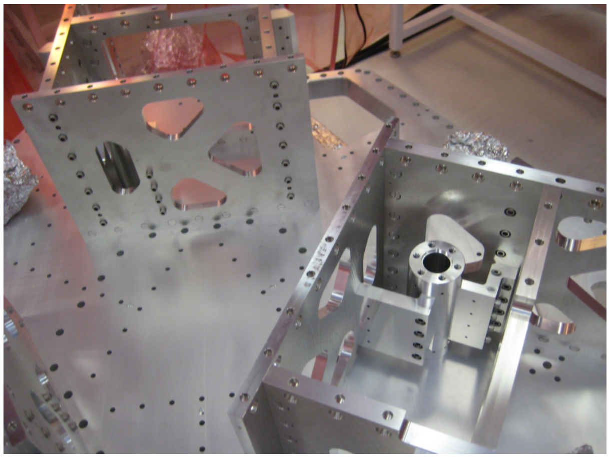

Figure 6. Two 'box-work' subassemblies mounted to the stage 1 floor.

When the two large assemblies have been put together, we put stage 1 onto stage 0, and bolt them together with the locker units.

Figure 7. Jeff Kissel guides the partially assembled stage 1 structure onto stage 0. The three large vertical spring posts can be seen on stage 0.

When stage 0 and the base of stage 1 are married, we install the springs onto the stage 0 posts, and pull them down against the stage 0 floor. This moves the springs out of the way of the optical table, but does not stress the stage 1 assembly. The spring pull down is a hazard concern, and is discussed in the assembly hazard analysis, as well as this document (below).

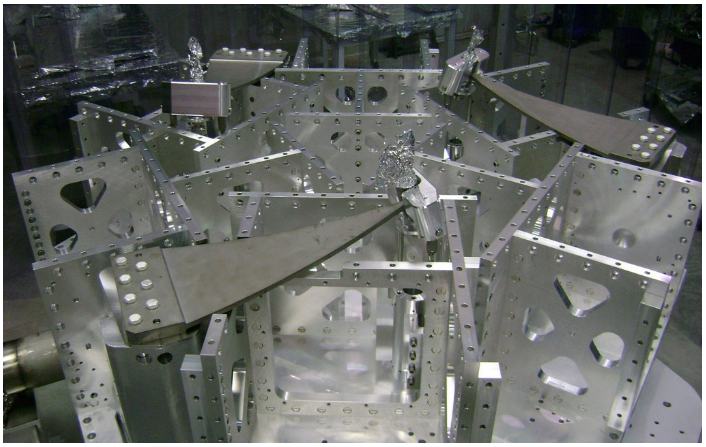

Figure 8. Stage 1 is now in place on stage 0. The 3 triangular springs have been attached to the top of the spring posts, but have not yet been tightened.

Once the springs have been pulled down the optical table is attached to the rest of stage 1.

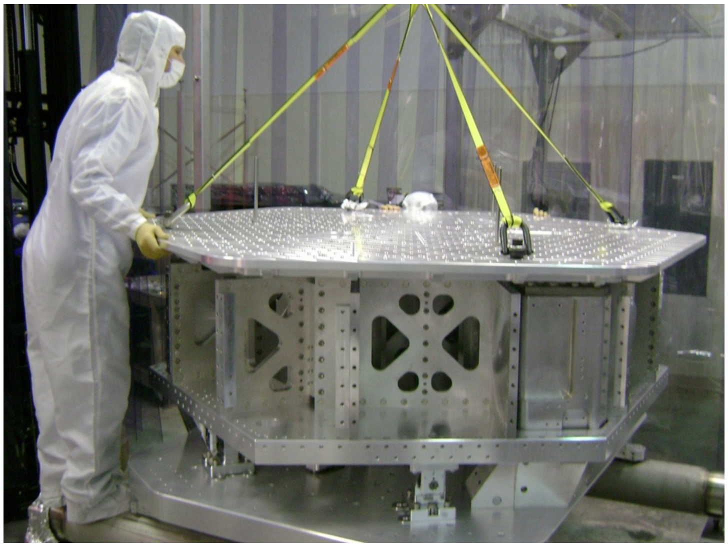

Figure 9. The optical table is guided into place as the top of stage 1.

Attaching the table top to the rest of stage 1 significantly stiffens the stage, and we finish attaching the springs to the flexures and onto stage 1. We load the flexures, and then release the spring pulldown tooling so that the springs are now pulling on stage 1 (which is attached to stage 0 with the locks). The stages do not move at this point; we have just changed the load lines to include stage 1. With the table in place we proceed to add the sensors and actuators.

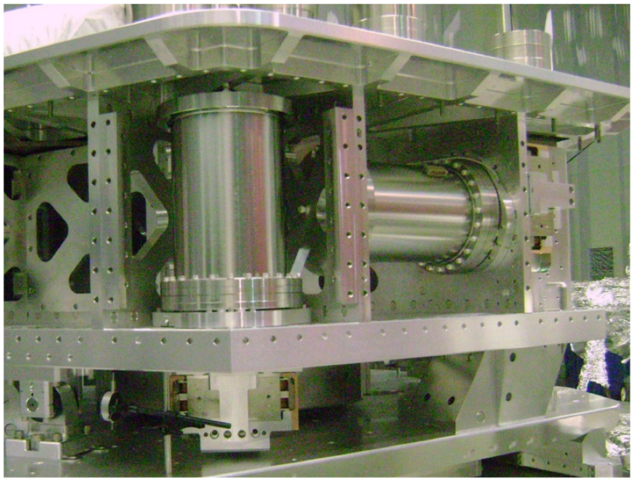

Figure 10. The GS-13 seismometers in cylindrical 'pods' are mounded on stage 1.

When the sensors and actuators are in place, we complete the assembly and balancing of the table and we do the alignment of the locker/ limiters, the displacement sensors, and the actuators.

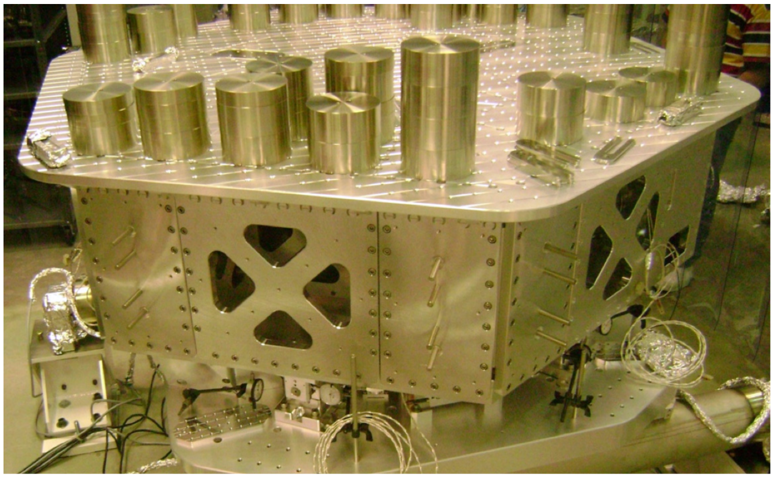

Figure 11. The close-out plates are put around the outside of stage 1, and dummy payload mass is installed to bring the table to its nominal hang location.

Issues with Assembly

Spring Loading Risk Analysis: The main concern is the loading of the main suspension springs. The springs are made of maraging 300 steel, with the top and bottom surfaces loaded to about ~~35%~~ 30% of yield, with a maximum stress of about 40% of yield at a small fillet near the base. There is some concern about the safety of the loading if the springs are defective in some way. We believe that the safest way to do the loading is on the platform. This is because:

1) There is excellent tooling designed and built to pull the springs smoothly to their loaded condition.

2) The loading point is not directly connected to the spring. The loading apparatus uses a screw assembly to pull down on a pair of rods which attach to the spring. The rod pass through a holes in the stage 1 floor – a very large, solid aluminum plate. Thus, the operator is very well shielded from the spring by the whole stage 1 structure.

3) The steel is designed to have a high strain-to-failure, and since only the outer skin is at the peak stress, if it starts to fail, we should get some small plastic deformation at the point which yields, rather than cracking. A cracked spring would be quite unpleasant.

These considerations are described in the hazard analysis [E070330].

The operator is well below the edge of the platform, and should be well protected from the spring. However, the area above the platform is exposed to the spring. We are currently designing a temporary cover which will attach to the top of the stage to enclose the spring during the pulldown. In this way we completely surround the spring, protect the operator, use a tested, well-designed pulldown apparatus, and we only have to do the pulldown once per spring.

2.5 Basic mechanical function tests

Once the unit is fully assembled and balanced on the final assembly stand, a set of checks can be run on it. This requires a full set of electronics including a control computer. A formal test procedure is still required for the testing. These tests will be similar to the test conducted at HPD and done for the two installations so far. These tests must include:

1) Loading and balancing the table.

2) 'Memorizing' the hang location, and centering the actuators and displacement sensors (these steps are already part of the assembly).

3) Insuring that the table moves freely.

4) Driving the system in 6 DOF with the control computer, and

4a) Confirming that non-linear effects from rubbing, etc. all small enough to be acceptable.

4b) Confirming that the natural frequencies are what we expect.

4c) Confirming that the tilt/ horizontal coupling is acceptable.

4d) Confirm that there are no unexpected plant features between 10 Hz and 300 Hz.

In addition, we may also want to:

5) Run a damping loop to check for proper control.

6) Run a simple blended isolation system to demonstrate some basic functionality.

2.6 Storage

Once we have demonstrated that the platform is assembled and working correctly, the systems for Advanced LIGO will be placed into storage. This has not yet been done, and will require considerable effort to put into practice. The platforms are equipped with heavy-duty shipping braces which securely lock the two stages together during storage and shipping. The springs and flexures are left in their stressed state.

Issues with storage: There are several issues which need to be addressed for the long term storage of these systems, including:

1) Spring corrosion: The blade springs and flexures installed in HAM6 are not corrosion protected. We plan to put a nickel plating on the springs, similar to the coating used for the HEPI springs. Suspensions is also putting these coatings onto their blades and we will be working together to be sure the coatings are vacuum compatible and that the strain on the blade surfaces does not cause the coatings to crack, etc. We are in the process of getting a coating applied to the spare springs for the BSC-ISI, which operate at the same stress and therefore have the same surface strains as the HAM blades. We have a test fixture for pulling the BSC blades to their loaded condition.

2) Storage Space: The Facilities Modification Plan is being developed with the intent of providing adequate space to assemble and store all the systems. This planning is still underway.

3) Instrumentation left on the system: It is not clear whether we will leave the GS-13 pods mounted to the HAMs for storage and shipping. One determining factor may be the availability of sufficient numbers of podded sensors at assembly time. Another is the reliability of the instruments to survive shipping.

4) Crate design: We do not yet have a storage crate designed. This is not a trivial task and will require some concentrated engineering effort and prototyping.

2.7 Removal from Storage

Once we are ready to install the systems into Advanced LIGO, the systems will be removed from storage and placed on the final assembly stand in the LVEA. The units will be run through the test procedure again, to be sure that everything is in proper order. This procedure will be nearly identical to the tests run after assembly.

Issue: This procedure remains to be written.

2.8 Installation

Once the system is assembled and tested, it will be ready for installation into the vacuum chamber. Fabrice Matichard has been leading the work on the installation system, in close consultation with the observatory staff. For installation, stage 0 and stage 1 are locked together, the HAM ISI is installed as a unit, and bolted onto the support tubes in the HAM chamber. The stage 0 base is designed to be extremely stiff, with the idea that all alignment achieved on the final assembly stand will be kept though the installation, so that no further alignment of the sensors, actuators, or locks is required when the system is placed into the chamber. The experience with the two installations done so far shows that realignment in the chamber was not required, so we deem the plan to do the alignment on the stand a success. This is a relief, because the system is much easier to access when it is on the stand than when it is in the chamber.

The installation plan is described in detail in the 'HAM ISI Installation Procedure' [E080012-01]. An assembly drawing of the installation fixture can be seen in [D070586-A-D], and a detailed load analysis of the system is documented in [E080053-A] 'HAM ISI Installation Fixture Dimensioning and Specifications'. The system is heavy and delicate, and a few of the installation clearances are small, and so there has been quite a bit of work done to be sure the installation is smooth and safe. The hazard analysis is [E080187-01].

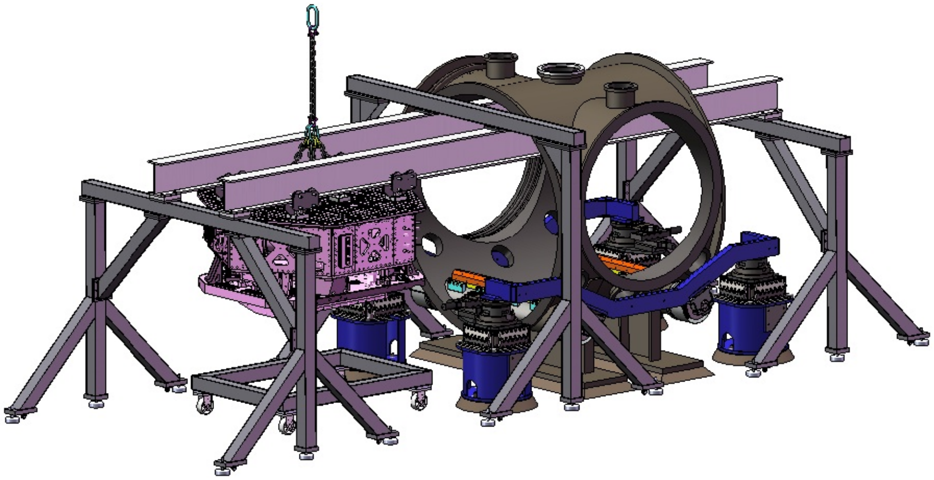

Figure 12. CAD view of the HAM ISI being lifted onto the rail beams of the installation fixture. Picture from [E080053].

Figure 12 shows the main components of the installation tooling. The two stages of the HAM-ISI are locked together, and then the system is loaded onto a cart. The cart is pushed under the two big rails of installation fixture. The crane lifts the HAM-ISI, and then it is attached to the rails with 4 rolling trolleys. The crane is released, and the HAM-ISI is pushed into the chamber. Once the HAM ISI is in the chamber, the crane hook is put into the chamber through the flange on the top of the chamber, and reattached to the platform. The trolleys are disconnected, and the crane is used to lower the platform onto the HAM support tubes. The platform is bolted to the support tubes. Once the fixtures are all removed, installation is complete.

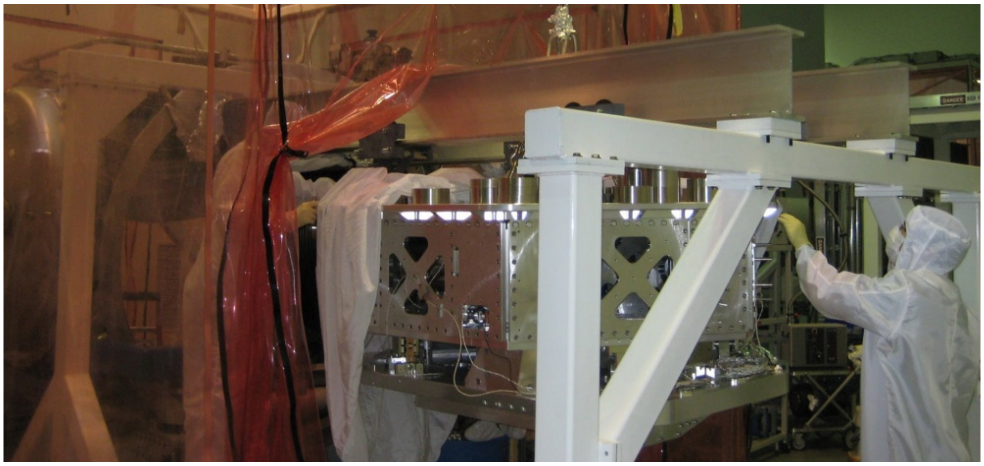

Figure 13. Stage 0 and stage 1 are locked together and installed as a unit into HAM6. The ISI system is attached to 4 trolleys which roll along the 2 installation rails that go through HAM6 (on the left side, in the portable cleanroom).

Issues: The installations to date have gone smoothly. There are a few items which need attention, and most are included in the HAM-ISI design modification document, including: increasing the size of the casters of the installation fixture to make it easier to move into position, changing the wheels on the cart so they don't deform the tile floor at LHO, and making some of the outriggers on the installation fixture removable so that it can be used for adjacent HAM chambers.

2.9 Sensors and Actuators

The sensors and actuators for the system all require special attention, for both performance and UHV reasons. Each platform uses 6 ADE capacitive displacement sensors to measure the relative motion between stage 0 and stage 1 (in 6-DOFs) and 6 GS-13 seismometers to measure the inertial motion of the platform in 6-DOF. There are 6 custom electromagnetic actuators which allow us to control the system in 6-DOFs.

GS-13 Inertial Sensors: The GS13 seismometer is a moving coil seismometer with a 1 Hz natural frequency. It can be set to run either horizontally or vertically. We replace the internal electronics board with one of our own design [D050358-01], which makes this device the best 10 Hz commercial seismometer available today. A plot of the measured noise performance seen by this instrument is shown in figure 14. This instrument must have its mass locked during installation, and the instrument is not vacuum compatible. A vacuum 'pod' has been designed to contain the instrument, and the instrument has been retrofitted with a remotely powered locking/ unlocking motor assembly. Twelve of these instruments were successfully modified, placed in pods, and installed in the Observatories. The instrument modifications, testing, and pod assembly are described in the 'GS-13 Seismometer Assembly Procedure' [E080086]. A checklist for the assembly of each instrument has also been created 'GS-13 Seismometer Inspection Checklist [E080XXX]. The testing includes huddle testing the device with an STS-2 and running the lock/unlock cycle ~~50~~ 10 times (with an automated system).

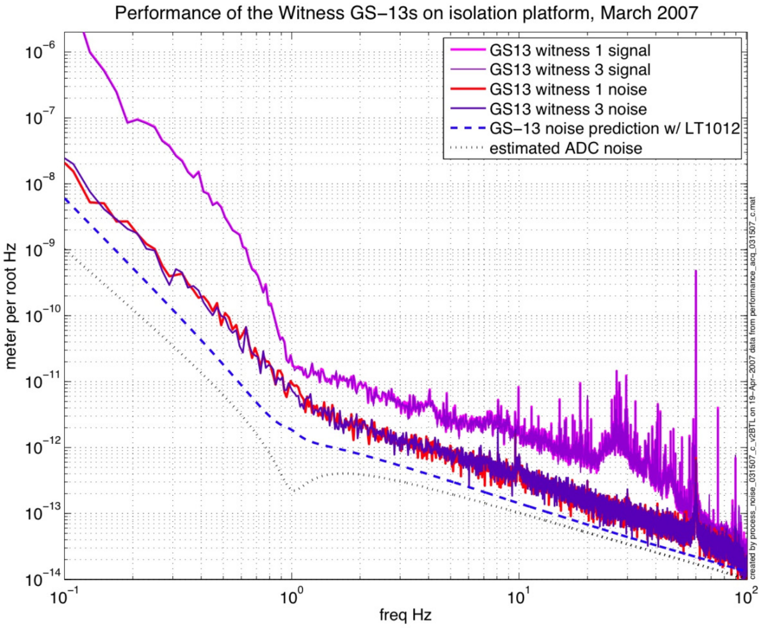

Figure 14. Noise performance of the GS-13s. This measured noise will allow us to reach the HAM requirements.

GS-13 Issues: The podding of the GS-13s was a difficult process. The locking and unlocking of the devices was not as smooth as it should have been. We noticed that some of the units were not well built when we received them from the manufacturer, which caused the proof masses to bind slightly against the locking ring, and made it difficult to unlock the unit. We have discussed this with the manufacturer and they are working with us to identify and fix the problem. They have been very responsive to our requests. They are examining two of the devices we returned to them, and we are setting up a visit to their facility to try and establish a way to be sure we don't get faulty devices in the future. We are optimistic that this route will be successful. We are also working to develop a set of replacement flexures which will allow the device to be used without a mass lock. These flexures are in development at Stanford. The flexures which come with the instrument fail due to Euler buckling at about 2 g. One design for the new flexures is to machine them from maraging 350, and should be able to withstand loads of 40 g's on the seismometer. A second design using copper-beryllium flexures is also being pursued which should be easier to make and less susceptible to external magnetic fields. However, the Cu-Be flexures can probably only withstand 20 g loads on the instrument.

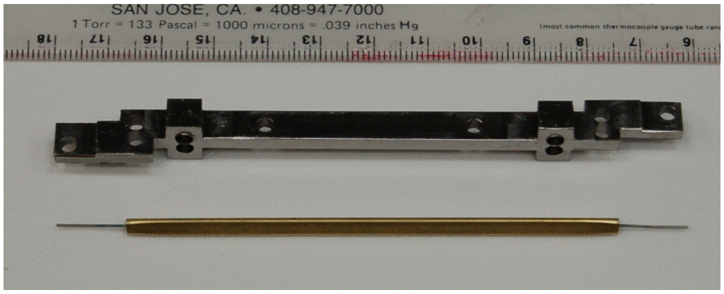

Figure 15. Flexures for the GS-13. The lower item is 1 of the 6 'delta-rods' used to guide the GS-13 proof mass. Above is a possible replacement made from maraging 350. The thin webs between the 4 pairs of holes will be the flexible webs. Slots will be cut in the outer section to release the flexures after the part is precipitation hardened. This device is designed to withstand 40 g loads on the seismometer without damage.

Another issue with the GS-13s is that they are only mounted on the 3 base feet. It may be possible to improve the stability of the unit inside the pod by placing a slip-fit hole with o-ring at the top of the pod, and a mating post on the top of the GS-13, so that when the GS-13 in inserted into the pod, the top of the unit will have a stiff, damped connection. This idea is still only conceptual.

Capacitive Sensors: The capacitive displacement sensors are sold by ADE. They include a UHV compatible head, designed for LIGO, and a readout board. Discussions of the electronics are below in the 'electronics' section below. The sensor range for the HAM-ISI is +/- 1 mm, and the noise floor is around 6e-10 m/rtHz. The heads are cleaned and baked at low temperature. The heads require a special strain relief for the cable [need to find and file these plans]. The heads are provided with special protective stops; calibrated shim washers are used in the installation, so that the heads of the four bolts which attach the sensor head to its mount ~~are slightly proud of the sensor head~~ protrude slightly above the head and contact the target before the head does.

Actuators: LIGO had custom actuators designed and fabricated for the ISI platforms. The design and fabrication is done by a commercial design firm, PSI. The actuators are humbuck wound, square coil actuators which maximize the drive linearity and minimize generation of external magnetic fields. A set of these actuators have been built and installed, and these actuators will also be the actuators for the first stage of the BSC-ISI. Since these actuators have potted coils, special cleaning procedures have been developed [E080497] to clean some parts of the actuators before they are fully assembled. The final actuators are cleaned and baked.

Actuator issues: Some minor redesigns of the actuators are being pursued to improve the wire connections. Currently, the stranded drive wires are attached to the actuators at a PEEK terminal block on the actuator. This will probably be modified by adding a crimp pin to the wire, and replacing the slotted bolt on the terminal block with a hex-head bolt. In addition, the kapton-based potting compound used for the HAM6 installations has been discontinued by the manufacturer and replaced with an upgraded material (PI-2525 resin). The new material is currently being investigated by the LIGO Lab. Tests indicate that it is still UHV compatible [T080148], and still difficult to apply correctly, but it more readily available and ships in more convenient quantities than its predecessor. Also, there are currently unit tests for the GS-13s and the displacement sensors, but we do not have any unit tests for the actuators. It would be useful to have a fixture to hold the actuator with a force gauge, and supply the actuator with calibrated current. This could be used to check the continuity, polarity and force constant of the actuators.

Floor mounted STS-2s: The sensor correction seismometers now used for HAM6 for Enhanced LIGO will be part of the HEPI system for Advanced LIGO. HAM6 does not currently have a HEPI system installed, which is why we do sensor correction directly to the platform. The baseline plan is for the sensor correction in Advanced LIGO to run to HEPI, as is currently implemented for the HEPI systems in used at LLO. We may find that other control strategies are more effective however, and perhaps the sensor correction will go to ISI, and then control offload will be run to HEPI. In either case, the STS-2 ground sensors were part of the HEPI review, and are not technically part of this review.

2.10 Electronics System

The entire system is made up of a set of electronics chassis described below, some timing chassis, and the “Blue Box” and computer system. The system schematic that shows the interconnection of all of the electronics chassis is found here: Single_Stage_ISI.pdf [D080114].

ISI Interface Chassis – This chassis gathers all of the signals from the GS-13 seismometers and the Capacitive Position Sensors and interfaces them with the computer via an Anti-Alias filter chassis. The chassis contains two main boards, the GS-13 Interface Board: D070115 Rev.B1 and the Capacitive Position Sensor Interface Board: D070132. The design is working fine, ~~and should not change from the one currently in place in the HAM 6 chamber of both sites~~. but we will probably add a second power switch so that the GS-13s and the displacement sensors can be power cycled independently.

ISI Coil Driver – This high-current driver receives signals from the computer via an Anti-Image filter chassis. It provides the high current signals to the ISI actuators. The Coil Driver Schematics are here: D060454 Rev.D2. The design is working fine, and will not change from the one in place in the HAM 6 chamber of both sites.

GS-13/STS-2 LSU Locker/Unlocker – This chassis was made at LSU to control the seismometer locking stepper motors. It outputs a pulse-width modulated signal that allows us to physically lock-down the seismometers to prevent them from damage due to excessive shaking. We currently use a few of these units which move around the labs as needed. We ~~may~~ will need to revisit the design in the future but, for now, we have enough for our needs.

Binary I/O Chassis – This chassis is essentially a patch-panel that takes one connector that goes to the Binary I/O card, and distributes the signals to the right places. Binary Out signals go to the ISI Interface chassis to control gain and filter settings, and Binary In signals come from fault monitors in the Coil Driver chassis. As can be seen from its schematic, D060078, it’s a simple board with 5 connectors on it, and it shouldn’t need any modifications from its present design, although we note that we have not yet been able to get these devices to work properly for the HAMs.

Anti-Alias Chassis – This chassis is a low-pass filter for all incoming signals, the cutoff frequency of which is set so that signal frequencies higher than the Nyquist frequency (determined as half the sample frequency) are greatly attenuated so that they don’t alias down into the passband. There are two versions of Anti-Alias filter in the HAM ISI system, Rev. 7B and Rev. 10. These two revisions differ only in their arrangement of frontpanel connectors. All of the boards have 32 channels of available filtration, which correspond to the 32-channel Analog to Digital Converters to which they connect. On the Rev. 7B chassis, these are split up into 4 25-pin connectors with varying number of signals to each, and the Rev. 10 has 5 9-pin connectors, 1 15-pin connector, and 1 25-pin connector distributing the signals to the ADC. The schematic for the filters is here: D050374, the Rev. 7B Personality Board is here: D050383 Rev 7B, and the Rev. 10 Personality board is here: D050383 Rev10.

STS-2 Interface Chassis – This chassis is currently being re-done for the HEPI system, and, when it has been perfected there, the new design will be available for use in the HAM ISI installations. The schematic of the new chassis is here: STS2_Interface .

Setup and Testing of the Electronics

In testing the system, two boxes and several small boards have been made to help with the task. The first box is the STS-2/GS-13 Tester box. This box is used when a particular seismometer is in an unknown state of health. By plugging this box into a STS-2 or GS-13 pod, one can assess whether the seismometer is working or not. This is helpful during construction, as it means that we can test the expensive seismometer without hooking it up to an untested control system. The GS-13 Controller schematic is here: GS13_L4C_Controller.pdf box. This box gets connected in the place of an in-vacuum seismometer, and allows us to test all of the wiring, and computer system without endangering an expensive seismometer. The Emulator has power supply LEDs that allow you to see, at a glance, if the incoming power is correct before tuning on the Emulator. Once it is on, it outputs a fake seismometer signal that can be detected on the control room screen. There are also LEDs and frontpanel BNC connectors to allow you to check the rest of the computer system functionality. The Emulator schematic is here: GS13_L4C_Emulator.pdf There are also several boards that help in testing. One is a switch board that emulates the functionality of the binary I/O modules, so gains and whitening can be set right at the rack, and several inline breakout boards that go inline with the cables, and allow you to clip onto any wire inside, and check the health of the signal there.

Along with the hardware, we now have a good documentation system that provides a system test procedure, and a new set of “quick start guides” that let people who might be receiving, or using the electronics have a quick overview of its functionality and “care and feeding”. The system test procedure can be found here: HAM_ISI_test , and some examples of Quick-Start guides are in these places: GS-13_L4C_Emulator_Quick_start, GS-13_L4C_Controller_Quick_start.pdf, and STS-2_Quick_Guide.pdf.

Electronics Design Work to be Done

There is some work that might come up as the result of slight changes in the electronics from the HAM6 installation. The current commercial Capacitive Position Sensor ADE 4800 Gauging Module might be changed to the newer 8800, which has lower noise, and a commercial satellite chassis that could replace the chassis we currently make. We plan to add the second power switch to the ISI Interface Chassis. Also, the Locker/Unlocker unit prototyped by LSU ~~might have to~~ should be re-designed and put into production by CDS.

If we move to the capactive sensor readout boards and chassis, it raises the question of what should be done with the installed HAM6 systems. Leaving them along would be easiest and cheapest in the short term. However, have different styles of electronics around might be problematic in the long term.

3 Performance

The current performance of the systems will be summarized in ‘HAM ISI performance, September 2008’, [T080251]. A nice description can also be seen in Jeff Kissel’s LSC presentation [G080463]. We are not yet done with the performance commissioning. So far the results look good, with one major exception. The basic mechanical performance of the system looks good, both for the passive isolation and for the design-for-control, as described above. The control for the system is turned on in three stages: Simple inertial damping, blended isolation, low-frequency sensor correction.

The damping loops are easy to run and are very robust. These loops have performance only around the rigid-body modes of stage 1 (0.8 to 1.8 Hz, depending on the DOF). We commissioned a damping loop at HPD is a few hours, and have commissioned the damping loops at both observatories very quickly. Changing the payload on the LHO system had no impact on the damping loops running there. At Stanford, we routinely run the damping loops while working on the table, since they are quite robust to saturations, and keep the table from bouncing around so much when we do things to it.

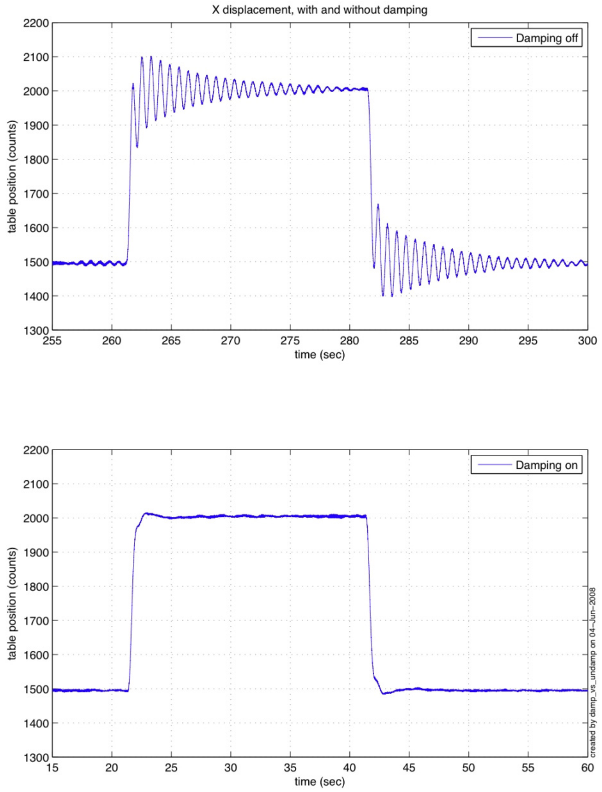

Figure 16. Impact of the damping loops. A force step is applied to the platform in the coordinate X direction, and then turned off again about 20 seconds later. The upper plot shows the output of the coordinate X displacement sensors for the undamped plant. The lower plot shows the response to the same input when the damping loops are running. The damping loops make the platform much easier to deal with.

The commissioning of the isolation loops is still in progress. In 2006, we made some models for the predicted performance. Figure 17 shows the predicted transmission of the ground motion using a particular set of blend filters.

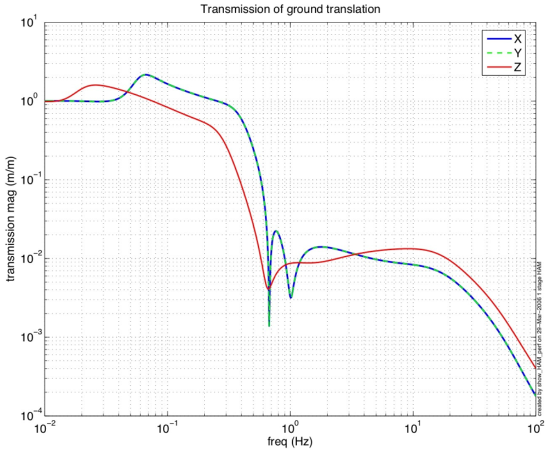

Figure 17. Transmission of ground motion predicted by the modeling effort in 2006. This shows the impact of damping and blended isolation, and does not include the low-frequency sensor correction.

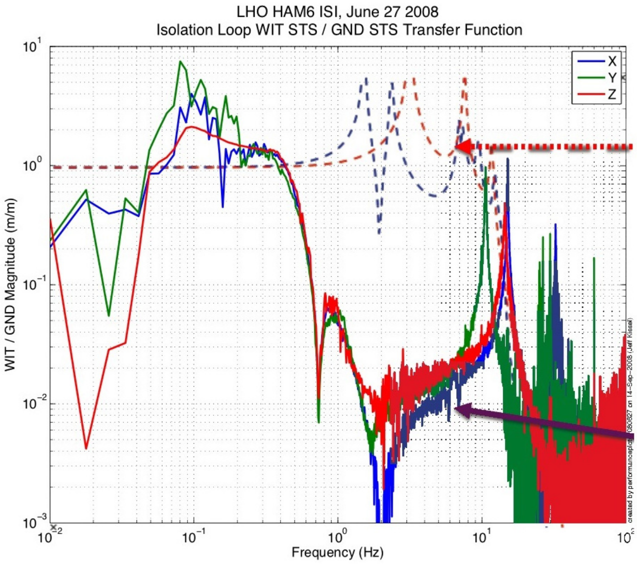

Figure 18. Measured transmission of ground motion to the platform at LHO on June 27, 2008. The dashed lines are transmission of the model of the Initial LIGO HAM stack. There is excess noise around 0.1 Hz for the X and Y data. The peaks at 11-14 Hz are resonances in support tubes and gullwings.

When one compares the transmission curves for the real system and the modeled system, one sees some similarities and some differences. The general shape and isolation level for the X and Y are similar in the 0.6 to 8 Hz range. The blend filters used for the model and the real system are slightly different and the loops are not quite the same, so the shapes are similar, but not quite the same. There is excess noise around 0.1 Hz, which is under investigation. The real system uses the same blend filters for X, Y, and Z, so the sub 1 Hz shapes are all the same. This will probably be changed to use less aggressive filters for Z, similar to the model, because the tilt-horizontal coupling is less of a problem for Z and so the inertial sensor does not need to be rolled off as quickly. The real system shows large peaks in the 11 to 14 Hz region, which are a result of flexible modes of the support tubes and gullwings. If nothing changes, this will represent a large problem for the HAM-ISI. We think that the new crossbeams and HEPI will make this problem much smaller, because the new crossbeams are better and the HEPI system provides significant passive damping at these frequencies. We can also try to put some feedforward sensors on the support tubes, and try to do feedforward correction from the support structure to the platform in this band. We have done this successfully at Stanford at these frequencies.

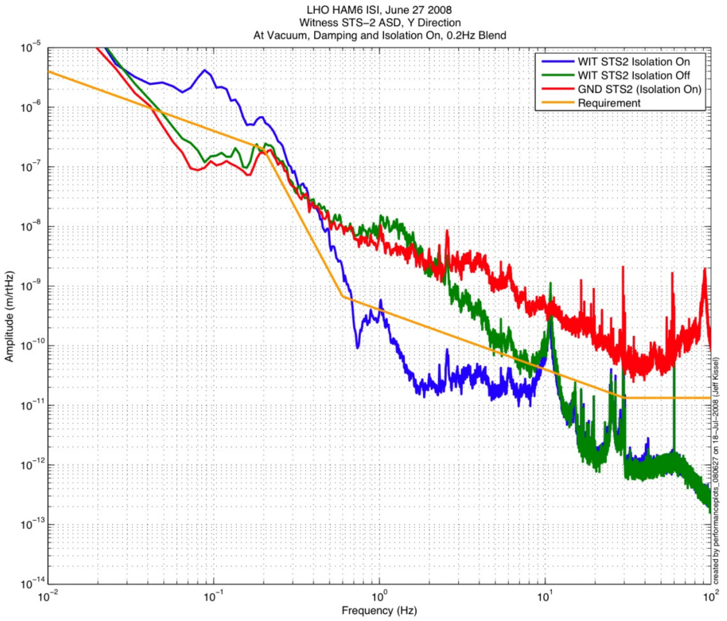

Figure 19. Measured performance in the beam direction. At 0.7 Hz and above, the motion of the table is at or well below the requirement curve, except for the support structure bending feature at 11.4 Hz and a few (probably related) peaks between 25 and 30 Hz. The blend filters have not been optimized, and there is no sensor correction, so the performance below ~~0.6~~ 1 Hz is still in development. There is excess noise at the microseism, which is under investigation. ~~There is a big peak near 11 Hz, which is from a resonance in the support structure.~~

In figure 19, we see the motion performance of the HAM ISI system at LHO in June 2008. Above ~~0.6~~ 0.7 Hz, the system performance looks excellent everywhere except the gullwing resonance.

For Enhanced LIGO, the sensor correction will be done directly to the HAM-ISI platform from the ground, as was done at the Stanford ETF by Wensheng Hua. For Advanced LIGO, the sensor correction may be applied to HEPI, as is done now at LLO for the existing HEPI systems, or we may send the signal directly to the ISI platform, and then off-load the low frequency control to HEPI. We have not had the chance to run the sensor correction to the HAM-ISI yet, although we expect to do so soon.

Issues: To recap, the issues of greatest concern are the excess noise around 0.1 Hz; the total SEI (HAM ISI + HEPI) performance at frequencies below 0.6 Hz, and the structure resonances between 11 and 14 Hz.

4 Commissioning:

Two systems are currently being commissioned at the observatories. This has been a valuable experience. We expect that having two running systems will make the commissioning of new systems go much more quickly. However, that will only be true if someone from this commissioning cycle is present for the commissioning of the Advanced LIGO systems.

All the code work for the commissioning is being archived in the seismic SVN, and we are attempting to carefully document it. We have implemented damping loops many times, now, and that is not difficult. Jeff Kissel has written up a detailed procedure for hooking up the damping loops [T080125], and we are trying to organize the code base at the observatories so that once one system is complete, most of the work for getting the other systems ready will be complete.

The isolation control is still a work in progress. It was expected to be straightforward. We have run one full set of isolation loops at Hanford before the OMC suspension was installed. The isolation performance will be described in detail in [T080251]. The performance above ~~0.6~~ 0.7 Hz looks quite good, except for the Initial LIGO support structure resonances. The low frequency performance needs improvement.

Operations

We have developed a user interface which is designed to be easy to interpret by the operations staff. This will be evolving as commissioning is completed and we train the operations staff on the system. There have been 2 1-hours training sessions for the operators. There will need to be several more when the systems are operational. We would like to get some tickle scripts build to test the function of the various sensors and actuators on a regular (if infrequent) basis.

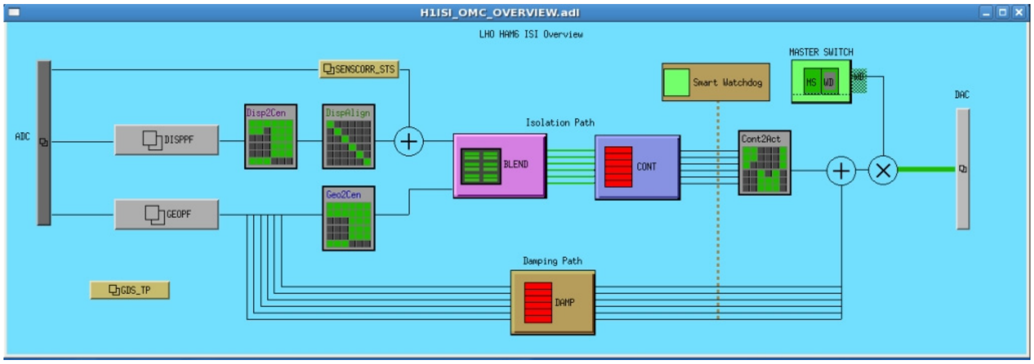

Figure 20. ISI overview screen in MEDM. This screen is slightly out of date. This overview shows the data paths and the overall status of the various filter banks. The damping loops and the isolation controllers were not engaged when this screenshot was taken (hence the red boxes).

There are also several scripts which are designed to get the system into operation, and which reset the system when a fault occurs (part of the 'smart watchdog').

The speed at which we commission the systems must be improved. In order for commissioning to proceed, one needs:

a) a skilled designer who is

b) present at the observatory

c) with a functioning system.

We now have several skilled designers: Brian Lantz, Jeff Kissel, Rich Mittleman, Fabrice Matichard, Brian O'Reilly and Mike Landry. Fabrice and Rich are concentrating on the BSC, and from the remaining 4, we only get about 1.5 FTEs, since only Jeff really has ~~any~~ uninterrupted time to concentrate on commissioning work on the HAM system, the rest of us are all too busy to do any work. Brian Lantz has a 1 week class on the HAM (and another for the BSC) system to show someone with basic control experience what is going on with this system, and more people need to be trained to do this work. In particular, operators and engineers from the observatories with controls experience should be educated on these systems. In the last few weeks, I'm pleased to say that Corey has started getting involved with the software commissioning. This type of involvement is important to the project success.

Many of our delays stem from the teething problems of the new CDS realtime system infrastructure. Fortunately, the beatings we are giving to the infrastructure with our commissioning seem to be making the CDS systems stronger. However, for these systems to be successful in Advanced LIGO, we need to develop a comprehensive set of unit and system tests for new CDS upgrades, similar to the tests we have developed for the electronics, sensors, and hardware.

Hurricanes and travel obligations also cause delays, but usually not more than a week at a time.

Schedule

The current schedule (as of September 4, 2008) for the HAM ISI is posted on the PDR wiki. We plan to start procurement on Dec 26, 2008 (although I won't be at work that day…). The cleaning of the parts is slated to begin in May 2009, and the first assembly is scheduled to begin in September of 2009.

Outstanding issues for going forward into Advanced LIGO

1) We need to get more people who can design the control systems who can spend time at doing this at the observatories.

2) We need to improve the reliability of the computing infrastructure, and we need to develop testing procedures for the software similar to the testing for the hardware.

3) We need to train the operators in how to use the system

4) We need to get some automated system health monitors running.

5) We plan to begin ordering the parts for the HAM-ISI systems in January 2009. Our team is going to be highly stressed at that time, since we will be giving operations support to the Enhanced LIGO HAM systems, working on redesigns of the BSC-ISI, and overseeing HEPI procurement. We need additional engineering staff to help with HAM-ISI procurement.

6) Since there will be a multiplicity of similar systems, the CDS conventions for system names, filter design, test data storage needs to be thought through. This process has been started, but needs close attention.

5 Conclusions

Our experience with the HAM-ISI systems build for Enhanced LIGO give us confidence that we should proceed to build a full complement for Advanced LIGO. We need to make a set of small changes to the design which will make the systems easier to build. Getting the systems all commissioned for Advanced LIGO will be a challenge. Our commissioning so far has pointed out a number of issues which need to be addressed. These are primarily management and programmatic issues, and will require attention going forward. We are optimistic that they can be resolved in the near future.

6 Summary of Issues

Throughout this document we have identified a number of outstanding issues. This is a summary list of those we have identified, and a summary of the actions proposed to resolve them.

Issue	**Proposed resolution**
Poor dressing of cables	Added to list of design changes
stainless-on-stainless bolt galling	Silver plate relevant bolts
Suggested design changes to improve ease of assembly	Design changes will be made in design documents
Helicoils in barrel nuts at LHO	Test to determine if use of helicoils in barrel nuts in LLO makes an appreciable difference in system performance
Spring pull down	Design temporary cover to protect operator
Storage: spring corrosion	Nickel plate the springs
Storage: storage space	Facilities Modification Plan in development
Storage: instrumentation on the system	Will depend on availability of GS-13 pods at assembly time and ability of pods to survive shipping
Storage: crate design	Perform required engineering and prototyping
Storage: removal procedure	Procedure remains to be written
Installation	Increase size of installation fixture casters, change cart wheels to avoid deforming LHO tile floor, revised outrigger design to allow some outriggers to be removable to enable installation in adjacent HAM chambers
Electronics upgrades	Switch to new 8800 readout for the displacement sensor, add a second power switch to the ISI interface chassis, improve GS-13 the locker/ unlocker box.
GS-13 locking/unlocking	Manufacturer is attempting to identify and correct binding of proof masses against locking ring; Stanford is also working to develop replacement flexures which will allow the devices to be used without a mass lock
GS-13 stability	Determine if concept to improve stability of pods is feasible
Actuator: wire connectors	Complete minor redesign to improve connections
Actuator: replacement potting compound	New material is being tested by LIGO Lab
Actuator: unit tests	Develop fixture to check continuity, polarity and force constant
Commissioning:	
Additional staff to help with control design	TBD

Improve reliability of computing infrastructure	TBD
Train operators to use system	Ongoing
Implement automated health monitors	TBD
Get procurement help for the build	TBD
Resolve computing multiplicity issues	Addressed in CDS review

7 Preliminary Design Review Checklist- M050220-09

System Design Requirements, especially any changes or refinements from DRR	Mechanical: E030180-02 Performance: find ref for HAM curve
Subsystem and hardware requirements, and design approach	HPD FDR document: E070156
Justification that the design can satisfy the functional and performance requirements	Initial modeling: G060167 Performance to date: see plots, this document Tech Demo Experience
Subsystem block and functional diagrams	Electronics:D080114 Control System: class notes G070475
Equipment layouts	NA
Document tree and preliminary drawings (information issued)	This document, and the PDR wiki http://lhocds.ligo-wa.caltech.edu:8000/advligo/HAM_Preliminary_Design_Review
Modeling, test, and simulation data	Performance modeling: G060167
Thermal and/or mechanical stress aspects	Spring and flexure stress: HPD FDR presentation - E070156. The rest of the design is a stiffness limited application, and as such the load stresses are very small. For HEPI springs, see E070156
Vacuum aspects	Structure: HPD FDR – E070156 Actuators: passed vacuum RGA tests ADE Capacitive sensors: passed RGA tests
Material considerations and selection	HPD FDR: E070156
Environmental controls and thermal design aspects	Thermal dissipation of the actuators, T060076
Software and computational design aspects	HAM Controls Class notes G070475
Power distribution and grounding	Electronics overview: D080114
Electromagnetic compatibility considerations	TBD
Fault Detection, Isolation, & Recovery strategy	TBD with controls commissioning
Resolution to action items from DRR	
Interface control documents	per SEI requirements E990303-03
Instrumentation, control, diagnostics design approach	HAM Controls Class notes G070475
Fabrication and manufacturing considerations	HPD FDR: E070156
Preliminary reliability/availability issues	See this document for GS-13 reliability issues

	All parts currently available
Installation and integration plan	Assembly: E070154 Installation: E080012
Environment, safety, and health issues	Assembly hazard analysis: E070330 Installation hazard analysis: E080187
Mitigation of personnel and equipment safety hazards Reflected in equipment design and procedures for use	Assembly hazard analysis: E070330 Installation hazard analysis: E080187
Human resource needs, cost and schedule	Need additional personnel to help oversee ordering. Schedule/ manpower with LIGO Lab, see this document for current best schedule estimates.
Any long-lead procurements	Lead times are typical for large quantities of large machine jobs, see schedule. Sensors are medium lead.
Technical, cost & schedule risks and planned mitigation	Advanced LIGO Risk Register
Test plan overview	Testing of initial units complete. Testing plan for mass production in development. Test plan for computer systems is TBD.
Planned tests or identification of data to be analyzed to verify performance	See results this document, testing continues
In prototyping phase	See results in this document
In production/installation/integration phase	In development for hardware Need test procedure for computers
Identification of testing resources	See Facilities Modification Plan
The test equipment required for each test adequately identified	1 complete, stand-alone control system
Organizations/individuals to perform each test identified	Testing to be done by assembly staff
QA involvement	TBD
Test and evaluation schedule, prototype and production	Each unit tested at assembly, see schedule. Sensors tested at pod assembly.
Lessons learned documented, circulated	See 'gotcha' list for assembly, and design change list. Computing system tests and documentation TBD
Problems and concerns	See 'Issues' items in this document