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Status Report for the Single Stage HAM ISI for Enhanced LIGO and Advanced LIGO, April 2007.

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1 Introduction

This is an update on the status of the single stage HAM ISI system. We have recently completed Part 1 of the Final Design Review for the Single Stage HAM mechanical system, we have gained some experience with the BSC ISI at LASTI, and have some new data from the Technology Demonstrator at Stanford which is relevant to the HAM design. This new information is relevant to the decision to continue with this system as the baseline plan for Advanced LIGO, and is also relevant to the decision to install 2 of these platforms in Enhanced LIGO. In this report we discuss various issues from the Design Review, such as ease of installation and commissioning, and ease of accessing the parts of the system. We also discuss the predicted performance of the system, and, finally, we present the current best estimates for cost and schedule for both Enhanced LIGO and Advanced LIGO.

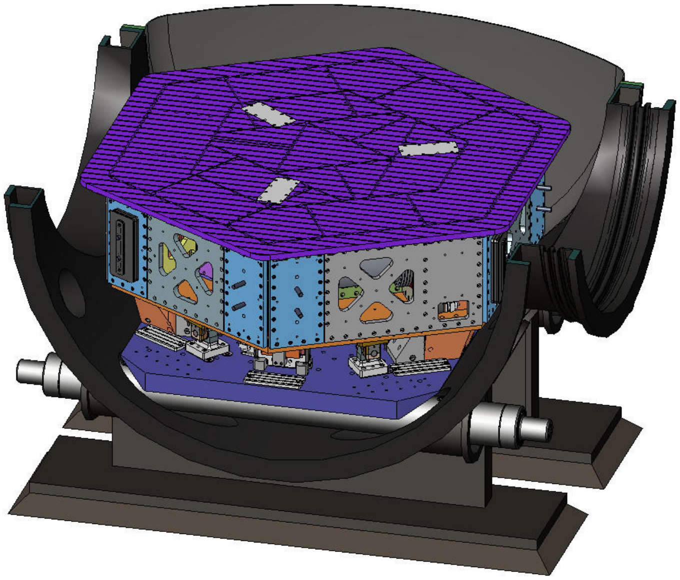

Figure 1. HPD rendering of the single stage HAM table installed in a chamber.

2 Final Design Review

Part 1 of the Final Design Review for the Single Stage HAM ISI system was held at the offices of High Precision Devices (HPD) in Boulder, CO on Monday, April 2, 2007. HPD is performing the mechanical design of the system for the LIGO Lab. The HPD slides for the review, "Advanced LIGO Single Stage HAM Vibration Isolation Table. Final Design Review, Part 1" can be found in the DCC at G070156-00-R. Most of the CAD drawings in this document (see figure 1, above) were extracted from their presentation. The LIGO team was quite pleased with the state of the design. The materials presented show that the final hardware should meet or exceed all the performance requirements set forth in the requirements document (E030180-02-R).

HPD described the basic assembly and installation procedures, and we are comfortable that the system can be readily assembled and aligned by the laboratory staff on a test fixture and then installed into the HAM chamber. We expect that the system will need some minor realignment after it is installed in the HAM chambers, due to the flexibility and the uncertainty in the external structure, which holds the support tubes, but we believe that the designers have done a good job in minimizing the impact of this uncertainty on the installation procedure.

The presentation by HPD is 117 pages long, and took more than 8 hours to complete; to do that material any justice is beyond the scope of this report. Instead, we include a quick guide, borrowed from the review materials, which may give a feel for the nature of the coverage, and act as a reference for follow-up questions.

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At the time of the review, there were still some details to be finalized, and some design changes were identified. A “punch list” of activities was generated (E070095) which describes outstanding issues which need to be addressed, by HPD and LIGO. These issues can be generally classified as refinements, clarifications, and tweaks to the design which was presented.

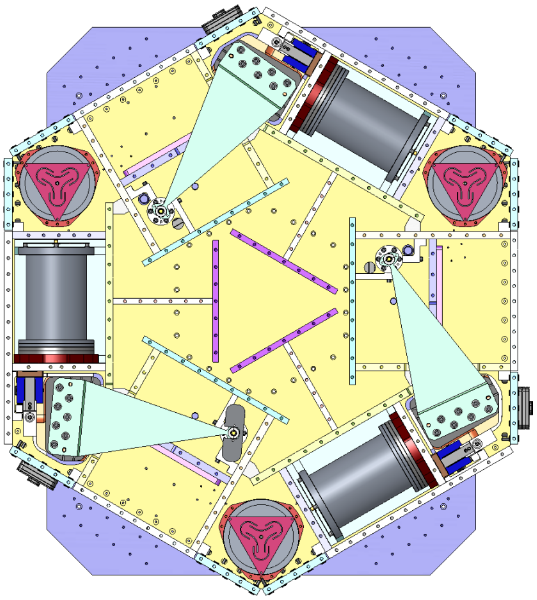

Figure 2. Top view of the isolation stage, with the table top removed to show the placement of major components such as the triangular blade springs and the GS-13 inertial sensors (in the 6 grey cylinders). The 3 horizontal actuators can be seen in blue adjacent to the horizontal GS-13s. The vertical actuators are below the vertical GS-13s. The displacement sensors are below the horizontal actuators.

The second half of the Final Design Review is scheduled for the week of April 27th. This will include the completion of all fabrication drawings, assembly procedures, and other deliverable documentation.

3 Operational Considerations for the HAM Design

There were several issues discussed in the Final Design Review which are of current interest, and they are discussed below. These include installation, the ability to handle various payloads, the locks and limiters, and access to various sensors and actuators after installation.

3.1 General Performance Issues

The performance requirements for the HAM ISI system can be broken into several large categories. The first set of requirements are that the passive modes of the system should be low enough to give good isolation at 10 Hz and above. The modes of the system[1] are at 1.32 Hz for the two translation modes (X and Y), 1.07 Hz for the tip and tilt modes (rX and rY), 1.8 Hz for the vertical translation mode (Z) and 0.9 Hz for the yaw mode (rZ) (see pgs. 63-66 of HPD’s FDR presentation). These are

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[1] True when the cg is aligned with the LZMP. Otherwise the eigenmodes have some element of both tilt and translation, those calculations are included in the FDR presentation. The mode coupling has minimal impact on performance.

all within the range given by the requirements document, and give substantial passive isolation at 10 Hz and above.

The second group of requirements are roughly translated as “the system should be easy to control.” Several things have been done to ensure this. HPD has done careful FEA analysis to put the zero-moment points of the flexures within 1 mm of the spring neutral axis (pgs. 77-79 of the FDR presentation), and has a mechanical design which should allow the horizontal actuator to be within 1 mm of the lower zero-moment point of the flexure. This alignment will minimize the low frequency tilt-horizontal coupling of the stage. The cg of the system can be adjusted from 2.7 cm above to 3.2 cm below the lower zero moment plane, which is well within the +/- 10 cm range. The ability to align the cg to the lower zero moment plane (LZMP) will make it possible to achieve good separation between the tilt and the horizontal translation modes. This separation is not essential, but will simplify the servo commissioning.

Another design feature which will simplify the control is that the sensors and actuators are well positioned on the stage, and the alignment precision built into the assembly procedure should make it possible to skip a system identification step and just use the design locations of the parts to generate the coordinate transform matricies used by the control loops (the design precision of the Technology Demonstrator, also by HPD, allowed this simplification to be successfully employed at Stanford).

There is a very stiff and direct connection between the inertial sensors and the actuators, which simplifies the control, and the first bending mode of the isolation stage should be above 250 Hz (the Tech Demo’s first mode is at 197 Hz, and the first mode of the BSC ISI is only about 150 Hz). By keeping the bending mode high, we again simplify the control issues.

3.2 Initial Installation and Ease of Use

The system is designed to be assembled outside the HAM on an assembly stand. The stand will be two HAM support tubes, supported at the ends by either a set of gullwings or by a support straight to the floor. The final science payload will not be installed. The system will be put together on the test stand, the lock/limiters will be aligned, and all sensors and actuators will be installed and aligned. Then the locks will be engaged and the system will be installed in the HAM chamber. At this point, depending on the readings of the displacement sensors and inspection of the gaps on the actuators and the lock, we may need to re-center the locks (a bit of work), re-align the displacement sensor gaps (which is pretty easy), and re-align the actuators (a bit of work). HPD has done FEA analysis on the support structure which shows that the difference between the hang location of the stage 1 table when the edges of the stage 0 support table are fixed in space and when the stage 0 support table is held by the HAM support tubes pinned at the ends is less than 0.007 inches. We expect that the difference between the assembly stand and the real HAM system will be substantially smaller than this. Since the nominal gaps are all 0.080 inches, and we expect changes in the gaps of less than 0.007”, we have reason to believe that the installation will not require any further adjustment. However, these adjustments can be make once the system is in place.

Based on the experience at LASTI with the installation of the BSC system, one can try to extrapolate to the commissioning time for the HAM system. The complications that we encountered in assembling the BSC system came mostly came from using straight blade springs (initially straight, and curved under load). The single stage uses curved blade springs that are designed to end up straight under load. That is the same design which was used on the ETF and worked well (no adjustments needed).

Wiring for the HAM system should be pretty straightforward. The wires for the displacement sensors and actuators attach only to the support structure. Wires for the GS-13s also attach to the isolated stage. A series of ‘wiring breadboards’ designed by Stephany Foley have been installed on the platform to simplify the wiring. All the wiring for the payload will run down the outside of the table, and then jump to the support structure. Since the system is much stiffer than the wires, and the location is set by sensors, so non-linearities in the cables as the hang locations change will not affect the system.

3.3 System Balancing and Adaptability to Handle Payload Variations

The system is designed to support a 510 kg payload with a cg which is located horizontally at the center of the table. Lighter payloads can easily be accommodated by adding mass. There are a set of mass attachment points around the outer edge of the table which support balancing masses, and a set of attach points on the bottom of the isolated stage which allow us to position mass low on the table so that the cg of the table can be aligned with the horizontal actuators and the lower zero moment point (LZMP) of the flexures.

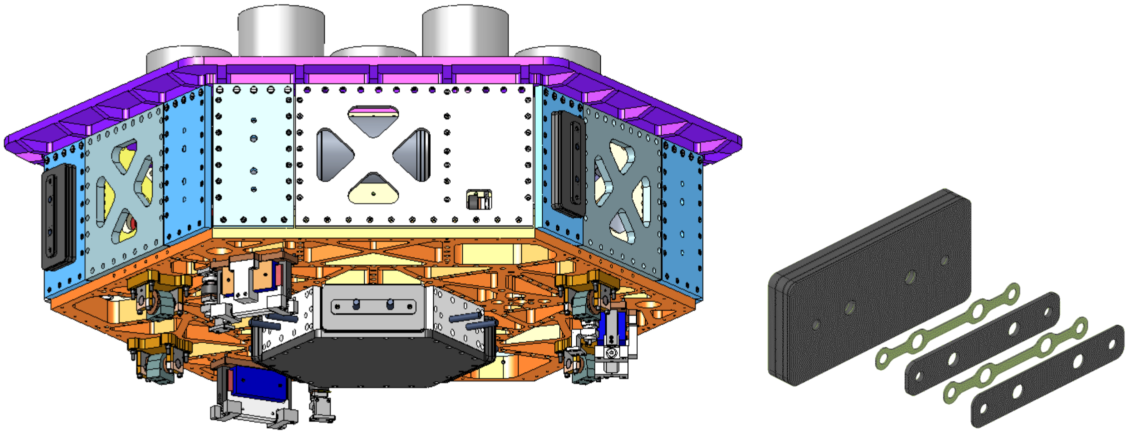


Figure 3. View of the stage 1 table (stage 0 has been omitted) which shows the bottom plate of the stage, in orange, and the grey, hexagonal stub-keel which sticks down from the stage 1 floor. The pairs of rods sticking out horizontally from the stub-keel are used to support masses which align the cg of the loaded stage with the LZMP and the horizontal actuator plane. Each of the light blue plates on the side of stage 1 also will have these mounting rods (the holes are shown, but the rods are not in place in all the plates). It should be sufficient to put weights on only 3 of the side plates, and the grey weights can be seen installed on two of them. The weight stacks can been seen on the right, with large weights, small weights, and vent plates. The rods slip through the two large holes in the weights for installation, and the small holes are used to bolt the weights onto the stage.

The mass increments of the weights are designed to allow us to level the optical table to within 0.2 mrad. In practice, we expect that most of the balance weight will be put on the side of the tables, but that the final balancing will be done by sliding around (and then bolting in place) some small weights on the table surface. However, because some of the Advanced LIGO HAM tables will be heavily utilized, we have retained the capability to do the final leveling from the sides.

3.4 Locks and Limiters

The system incorporates a set of locker/limiters which can be used (in the lock position) to accurately hold the stage 1 table fixed with respect to the support table, or (in the limit position) to limit the range of motion of the table to protect the displacement sensors and actuators from rubbing if we drive the system too hard. The locks on the system are very similar to the ones in use on the BSC ISI system. There are a few differences which are worth mentioning. Each of the locker/limiters are essentially spheres centered in cylinders. The cylinders have a stepped radius, so they can either be moved to the lock location, which allows (in our lab experience with the BSC ISI) about 0.001 inches of travel, or moved to the limiter location, which has a 0.012 inch gap for the BSC ISI and will have a 0.025” to 0.030” gap for the HAM ISI. The exact size is still under discussion. Given the limiter locations and gaps, ASI developed an algorithm to calculate amount of motion which could result at each of the sensitive components (actuators and displacement sensors) in the critical directions (stroke direction for the displacement sensors, magnet direction for the actuators). Brian Lantz and Jonas Waterman implemented this with a short Matlab code. We calculate that the largest allowed motion is about 1.8 times the limiter gap size. For a 0.028” gap (0.710 mm) this allows a motion of 0.051” (1.30 mm) at the actuator, which has a 0.080” (2.03 mm) gap. The sensors and actuators also have their own built in stops, so this should be adequate to protect the various parts in most situations. It is possible that a major, local earthquake will necessitate replacing some actuators or sensors. There are 3 locks on the BSC, in a kinematic orientation. The HAM system has 4 locks, which is overdetermined, but since the locks have about 0.001” of play (ie they don’t lock perfectly) we have added a fourth lock to give better access to the locks, and, given a particular gap in the locks, better constrain the stage motion.

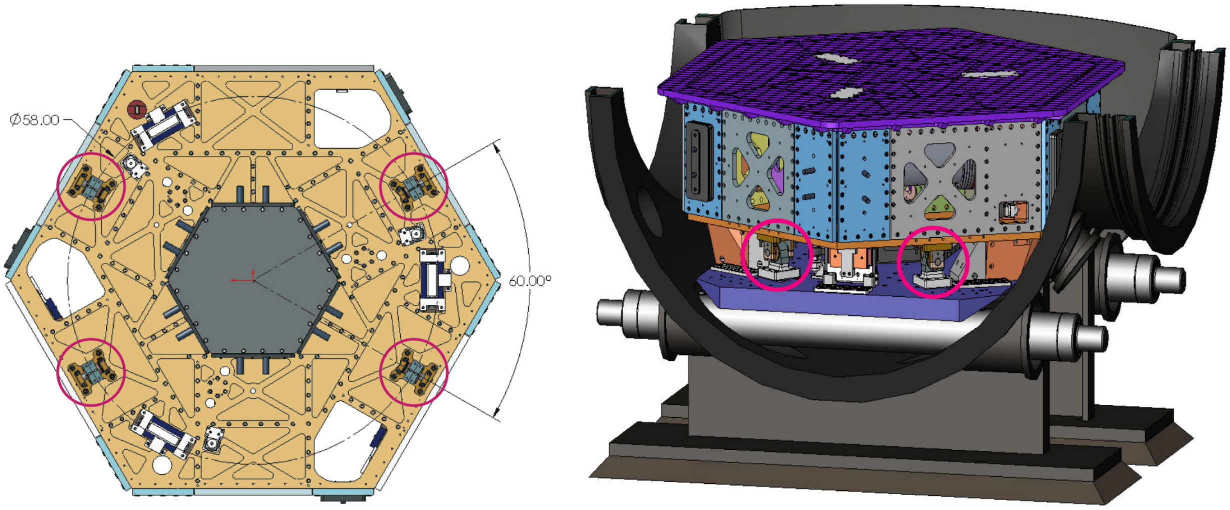


Figure 4. Lock/ limiter locations. The locker/ limiters are circled in magenta. The view on the left shows the location of the locker/ limiters on the floor of the stage 0 structure. The isometric view of the system on the right shows the locks are easy to access when the HAM doors have been removed.

3.5 Accessing components after installation.

All the sensors and actuators can be removed with the payload in place, all are accessible, and most are easy to access. For any work on the system, one will probably want to access the locks and the balance weights. This is straightforward if both HAM doors are removed, as described above.

Access to the Vertical Actuators and Vertical Displacement Sensors

The vertical actuators and the vertical displacement sensors are located in the gap between the support table and stage 1, and should be reasonably easy to access. As can be seen in figure 5, the 3 vertical actuators are all easily accessible from the doors. Two of the vertical displacement sensors are also easy to reach, but the third (on the lower left side of the table in figure 5) will require more dexterity.

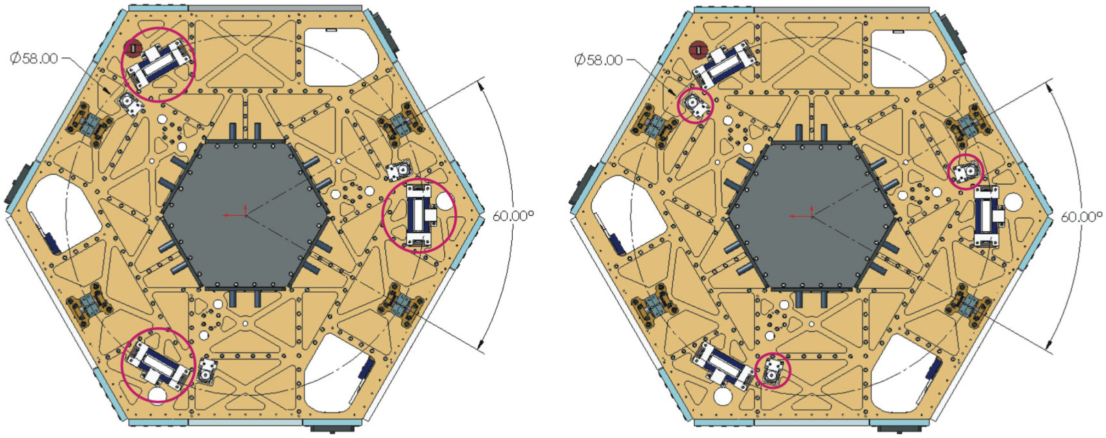


Figure 5. The locations of the vertical actuators (left) and vertical displacement sensors (right) are circled in magenta. Access to the table is from the left and right in these drawings (where the 60° notations are). This gives good access to the actuators, but the sensor on the lower left will require some dexterity.

Access to the Seismometers and Horizontal Actuators

Access to each of the GS-13 seismometers and the horizontal actuators requires the removal of a side plate, which is straightforward but probably tedious.

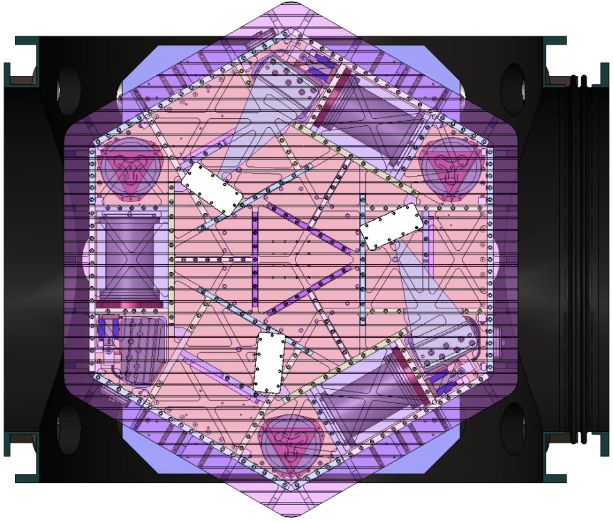


Figure 6. Top view of the table in a HAM. Five of the six seismometer cans can come directly out through the main doors. However, to remove the horizontal seismometer on the left side of the drawing, it must be pulled sideways into the beam tube, and then either lifted over the table, or go out the through the beam tube via the removable bellows or endcap, if available.

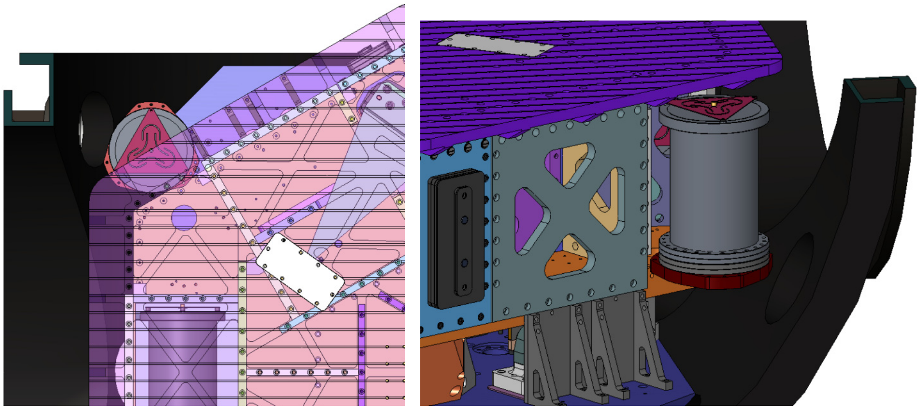


Figure 7. Drawings showing the removal of the vertical seismometer pods near the chamber edge. This shows a pod which has been moved part way out, to the point where it is closest to the chamber wall. The space is adequate, although not generous.

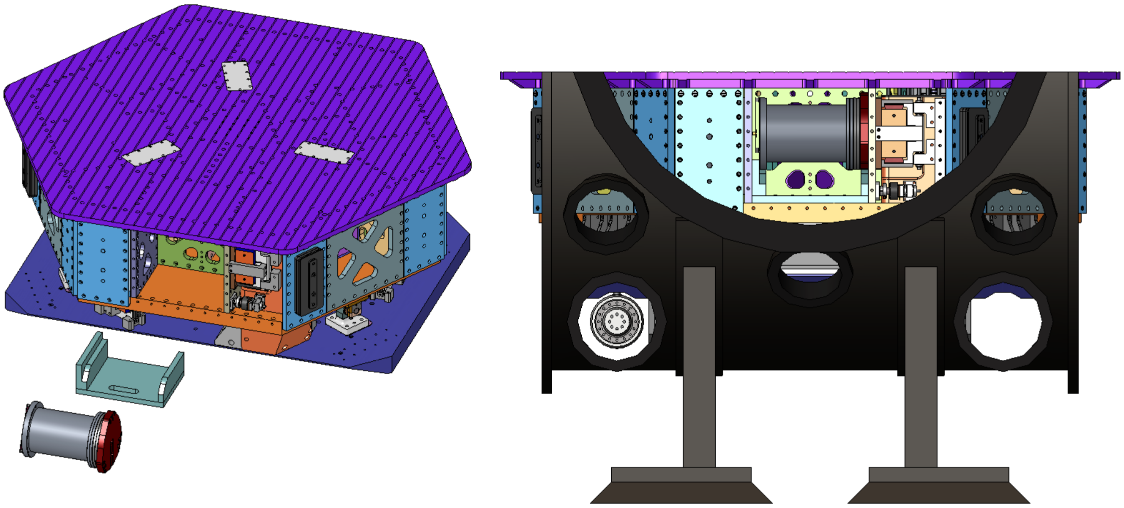


Figure 8. Drawings of the removal of the horizontal GS-13 pod to the beam tube. On the right we see that the access to the pod from the tube is good. On the left is a drawing of the installation fixture which supports the pod in the correct place while the bolts are installed. The fixture much be removed before the side plate can be reattached, so that we don't accidentally leave it in the table.

One of the 3 horizontal GS-13s will be difficult to remove. The person removing the instrument will need to sit in the beam pipe to get the instrument out. Since the table can be installed with the instrument on either side, there is some flexibility to choose which pipe will be used, so we can situate the pod in the more convenient location.

Replacing the Springs

In order to remove the springs, the table top must be removed. This necessitates removal of the payload as well. Due to the number of bolts involved, the simplest thing would be to remove the payload, then remove the entire ISI system from the chamber and change the springs on the assembly stand. We decided to do this because it allows us to put the springs right underneath the optical table and not put big removable panels in the optical table. Putting the springs high in the structure helps keep the alignment between the LZMP and the cg. This performance improvement seems worthwhile, since we have never had to remove the springs on the Technology Demonstrator.

Replacing the Flexures

The flexures can be removed and replaced with the payload in place. The top of each flexure is accessible via a small panel in the table top (the three gray panels in the purple table top). The bottom of each flexure is accessible via a removable 'picture frame' panel, and the spring tensioning tool can be used to hold the spring and replace a flexure while the table top is in place.

4 Performance Update

We have at least three ways of predicting the performance of a single stage HAM system: modeling, measured performance of the microseismic isolation with the Rapid Prototype, and the measured performance of the Tech Demo at frequencies above the microseism.

4.1 Modeling Results (from April 2006)

Extensive modeling of a single stage HAM table, supported by HEPI, and supporting a triple modecleaner suspension was done in April 2006 for the Conceptual Design Review of the new HAM requirements and the single stage HAM isolation approach (G060190). A summary of that modeling is included below. The modeling is based on the full DOF model system developed by Wensheng Hua, and includes the coupling of sensor noise and 6 DOF HEPI motion to both the table cg in 6 DOF and to the suspension point of the triple pendulum, which was assumed to be about 1 meter above the table cg (82.8 cm above the table top), and 0.9 meters to the side, so that the horizontal motion of the pendulum support point includes contributions from the translation (X), the pitch (rY), and the yaw (rZ) of the cg. Likewise the vertical motion of the suspension point contains contributions from the vertical (Z) and the roll (rX) of the cg.

As can be seen below in figure 9, the predicted performance of the table above 0.6 Hz meets or exceeds the requirements. Below 0.6 Hz, the table does not seem to meet the requirement, because of the tilt contribution from HEPI. Several comments are in order here. First, the tilt estimate used for the calculation (seen in figure 10) is a factor of 5 to 10 above the HAM structure tilt when HEPI is off between the microseism and 1 Hz. Time constraints imposed by the beginning of S5 meant that not much time was dedicated to the tuning of the HEPI tilt, and we expect that HEPI can be made much better here, especially with new gullwings. Second, the critical issue for the optical tables at these frequencies is not the absolute motion, but the relative motion. Since all the HAM HEPI systems work from the same sensor correction signal, most of this tilt motion should be the same from one tank to the next. In fact, the modecleaner control signals show that the relative motion between adjacent tables is smaller than the absolute motion of a single table shown here. Thus, we believe that the microseismic tilt coupling issues here can be addressed in Advanced LIGO.

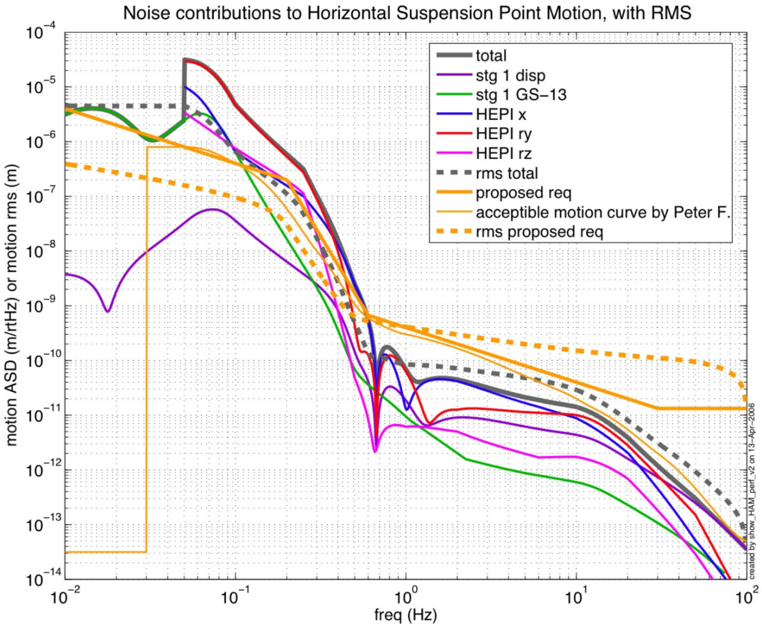


Figure 9. Predicted horizontal performance of the Advanced LIGO HAM system supported by the current HEPI implementation. The performance is calculated for horizontal motion of the support point of the triple pendulum, which is about 83 cm above the table and 90 cm off to the side. The performance is dominated by the horizontal and tilt motion of HEPI.

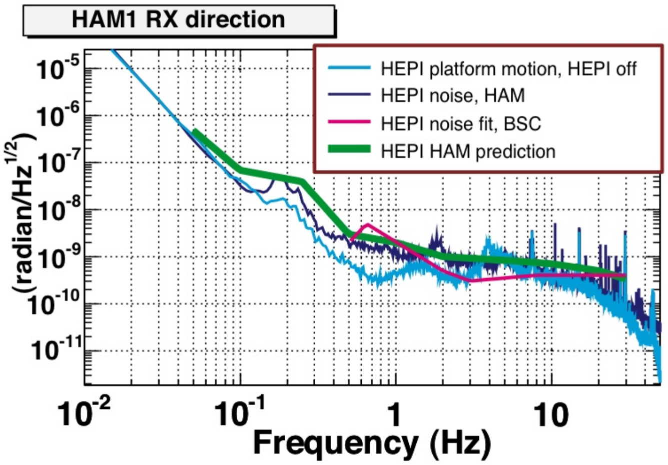


Figure 10. HEPI tilt motion used for the performance estimate in figure 9. Note that the HAM prediction (green) is very conservative – between the microseism and 1 Hz it is a factor of 5 to 10 above the tilt motion of the platform when HEPI is off.

The predicted vertical performance is shown in figure 11. There is no explicit requirement on the vertical motion, but there is an implicit requirement that the motion coupled through the transfer function of the pendulum with cross couplings not exceed the horizontal motion requirements of the optics.

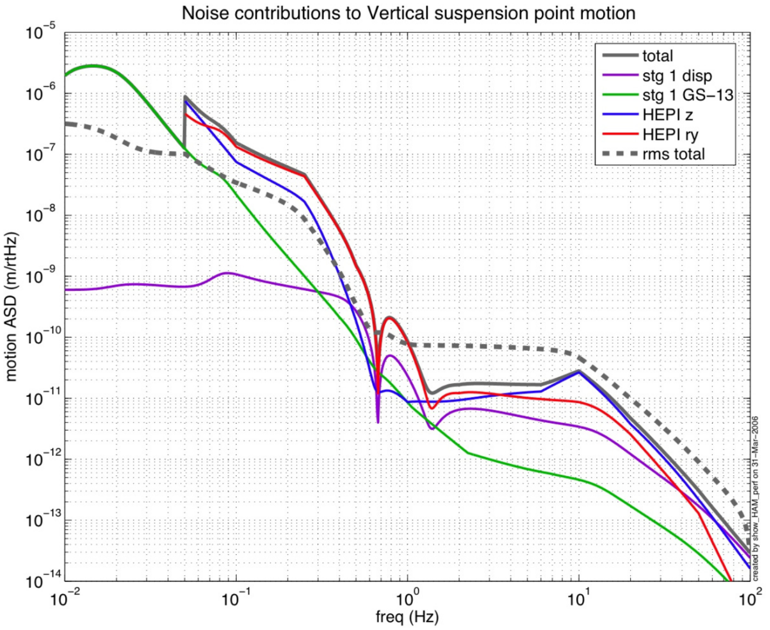


Figure 11. Predicted vertical performance at the support point.

Using a model of the triple pendulum provided by the suspension team, one can use the motion of the suspension point to predict the motion of the modecleaner optic. That prediction, including a variety of cross-couplings, is shown below in figure 12. The predicted motion of the optic at 10 Hz is 2.2e-16 m/rtHz, and the integrated rms from 0.6 Hz to 100 Hz is about 0.9 nm.

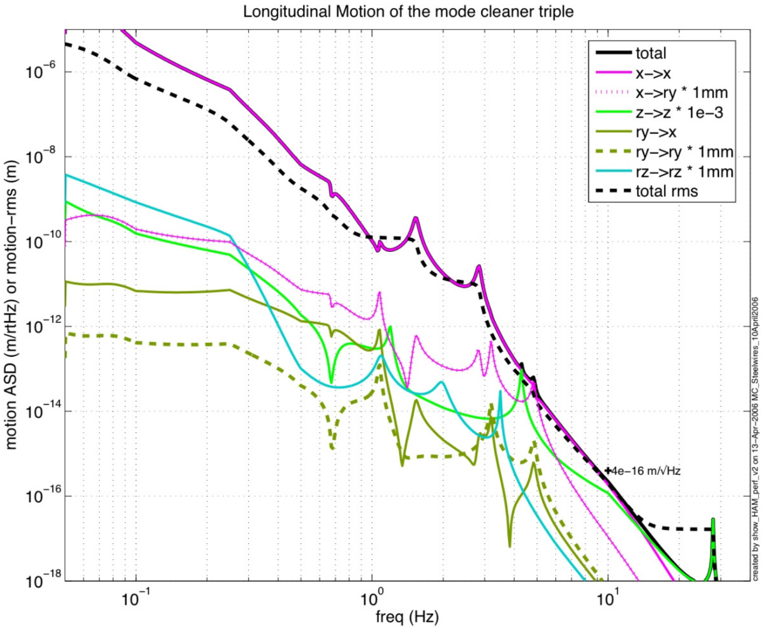
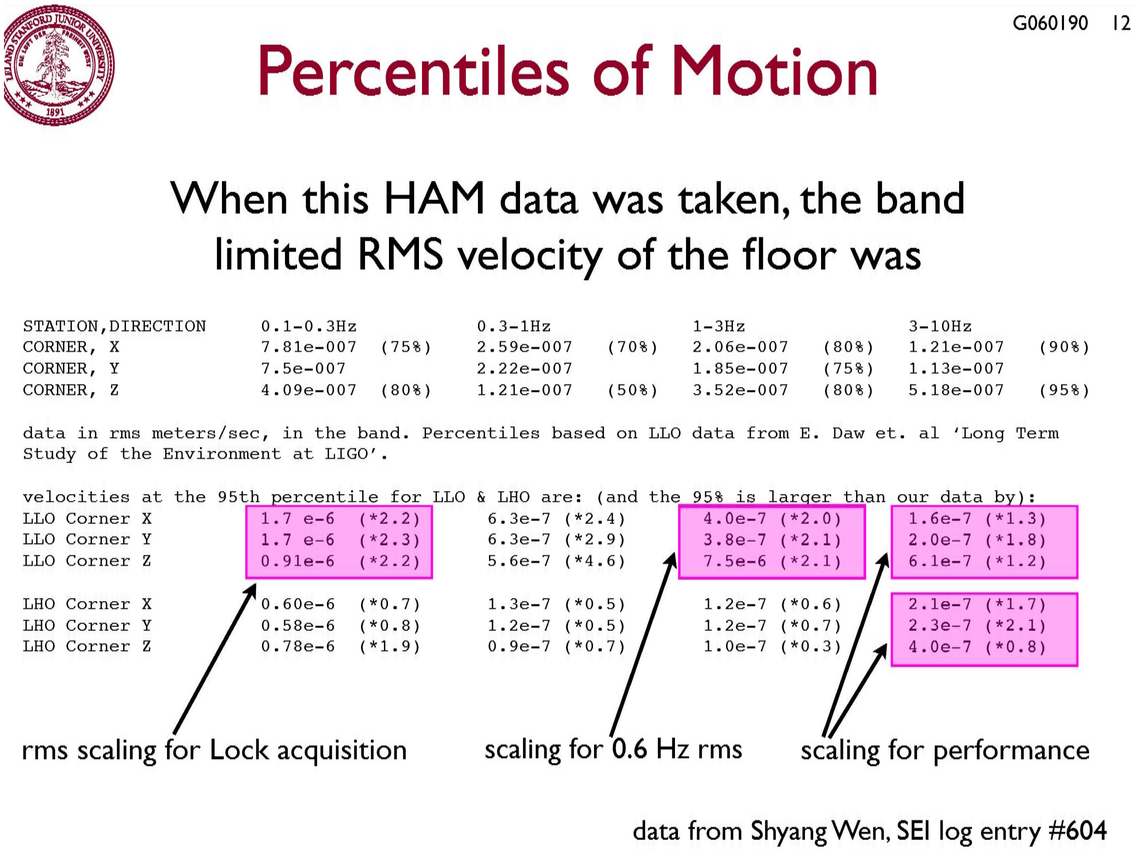


Figure 12. Predicted motion of the modecleaner optic in the beam direction.

These estimates are based on motion inputs from HEPI at specific times. Shyang Wen compared the spectra of ground motion at these times with the percentiles of motion generated by E. Daw et. al in the 'Long Term Study of the Environment at LIGO'. The motion estimates here are at about the 75%-80% percentile for the microseism and about the 90-95% percentile for the 3-

1 Hz band. The 95% percentile motion of the microseism is about 2.2-2.3 times larger amplitude than these inputs. The page of percentiles is shown below in figure 13.



G060190 12

Percentiles of Motion

When this HAM data was taken, the band limited RMS velocity of the floor was

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STATION,DIRECTION      0.1-0.3Hz              0.3-1Hz                1-3Hz                  3-10Hz
CORNER, X              7.81e-007   (75%)      2.59e-007    (70%)     2.06e-007    (80%)     1.21e-007    (90%)
CORNER, Y              7.5e-007               2.22e-007              1.85e-007    (75%)     1.13e-007
CORNER, Z              4.09e-007   (80%)      1.21e-007    (50%)     3.52e-007    (80%)     5.18e-007    (95%)

data in rms meters/sec, in the band. Percentiles based on LLO data from E. Daw et. al 'Long Term
Study of the Environment at LIGO'.

velocities at the 95th percentile for LLO & LHO are: (and the 95% is larger than our data by):
LLO Corner X           1.7 e-6   (*2.2)       6.3e-7 (*2.4)           4.0e-7 (*2.0)         1.6e-7 (*1.3)
LLO Corner Y           1.7 e-6   (*2.3)       6.3e-7 (*2.9)           3.8e-7 (*2.1)         2.0e-7 (*1.8)
LLO Corner Z           0.91e-6   (*2.2)       5.6e-7 (*4.6)           7.5e-6 (*2.1)         6.1e-7 (*1.2)

LHO Corner X           0.60e-6   (*0.7)       1.3e-7 (*0.5)           1.2e-7 (*0.6)         2.1e-7 (*1.7)
LHO Corner Y           0.58e-6   (*0.8)       1.2e-7 (*0.5)           1.2e-7 (*0.7)         2.3e-7 (*2.1)
LHO Corner Z           0.78e-6   (*1.9)       0.9e-7 (*0.7)           1.0e-7 (*0.3)         4.0e-7 (*0.8)
```

rms scaling for Lock acquisition

scaling for 0.6 Hz rms

scaling for performance

data from Shyang Wen, SEI log entry #604

Figure 13. Percentile analysis for the ground motion input used in this analysis.

4.2 Experimental Results

There are experimental demonstrations of isolation which, in combination with the modeling tools described above, give confidence in our ability to reach the HAM performance requirements. It should be noted that installation of the HAM ISI in Enhanced LIGO will be different than the Advanced LIGO scenario modeled above, because HEPI will not be present for Enhanced LIGO. Instead, the sensor correction signals from the STS-2 mounted on the ground will be fed directly to the isolation stage. This is the way Wensheng Hua originally implemented the sensor correction on the Rapid Prototype, and it worked extremely well. In fact, this will make the sensor correction simpler, and will probably make it work better (ie less tilt will be generated by the flexing gullwings), but at the expense of carrying large static offsets inside the vacuum system.

The first system ever to demonstrate a factor of 10 isolation at the microseism in all 3 translation directions simultaneously was the Rapid Prototype when it was installed in the Stanford engineering test facility, see figure 14 below. This was the system on which Wensheng Hua developed the control techniques (e.g. polyphase FIR filtering) which were later employed by HEPI at LASTI and LLO. The microseismic isolation for ELI will be almost an exact copy of the sensor correction used by the Rapid Prototype.

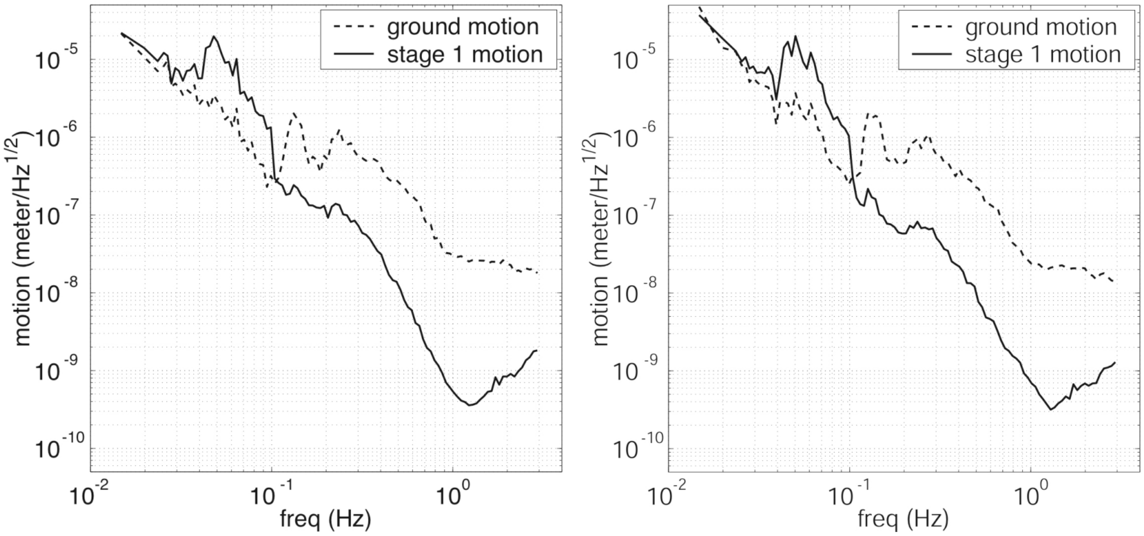


Figure 14(a). Horizontal performance of the Rapid Prototype (x left, y right). The microseism is reduced by about a factor of 10, to about 2e-7 m/rtHz. The amplification between 40 and 100 mHz is from the FIR filter shape.

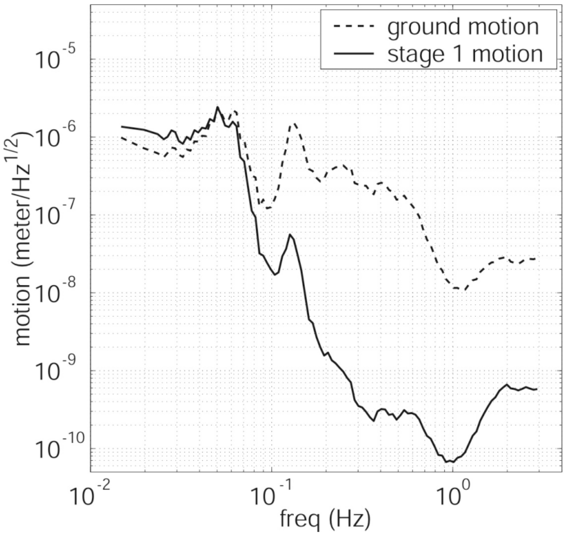


Figure 14.(b) Vertical performance of the Rapid Prototype. The vertical isolation of the microseism is about a factor of 30, and the motion is well below 1e-7 m/rtHz. The low frequency amplification is much smaller, since the high performance tilt-rejection FIR filters are not necessary for the vertical direction.

The implementation of the microseismic sensor correction on the HAM ISI will be much easier than it was for HEPI because the methods of addressing tilt of the stage are much simpler. The control for the Rapid Prototype employs high gain feedback loops for the tilt directions, based on signals from the vertical displacement sensors (at low frequency) and the vertical inertial sensors (at high frequency), so that the stage moves horizontally without tilting. This is easier to implement on an ISI system than on HEPI, because the ISI stages are quite stiff, so the three vertical sensors give an excellent rendition of the tilt everywhere on the stage. In contrast, the four corners of the gullwings (where the vertical displacement sensors for HEPI are located) twist independently, so the tilt of the horizontal geophones mounted on the ends of the gullwings is essentially unrelated to the differential vertical signal between the various displacement sensors. This is the driving force behind the redesign of the HAM gullwings for Advanced LIGO.

Results from the Technology Demonstrator

Recent measurements from the Tech Demo can also be used as a guide to the expected performance from the single stage HAM. It is important to note that the Tech Demo is currently set up to prototype Advanced LIGO BSC-style isolation systems, so we have assumed that HEPI will be installed on the outside. Therefore, we have not allowed ourselves the use of sensor correction for the internal system, and all the performance in the current measurements below about 2 Hz uses feedback only, which is complementary to the sensor correction. However, the feedback loops are aggressive, so the performance between 0.2 Hz and 1 Hz meets the HAM requirements. This performance will improve when we use the sensor correction described above.

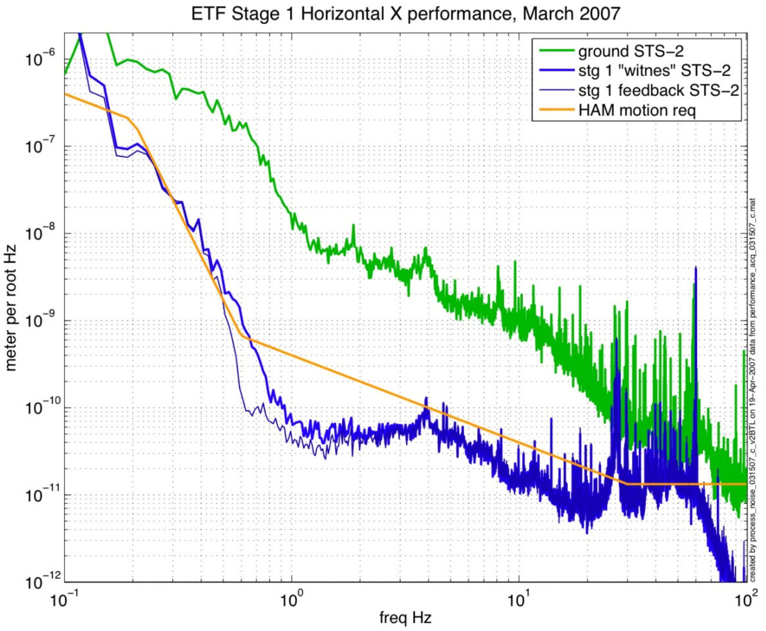


Figure 15. Horizontal Performance of Stage 1 of the Technology Demonstrator. The Y performance is not as good. The peak at 27 Hz is from the tilt motion of the support table.

There are a few important differences between the first stage of the Tech Demo and the HAM design. First, the HAM will use GS-13s as inertial sensors, whereas the Tech Demo uses STS-2s and L-4Cs. The second stage of the Tech Demo does use GS-13s, and the noise performance we measure from those sensors is sufficient to meet the HAM requirements, as shown below in figure 17. The second difference is that the tilt modes of the Tech Demo are at about 12 Hz, whereas the tilt modes for the HAM are at 1.07 Hz. These modes were lowered because the horizontal performance of the Tech Demo is compromised by tilt coupling above a few Hz. The peaks at 27 Hz in figure 15, for example, are primarily generated by tilt. Thus, we expect the performance of the HAM above 10 Hz to be significantly better the performance of the first stage of the Tech Demo. Finally, the Tech Demo has tip, tilt, and vertical feedforward loops running from the support structure to stage 1 which improve the isolation around 10 Hz. These loops are not in the baseline for the HAM (although they could be easily added, later, if we decide they would be useful).

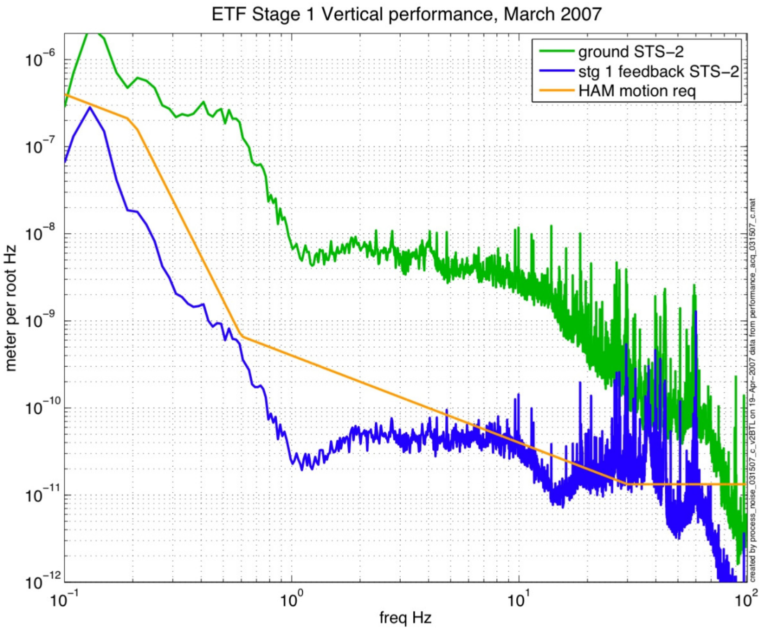


Figure 16. Vertical Performance of the first stage of the Tech Demo. There is no explicit requirement for the vertical motion of the table, so the horizontal performance curve is included for reference.

The Tech Demo is a two stage isolation system, and we have mounted several witness sensors of the optical table of stage 2 to evaluate performance. Included are 2 GS-13 witness sensors. The motion measured by those sensors (in line with each other, aligned along the X direction), and the estimated noise, is shown below in figure 17. We see that the measured motion is smaller than the HAM requirement at all frequencies above about 0.18 Hz. Then, we use the multi-channel coherent subtraction technique to remove all the signal from the sensors which is coherent with the 6 feedback GS-13s on the stage, which should leave us with a good estimate of the noise performance of the sensor in operation. Those curves are much quieter than the HAM requirements, although still about a factor of 2 above the value we expect from calculation. The discrepancy may arise from the ADC noise on the feedback sensors used in the fitting process.

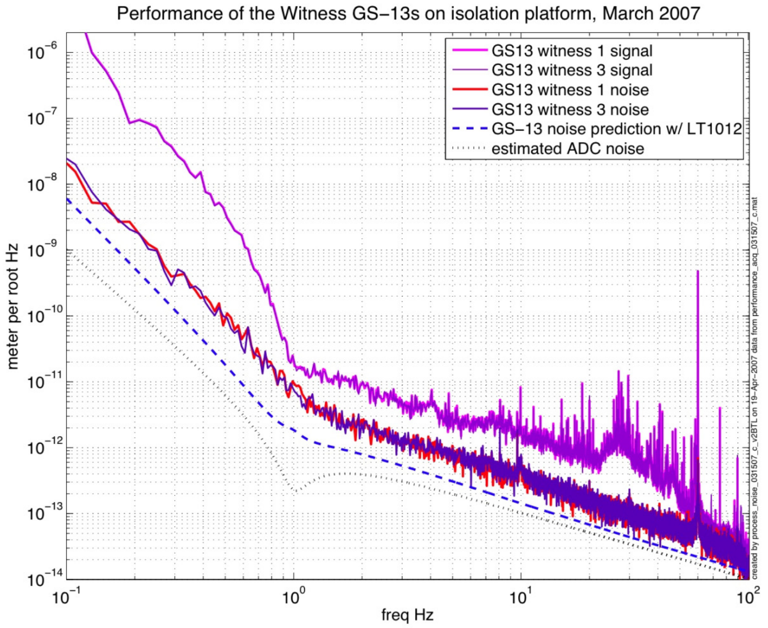


Figure 17. Noise performance of the GS-13s. This noise will allow us to reach the HAM requirements.

5 Other Performance and Technical issues

5.1 Integration with a hierarchical control system

This system should be very easy to integrate with a hierarchical control scheme. The controlled table presents an extremely high back-impedance to the pendulums (as was first shown experimentally at Stanford in 2000). Furthermore, the fast, 6 DOF control of the table can be easily exploited by signals from any source, either to offload control authority from the pendulums, or provide another drive point for the global length or alignment system.

5.2 Sensor Reliability

There are two types of sensors used on the platforms, capacitive displacement sensors from ADE, and GS-13 inertial sensors. Of the GS-13 we have inventories, the 12 at LLO seem to have never failed, although the fancy readouts (which we are replacing with low-noise readouts) come in two flavors – ones with 2 poles at 10 Hz, and ones with 2 poles at 20 Hz. The factor of 4 difference in response above 20 Hz has caused some confusion, but we don't thing that they have ever failed. Of the 9 at Stanford, 2 were broken when they arrived after rough shipping, and have been repaired. Internal mechanical parts had come off, and when they were bolted back on, they worked fine. In one case, parts of the internal mechanism had come loose (see http://ligo.phys.lsu.edu:8080/ETFseismic/119) , and in the other, the attachment ring for the sensor coil and several other mechanical parts had come loose (see http://ligo.phys.lsu.edu:8080/ETFseismic/101) . We should see this in the initial assembly into the pods, or in the testing. A third sensor which was initially damaged and didn't work properly, but we never found the reason or and were note able to fix it. It should be noted that these sensors were packed incorrectly when they were shipped to Stanford, and were probably damaged in transit.

Summary: 21 GS-13s, most in use for about 4 years. 3 have failed, probably in shipment. We don't know of any which have failed in service.

We have had some operational issues with the displacement sensors. There have been electronics issues with the readouts, which required some rework of the boards, for both noise issues and oscillation issues, and some problems with the LIGO crates to hold the electronics. We think that these issues have all been resolved.

We have also broken either 2 or 3 of 12 (Brian's memory is not clear) sensor heads at Stanford. This was probably due to rubbing between the sensor head and the target. This has been addressed in two ways. The motion limiters of the Tech Demo do not actually fully restrain the stages in the way we though they would, and they allow rubbing. The new motion limiters have been much more carefully designed and the allowed motion at various critical gaps is now being calculated properly (see http://ligo.phys.lsu.edu:8080/LIGO+HPD/69). In addition, we have added local motion stops at the sensor head - the attachment bolts for the sensor head now stick up slightly past the sensor head, so the target hits the bolts rather than the head. After we installed this, we have not had any problems with the heads in operation. There is one of our sensors which has occasional bursts of noise when the velocity of the stage gets large. We don't know what causes this, but since the motion is usually small we haven't fixed it yet. This problem is probably in the electronics which sit outside the vacuum system.

The actuators have also given some problems. We have taken several steps to address this, following the path taken on the displacement sensors. The stage motion limiters should protect the actuators. The actuators have been redesigned with larger (2 mm nominal) gaps in the critical direction, and much larger (~5 mm) gaps in the other directions. In addition, the actuators are designed so that they are self protecting, ie the inner surface of the coil form contacts the metal core of the actuator 0.020 inches before anything can come in contact with the magnets.

5.3 Need for HEPI

As described in the performance section, we do not expect to need HEPI to get microseismic isolation, although having another stage may be useful. We see the main role of HEPI as the long-throw actuator in the system, designed so that the electromagnetic actuators in the chamber can be kept near 0 current, so that they do not get too hot. This still seems like a worthwhile goal.

A few numbers:

maximum throw of the HAM (x_{max})	0.6 mm
max tidal throw of the HAM (x_{tide})	0.12 mm
comfortable rms throw (x_{typ})	0.030 mm (comfortable motion, excluding tides)
actuator coil resistance (R)	7.1 ohms
force constant (C)	9.2 lbs/amp (41 N/amp)
stage vertical stiffness	2.4e5 N/m
stage horizontal stiffness	1.3e5 N/m
max proportion of total force seen per actuator	
vertical (Pv)	1/3
horizontal (Ph)	2/3

maximum power in an actuator to drive a displacement, is,

$$power = R \cdot \left(\frac{P \cdot k \cdot x}{C} \right)^2$$

For the numbers given above, the power dissipated in an actuator would be

	vertical	horizontal
max throw:	9.7 watts	11.4 watts
tidal throw:	390 mW	450 mW
typical motion:	24 mW	29 mW

The power dissipation for typical motions is clearly nothing to worry about, and even the tidal motions seem to not be much cause for concern, so long as some care is taken to ensure good thermal contact from the actuator to the mount, such as a thin piece of very soft aluminum. The max throw is clearly unacceptable, except for short periods of time. We see that the HEPI systems does go to 700 microns from time to time, but only in transient ways.

In all, I'd guess that dissipating a watt on a continuous basis might start be an issue, and 10 watts for static situation seems sure to cause problems. Thus, dropping HEPI will both limit the number of stages in which we might do isolation, were it necessary, and it would certainly constrain our ability to move the optics by more than about 200 microns.

6 Cost and Schedule Update

Enhanced LIGO Cost and Schedule Plan

	1st UNIT	2nd Unit	Production Units
ISI HAM Mechanics	280,264	280,264	235,396
PSI Actuators (6)	30,858	30,858	25,428
ADE Displacement Sensors	29,328	29,328	25,500
Geotech GS-13 Seismometer	45,920	45,920	38,268
AccuGlass In-Vac Cabling	6,906	6,906	6,906
Total ISI Procurements	393,276	393,276	331,498
Shipping Costs	6,000	6,000	
Cleaning Costs	7,500	7,500	
Assembly Tooling	5,000		
Rework/Mods	5,000	5,000	
HPD Procurement Costs	12,500	12,500	
HPD Burden on Purchases	58,015	58,015	
HPD Assembly & Fit Test Labor	21,600		
HPD In-air Dynamic Testing Labor	9,840		
HPD Disassembly and Packing Labor	12,900		
HPD Disposable Parts for Dirty Assembly	7,000		
HPD Cleaning Labor	3,200		

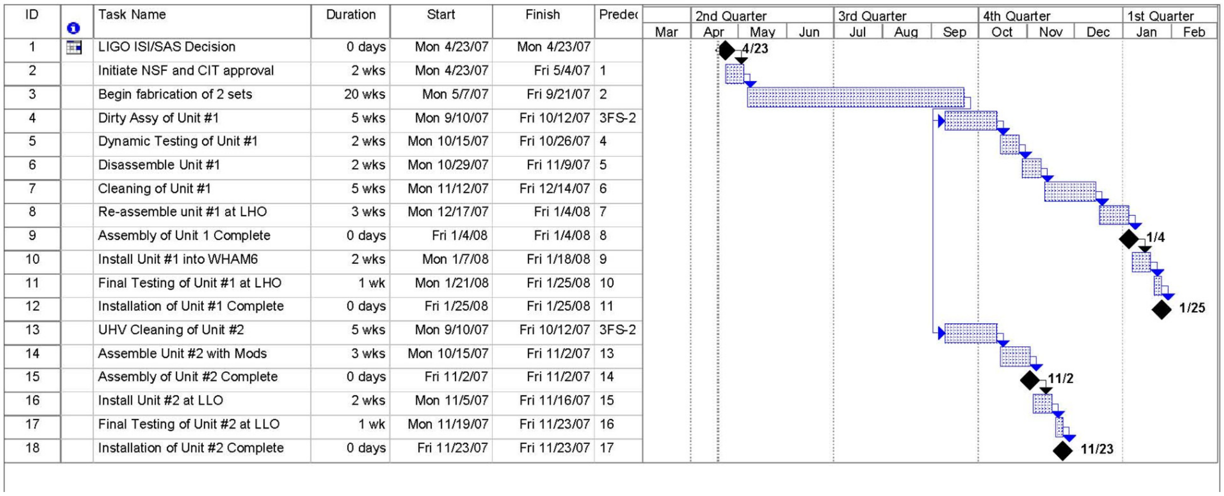
HPD Project Management	21,353		
TOTALS	563,184	482,291	331,498

For Enhanced LIGO, the following parts will be needed to upgrade WHAM6 and LHAM6:

(4) Crossbeams	28,000
(4) Support Tubes	50,000
(8) Spherical Bearings & Caps	24,000
(8) Expansion Bellows	32,000

The piers, scissor tables, and air bearings will come from those removed during the HEPI installation at Livingston.

The Advanced LIGO production unit cost is coming in below the BOE submitted to the NSF on April 5, 2006. These costs are based on actual quotes received by HPD. They will convert this into a formal proposal which will be given to us the week of 4/23/2007.



ID		Task Name	Duration	Start	Finish	Predec
1		LIGO ISI/SAS Decision	0 days	Mon 4/23/07	Mon 4/23/07	
2		Initiate NSF and CIT approval	2 wks	Mon 4/23/07	Fri 5/4/07	1
3		Begin fabrication of 2 sets	20 wks	Mon 5/7/07	Fri 9/21/07	2
4		Dirty Assy of Unit #1	5 wks	Mon 9/10/07	Fri 10/12/07	3FS-2
5		Dynamic Testing of Unit #1	2 wks	Mon 10/15/07	Fri 10/26/07	4
6		Disassemble Unit #1	2 wks	Mon 10/29/07	Fri 11/9/07	5
7		Cleaning of Unit #1	5 wks	Mon 11/12/07	Fri 12/14/07	6
8		Re-assemble unit #1 at LHO	3 wks	Mon 12/17/07	Fri 1/4/08	7
9		Assembly of Unit 1 Complete	0 days	Fri 1/4/08	Fri 1/4/08	8
10		Install Unit #1 into WHAM6	2 wks	Mon 1/7/08	Fri 1/18/08	9
11		Final Testing of Unit #1 at LHO	1 wk	Mon 1/21/08	Fri 1/25/08	10
12		Installation of Unit #1 Complete	0 days	Fri 1/25/08	Fri 1/25/08	11
13		UHV Cleaning of Unit #2	5 wks	Mon 9/10/07	Fri 10/12/07	3FS-2
14		Assemble Unit #2 with Mods	3 wks	Mon 10/15/07	Fri 11/2/07	13
15		Assembly of Unit #2 Complete	0 days	Fri 11/2/07	Fri 11/2/07	14
16		Install Unit #2 at LLO	2 wks	Mon 11/5/07	Fri 11/16/07	15
17		Final Testing of Unit #2 at LLO	1 wk	Mon 11/19/07	Fri 11/23/07	16
18		Installation of Unit #2 Complete	0 days	Fri 11/23/07	Fri 11/23/07	17

HPD is scheduled to complete the fabrication drawings by 4/27/07. The drawings have been completed enough to get quotes with lead times for all critical parts. This schedule assumes a decision on either the ISI or SAS is made the week of 4/23/07 and approval from the NSF and Caltech is made 2 weeks later. The large machined parts, springs, and smaller machined parts have a 12 – 14 week delivery with the longest lead item being the actuators which can be ordered sooner than 5/7/07. This may result in a shorter schedule than above. The plan would be to ship the air bake furnace at Galli & Morelli to LLO or build our own whichever is most cost effective and it is operational by 9/1/07.

Andy Stein is a mechanical engineer who will be starting on May 7th at MIT. He will be asked to play a big role in the HAM ISI project. His first task will be to analyze the HAM gullwings to help us determine if a new design would be beneficial. He will then spend time with Brian Lantz at Stanford training on the ETF. Ken Mason and Rich Mittleman will concentrate on completion of the BSC ISI system.