LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T070087-00 *ADVANCED LIGO* 04/19/2007

Second Report to the HAM-SAS Evaluation Committee

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Introduction

This report is a follow up report to the initial report provided to the HAM-SAS evaluation committee, T070079-00. In this report answers to questions posed by the committee are provided as well as an update on the latest results from LASTI prototype testing..

In addition to the authors of this report the following people have made significant contributions to the installation, commissioning, modeling or understanding of the HAM SAS prototype: Ben Abbott, Yoichi Aso, Mark Barton, Dennis Coyne, Valerio Boschi, Carlo Galli, Gianni Gennaro, Yumei Huang, Jameson Quave, David Ottaway, Virginio Sannibale, Alberto Stochino, Chiara Vanni, Hiro Yamamoto and Sany Yoshida

1. New Results and Understanding

When the HAM-SAS team and the evaluation committee met (April 13th), we agree that the following are the priorities for further experimental work:

Priority 0: Optics Table Motion Measurement: Use the available sensors (in particular the L4C geophones on the table and the optics lever) to better determine the actual table motion.

Priority 1: Reduce Low Frequency and RMS Motion: Figure out what to do about low-f excess vibration and effect of measures taken on higher frequency isolation. Without reduction of the microseism, HAM-SAS won't be useful.

Priority 2: Reduce Motion due to Ancillary Spring Modes: Show that all those 10-30 Hz resonances and 100-ish Hz resonances can really be damped.

Priority 3: Drift: Get drift data

Priority 4: Triple Pendulum Interaction: Release triple and explore/measure the interaction.

Priority 5: Upper Unity Gain: Demonstrate upper unity gain frequency possible with active feedforward or feedback

Due to short intervening time as well as a number of problems not intrinsically related to HAM-SAS[1], not much of the above list has been addressed. In the following the status for each of these concerns are addressed.

1.1 Optics Table Motion Measurement

The original seismic isolation system performance requirements defined in E990303-03 (figure 2) only defined a requirement above 0.1 Hz. More recently, Peter Fritschel proposed an "acceptable motion curve" in T060075-00 (figure 3, red curve labeled "SEI displacement"). Subsequently Brian

[1] In the last week we have contended with a seriously non-cooperative data acquisition system, a failure on the LASTI vacuum system which caused an unintentional vent and a pair of actuator coil drivers intermittently going into oscillation.

Lantz proposed[2] a requirement amplitude spectral density (ASD) which is compared to Peter's "acceptable motion curve" in G060190-00 (pg. 4 & 5).

The overall best (lowest) amplitude spectral motion measurements for the optics table remains Figures 3-3 and 3-4 from the first report to the committee (T070079-00). These figures are repeated below for easy reference. When the committee met with the HAM-SAS team April 13th a very recent amplitude spectral density plot was shown[3], which indicated that the top of the inverted pendulum acted as though inertially isolated (the LVDT and Guralp ground seismometer signals matched). It was noted at that time that the amplitude of the witness geophone spectrum in this plot was considerably higher (~10x) than shown in Figure 3-3 of T070079-00 (repeated as Figure 1 below). At the time we had no explanation and this raised concerns of lack of stability or repeatability of the system. We now know that the servo gain was too high and this contributed to some injected noise, but the principal cause for the excess optics table motion appears to be significantly higher optics table tilt, a likely transient glitch in the data acquisition and a pair of coil actuator drivers going into oscillation.

[2] This proposed requirement is the de facto current isolated motion requirement. The SEI subsystem requirements document, E990303-03 needs to be revised to reflect this fact.

[3] D. Ottaway, LASTI elog entry: "Preliminary data from last night", Apr 13, 2007.

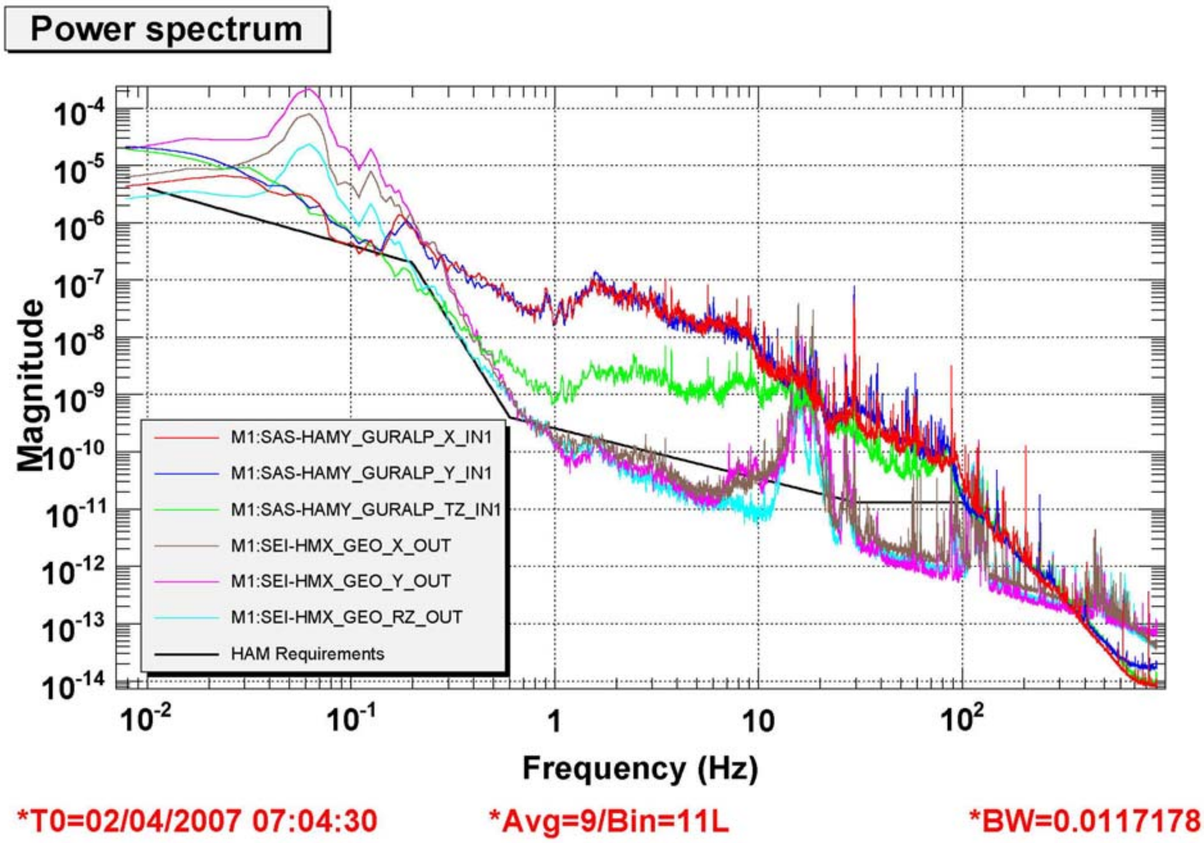

Figure 1: Horizontal Isolation Performance of HAM SAS. Note the vertical axis units are in m/√Hz. The Guralps are mounted on the ground and the GEO signals are the table geophones. *[this is Figure 3-3 from T070079-00]*

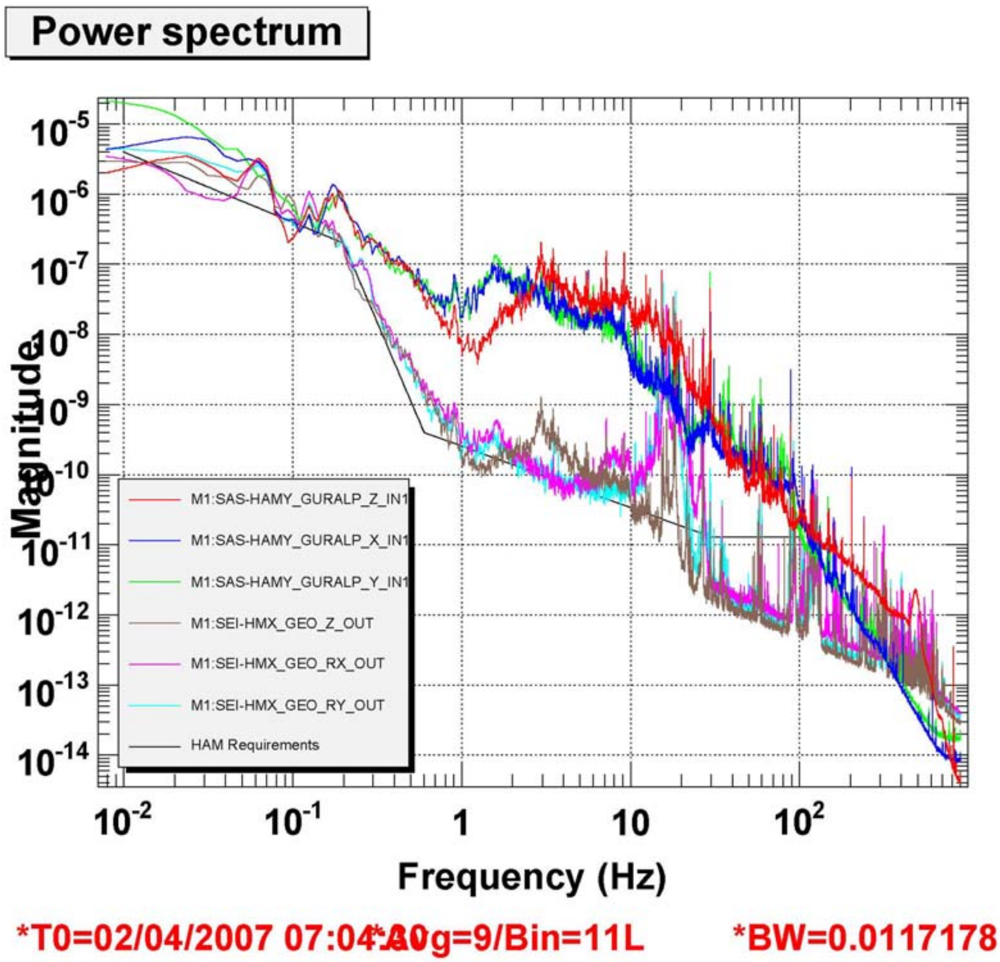

Figure 2: Vertical Isolation Performance of HAM SAS. Note the vertical axis units are in m/√Hz *[this is Figure 3-4 from T070079-00]*

1.1.1 Excess motion between 0.1 Hz and 1 Hz

Almost all of our effort in the last week has been spent investigating this aspect of the performance. However very recently it was realized that the data is corrupted by a voice coil channels going into oscillation.

1.1.2 Ground tilt is not the dominant source of displacement

Simulation results[4] for the HAM-SAS inverted pendulum indicates higher motion due to ground tilt as the inverted pendulum (IP) frequency is lowered, as expected. Two cases are shown in Figure 1, a 100 mHz IP and a 30 mHz IP.

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[4] Obtained by Valerio Boschi using MBDYN; a report is pending.

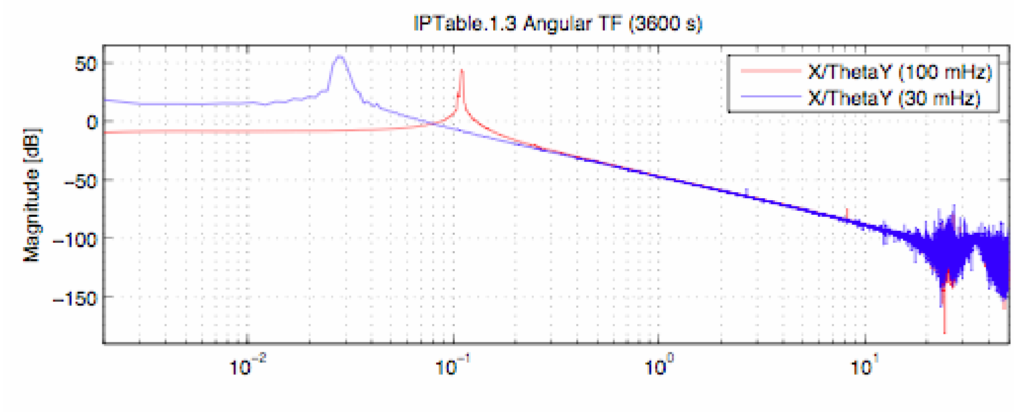


Figure 3: Simulation of the HAM-SAS Inverted Pendulum for two different IP fundamental frequencies, 30 mHz and 100 mHz. Magnitude (m/rad, dB) vs Frequency (Hz).

Multiplying the ground tilt to horizontal motion transfer function, shown in Figure 1, by the LLO ground tilt measurement[5] results in a predicted motion, due to ground tilt with passive isolation, which is well below the HAM isolation requirements, except at the IP rigid body frequency (as shown in Figure 2).

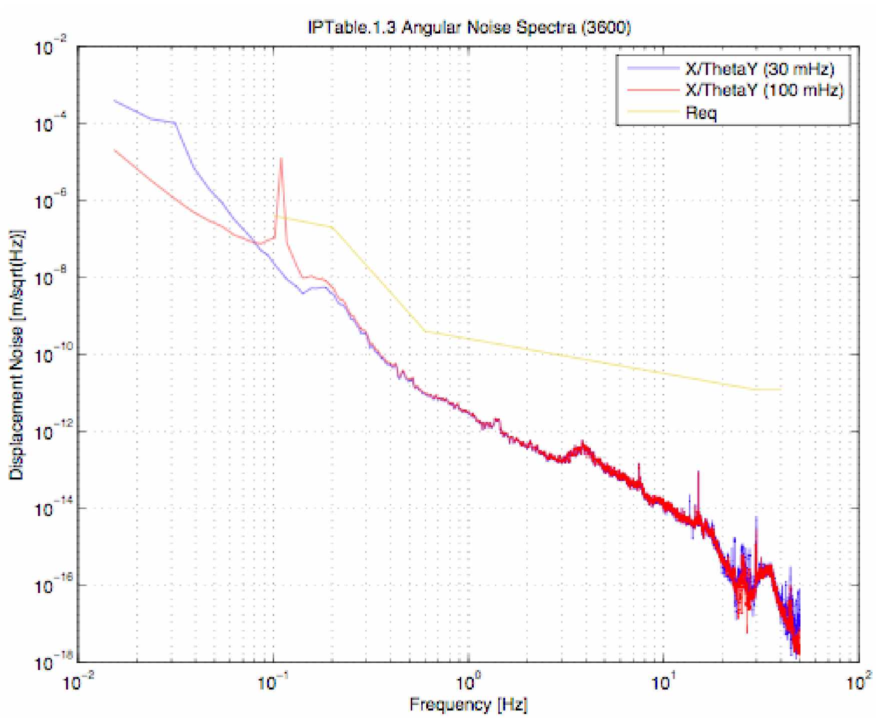


Figure 4: Predicted horizontal motion due to ground tilt (passive).

[5] Data from J. Giaime and S. Wen

1.1.3 Sensor Limitations

The chosen witness sensors are less than optimal in some frequency regions. One expects coherence between the Guralp ground seismometers at low frequency. However, there is no coherence between the Guralp signals below 0.1 Hz. When this was recently realized, we added a couple of STS2 ground seismometers and have used them for more recent comparisons.

The optics table witness geophones (L4Cs) are limited at or above the requirement level due to electronics noise, below 70 mHz and from ~0.5 to 0.7 Hz (Figure 9). This compromises the capability to derive optics table tilt motion (from the vertical geophones, in this frequency band) and properly scale these motions to the much lower ground noise at the observatories.

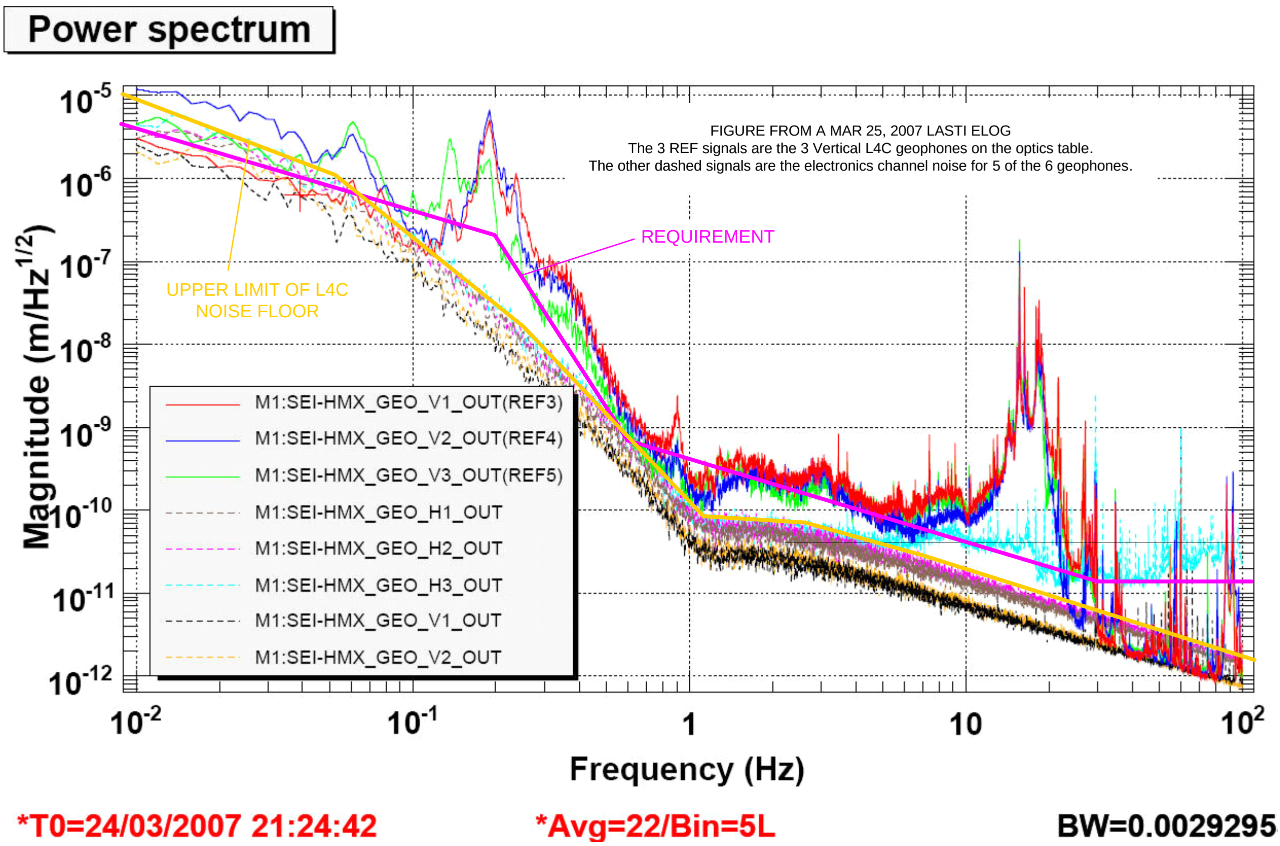


Figure 5: Comparison of the noise floor for the witness geophones (L4Cs on the optics table) to the required amplitude spectral density. Note that the comparison geophone traces in this plot do not correspond to the best machine state for isolation. Witness L4C measurements below ~70 mHz are limited by electronics noise.

1.2 Reduce Low Frequency and RMS Motion

No further progress due to testing problems not intrinsic to HAM-SAS.

1.3 Reduce Motion due to Ancillary Spring Modes

The system was not vented to try the eddy current damping fix to the vertical stepper motor springs. Reducing the motion due to the tilt stabilization springs will require a relatively minor modification of the arrangement of these springs; this modification is not yet ready to implement. See the response to question 3 below for more details.

1.4 Drift

The controlled currents of all 8 actuators (horizontal and vertical) over the last week have remained stable to within +/- 500 counts, which is about +/- 2 V out of the +/- 24 V available. The witness LVDTs are similarly stable.
The optical lever signals (which are not currently recorded to the frame data) have not been examined due to distraction on other activities.

1.5 Triple Pendulum Interaction

No measurements were made; the triple remains clamped with its earthquake stops on the HAM-SAS optics table. However, see the related discussion in response to question 9 below.

1.6 Upper Unity Gain

See the response to question 5 below.

2. Questions on HAM-SAS report

1) Regarding vacuum compatibility, does the list of materials given in 3.1 includes the stepper motors. I've been concerned about the steppers, and it would be good to see a list of materials in them (if not covered by the existing list), and the vacuum compatibility data we have taken so we can judge this.

Materials used in the AML stepper motor assembly (as far as we know):

- Silicon Nitride (ceramic) balls in bearings
- Stainless Steel (bearing cage & race)
- self-coloured polyimide (electrical insulation)
- PEEK (electrical insulation)
- metal surfaces are etched & coated with DLC (Diamond-Like Coating)
- Copper (wiring)
- FEP (power lead insulation)

Suitable for use in vacuum below 1e-10 mB = 0.8e-10 torr (manufacturer spec). See also traveler E050105-00 for a photograph and dimensions if interested.

Also, is nickel plating allowed on type A components?

Yes, nickel plating has been approved for use. Nickel plated rare earth magnets have passed vacuum compatibility testing. Note also that nickel is a component of Stainless Steel. The HAM-SAS nickel plated parts are baked above 200oC (425oC for the Maraging parts) for 2 days.

2) Not all readers will be able to identify the correspondence between channel names and measured quantities. It would be useful to define axis orientation for x, y, z channels and define what RX, TX for instance refer to.

RX and TX are synonymous (R for Rotation, T for Theta or the angle of rotation) and designate rotation about the X axis. The X axis is horizontal and along the main beam line direction for the HAM (parallel to the support tubes). The Y axis is horizontal and perpendicular to the support tubes (in the direction of the main HAM access ports). The Z axis is vertical (positive is up).

3) Fig 3.3 and 3.4 and page 9. Why are the resonances in the vertical springs in 10 to 30 Hz region (as yet undamped) so clearly coming through in both horizontal and vertical directions?

In the first report to the committee (T070079-00, section 3.4, pg 9) we attributed all of these undamped modes to the vertical stepper motor springs; this was not completely correct. These resonances are in part due to the vertical stepper motor springs, mounted on top of the horizontal attenuated stage (spring box). They oscillate like violin modes, pulling vertically on the vertical stage and recoiling horizontally against the spring box. In addition, the tilt-stabilization springs which act horizontally on the optics table, through a lever arm to impose a restoring moment, also contribute to these modes. Both can be eddy current damped (like the horizontal stepper motor springs) and both can be improved by a relatively small mechanical redesign to use spring flexures (rather than coil springs) and a stiff bar rather than wires for the tilt-stabilization system.

In vertical (fig 3.4) there also appears to be a peak a round 3 Hz (brown curve) - is that another spring resonance?

No, this is a well known feature in the ground PSD (perhaps a building resonance). It is visible on the ground seismometer channels in the vertical direction.

What were the frequencies of the horizontal springs?

The springs for the horizontal stepper motors have resonances from 7 to 10 Hz.

4) It would be useful to supply RMS values for figure 3.3 and other vibration spectra. Can that be generated and added to report from stored data?

TBD

5) It's not clear to me what the controls configuration was for the vibration data shown in 3.4. DC position control only, I guess, but on what modes and with what bandwidth?

A modal based control was employed at the time the data was taken for figures 3-3 and 3-4 of T070079-00, and ever since. The canonical modes are projected with a frequency independent matrix that converts the 4 horizontal LVDT position signals into X, Y and RZ (horizontal translation along the beam line, horizontal translation transverse to the beam line, and rotation about the vertical) and the 4 vertical LVDT position signals into Z, RX and RY (vertical translation, rotation about X and rotation about Y). All of the 6 modes (X,Y,Z, RX, RY and RZ) were under control. All 6 modal degrees of freedom had a simple integrator (zero frequency pole) with a gain set to achieve a rather low upper unity gain frequency (about 0.1 Hz in all cases). In addition the vertical degrees of freedom had positive proportional feedback, with no roll off in frequency, as the Electro-Magnetis Anti-Spring (EMAS) control to lower the vertical stage resonances.

More recently, the upper unity gain frequency for the negative feedback control (DC integrator control) has been increased to ~0.5 Hz horizontal and ~1.5 Hz vertical, in order to more effectively decrease the motion at the rigid body resonances of the system. In order to avoid exciting the spring resonances at higher frequencies the compensation is rolled off, as indicated in Figures 11 and 12. However this strategy compromises the desired passive isolation at the microseismic frequency (0.15 Hz). More work on the control compensation is required to effect adequate suppression of motion of the rigid body modes while not defeating passive isolation at the microseismic frequency.

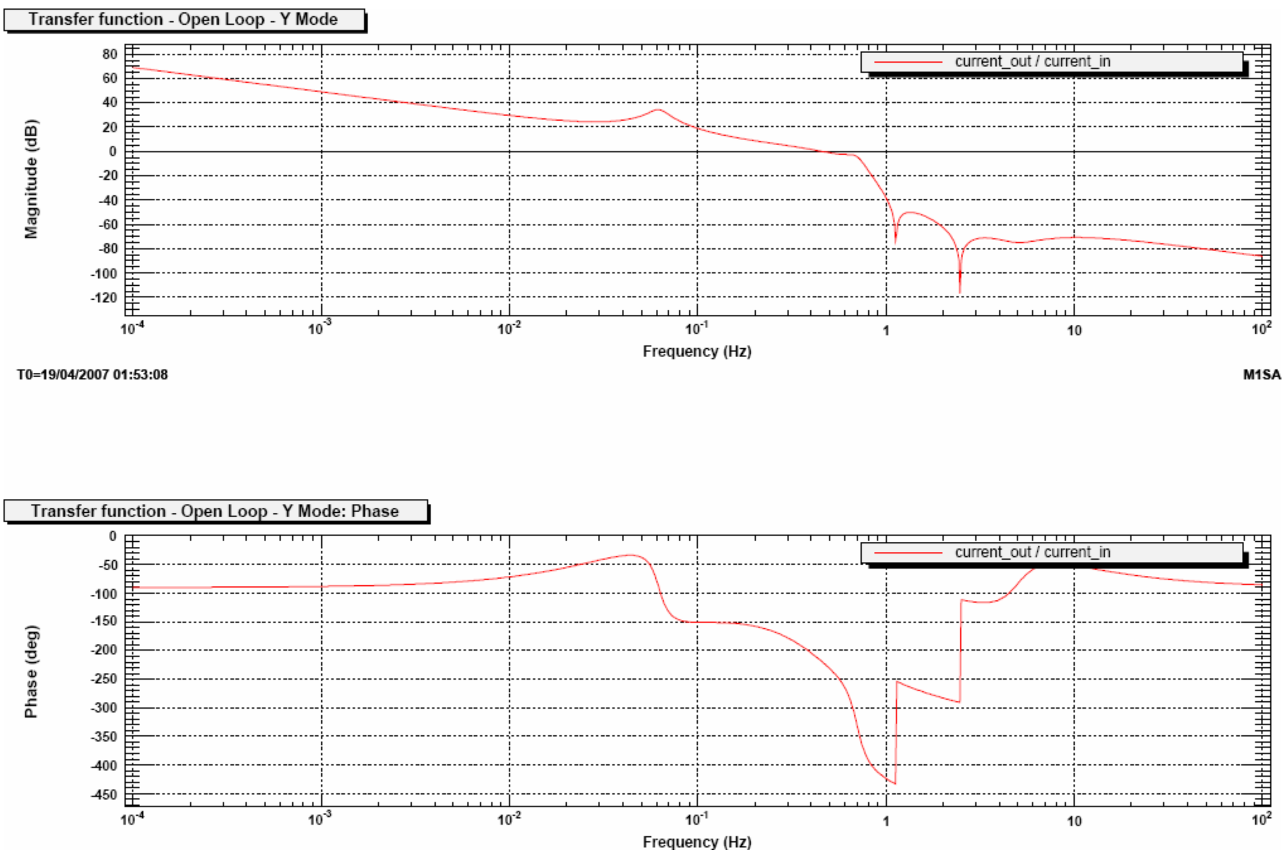
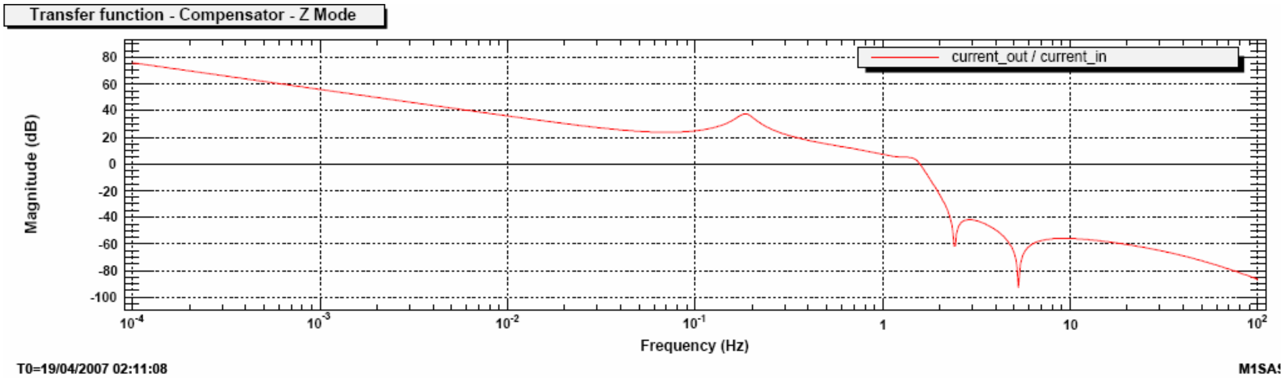


Figure 6: Open Loop Bode Plot for the Horizontal Y-Mode. The X and RZ open loop bode plots are similar; the peak associated with the rigid body mode is at slightly different frequencies for X and RZ. Note that this bode plot is formed using an analytical approximation to the modal plant response at its fundamental mode. The real plant response shows some residual cross-coupling between modes as well as high frequency resonances.



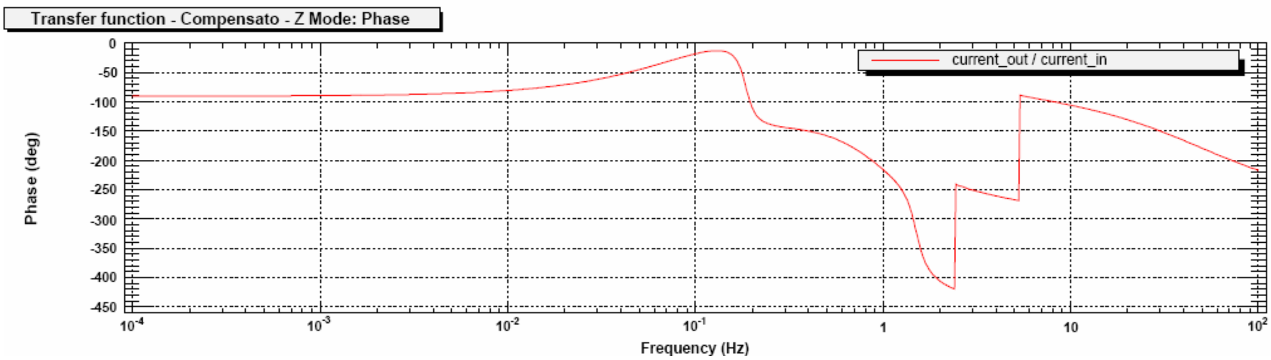


Figure 7: Open Loop Bode Plot for the Vertical Z-Mode. The RX and RY open loop bode plots are similar; the peak associated with the rigid body mode is at somewhat different frequencies for RX and RYZ. Note that this bode plot is formed using an analytical approximation to the modal plant response at its fundamental mode. The real plant response shows some residual cross-coupling between modes as well as high frequency resonances.

6) Figure 3-5 shows a step response time constant of about 100 sec, but the text in 3.10 says the requirements is time constant of less than 6 sec for micro-seismic correction -- and yet the text says the SAS has sufficient range to meet these requirements (tidal and microseismic). This seems incompatible, and I'd like to have this clarified.

The statement made is that the "range" (microns) is sufficient but that the bandwidth (or speed of response) may not be fast enough, without compromising isolation performance. The force range (N) is also more than adequate. To push the 1064 kg system at 0.15 Hz with an amplitude of +/- 10 microns requires ~1 mN of force, which is within the capability of the horizontal coil actuators. As for whether active control (via feedforward or feedback) can suppress the microseismic motion adequately while not injecting noise at higher frequency such that the isolation requirement is not met, the question is still not yet resolved.

7) Section 3.6 10mm range sounds large to me before the table hits its stops - is that value finalized?

It can be reduced at will, but it is left at 10 mm for earthquake protection. The Olympia, WA Feb 28th, 2001 earthquake caused a peak acceleration of 2% g and a maximum displacement of 1 cm at the Hanford Observatory[6]. According to the USGS, the probability of exceeding 8.5% g at the Hanford Observatory is 10% in a 50 yr period. For Livingston the probability of exceeding 2% g is 10% in a 50 yr. period. Any reason to reduce it?

8) Section 3.8 Tuning beyond 100mHz is done after release of triple suspensions - is that safe?

After developing the correct procedures and watchdogs, we believe it will be. However, if necessary this can be done after mechanically locking all of the payload elements (suspensions). Once the electromagnetic anti-spring (EMAS), DC integrator and damping controls are established for the table, the payload can then be released again.

9) Regarding interaction with a suspension: assuming the table really is moving around by microns or tens of microns, a triple suspension would need to move around with respect to the SAS table by this amount, to keep a cavity locked. Has any analysis been done to determine the interaction/stability of this scenario? It wasn't clear that any of the stuff in 3.9 addresses this.

When thinking about interaction between HAM SAS and the triple pendulum it is often easy to dismiss this effect because of the mass differences between the HAM SAS optics platform and mass of the suspended optics. However this neglects a potentially more serious cross coupling path. This path is motions of the test masses causes torque changes on the table which in turn causes table tilts and other optics on the table follow the tilts. A simple worst case calculation ignoring the effect of the servo-control system goes as follows:

The rotational stiffness of the table is given by the following formula:

$$k_\theta = (2\pi f_{res})^2 I$$

where f_{res} is the tilt frequency mode and I is the moment of inertia of the table. The change in torque due to the shifting triple mass is given by

$$\Delta\tau = mg\Delta x$$

Where Δx is the shift in the position of the suspended triple mass, m is the mass of the suspended mass and g is the acceleration due to gravity The change in the angular position of the table is given by

$$\Delta\theta = \frac{\Delta\tau}{k_\theta}$$

A change in the angle of the HAM SAS table will result in a change in the position of another suspended optics given by

$$\Delta x_o = \Delta\theta h$$

where h the height of the other pendulum. Putting this all together you get

$$\frac{\Delta x_o}{\Delta x} = \frac{mgh}{(2\pi f_{res})^2 I} = 2\left(\frac{m}{20kg}\right)\left(\frac{h}{1m}\right)\left(\frac{50mHz}{f_{res}}\right)^2\left(\frac{1000kg\ m^2}{I}\right)$$

[6] D. Coyne, Earthquake Risk & Recovery: Lessons from the 2/28/01 Olympia, WA quake, LIGO-G010208-00.

So in other words the cross coupling between a suspended recycling mirror on the HAM SAS table and the other suspended optics on that platform will be very significant. Note that this calculation does not take into account the effect a servo system.

Virginio and Valerio did a simulation using MBDYN and obtained the transfer function x2/x1 (Figure X) where

- x1 is the displacement of a 0.5 m long pendulum with a mass of 12 kg (PRM)
- x2 is the displacement of a 1.0 m long pendulum with a mass of 3 kg (similar to the MC, but the MC length is also ~1 m)

This is a rather preliminary result and has not been reviewed carefully as yet. The simulation is a full multi-body, nonlinear simulation of the HAM-SAS system with the two pendulums added to the optics table. No controls have been added. The prominent peak at 0.5 Hz is the responding (1 m long) pendulum suspension. The peak at ~0.1 Hz is the pitch mode of the HAM-SAS optics table. The suspensions are assumed to have infinite Q (the peak amplitude is not resolved). The amplitude of the transfer function at low frequency is 4 dB or a factor of 1.6. The above simple analysis indicates a factor of 0.3 for a 12 kg mass and a table tilt frequency of 0.1 Hz.

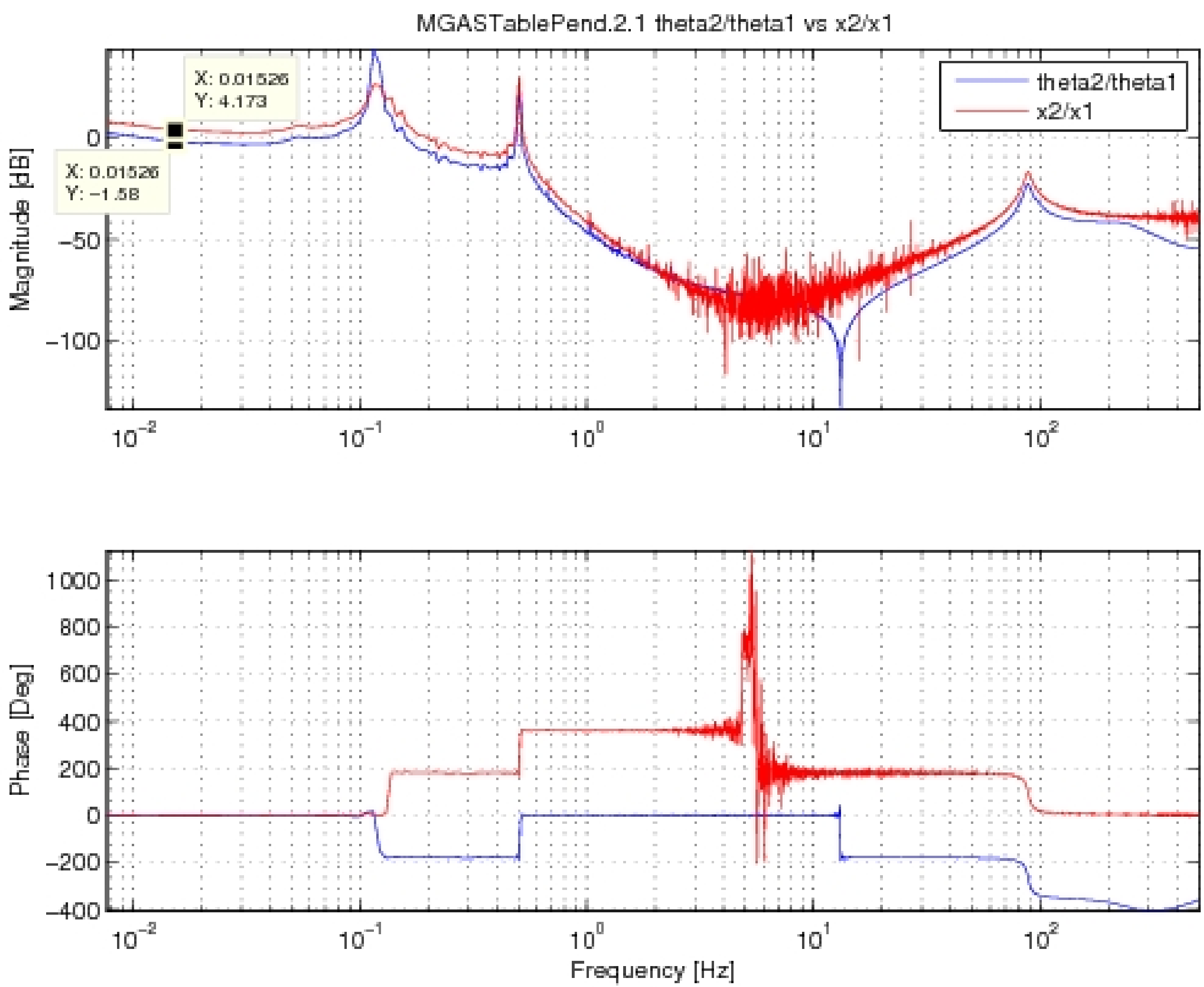


Figure 8: Simulation of the Cross-Coupling of the Motion of one suspension to another

10) ref. 3.1 What is the PEEK material used for the coil spools? How robust is it?

PEEK is Polyetheretherkethone, see for example: http://en.wikipedia.org/wiki/PEEK

PEEK is a LIGO approved UHV plastic, with high temperature and low outgassing properties. It can be machined easily, but it is softer than a metal, although more rigid than some. It is also used as the webbing in the initial LIGO ribbon cables.

11) ref.3.3 LIGO has plenty of Oring and flange protectors that we normally use for installations that should be incorporated into the HAM SAS installations.

We concur; LASTI should procure flange/o-ring protectors like those used at the observatory (aluminum ring segments bolted to the flange). This would prevent potential damage for the elevator contact scenario mentioned in the report.

12) ref.3.8 I assume that the 10mm table travel limit stops is +/- 5mm from the balance point. Causing the table to hit these stops with the triple's earthquake stops released will transfer that full hit to the optic (not so unlike LIGO 1) but, the HAM SAS is softer and more easily moved if bumped. Should we incorporate some sort of temporary spring damping that gets pulled until the 'busy' near chamber work ends and prior to door replacement? Can this work without influencing LVDT reading etc.?

The range is reduced from ±10 to ±5 mm with half rings that are taken out prior to closure. We could replace these half rings with metal rings carrying Teflon baffles if deemed necessary. This would not affect the LVDT readings.

13) How effective (accurate) will the table alignment need to be with respect to minimizing coil driver currents (gain noise). Would optical levers help here temporarily?

We did the table alignment with ¼ pound precision and then did final adjustment with the stepper motors. We need to level with respect to the gravity vector and so used an inclinometer (precision bubble level). An optical level does not (directly) provide a reference to horizontal.

14) What disaster lays waiting should one of the 4 stabilizing springs or cables break?

The table would tilt to the end stop. Note that after finding the lose bolt problem we came back to softer springs with tensioning of several turns only. The springs, attachment clamps and wire are not highly stressed, so there is no reason to suspect a catastrophic failure. Two of the intended relatively minor modifications (a) changing from a wire/coile-spring to a bar/flexure attachment for the horizontal roll stabilization system and b) making the vertical post to table interface monolithic) should further increase the safety margin.

Would a counter weight (disk) placed at the bottom of the post help here?

An uncomfortably large counterweight would be needed; no space for it.

15) ref. 3.4 What effects will adding Eddy Current Damping to help with the 10Hz -30Hz seismic isolation have?

When we incorporated eddy current damping for the horizontal springs, we did not observe any deleterious effects. It will add a 1/f slope below the 1/f^2 attenuation curve which should remain unobservable in the range of interest.

16) What if any lubricant is used in the slider units on the rails of the elevator system? Is there any chance of it escaping and contaminating the chamber, say via the clothes of personnel who bump against it?

None, we washed the rails and bearings with alcohol and rely on the fact that they operate at low speed to prevent bearing damage.

17) The system sits on two support tubes spanning 4 HEPI units or similar, which entails an over-constraint. Is there provision in the installation procedure for ensuring that the tubes are sufficiently coplanar? Is there any risk of damage or malfunction if they deviate from this, say via user error during leveling?

We used levels between and along the support tubes. When we put the HAM-SAS base structure down, we found a small gap due to warpage, but we found also that the compliance of the HAM-SAS baseplate edges (where it ties into the support tubes) was sufficient to pull the gap closed with a single 3/8-24 socket screw pulling it with an Allen wrench and moderate torque (single hand).

In addition, there is sufficient adjustability in both the HEPI systems (at LLO) and the Coarse Alignment Systems (CAS, at LHO) to adjust the 4 pier heights independently to mate the HAM-SAS to the support tubes.

18) T070080 suggests that the performance may be suboptimum due in part to a warped plate that is forcing the GAS filters (especially #1) out of alignment. How confident can we be that this can really be compensated for by more sophisticated diagonalization? What are the pros and cons of swapping it out?

Lack of diagonalization is expected to reduce the amount of EMAS gain that can be applied. Of course disassemblying and fixing the problem would be useful (recommended for long term use), but not feasible in this short time scale.