LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Proposed Upgrades to Advanced LIGO Seismic and Suspension Systems

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1 Introduction

This document provides a list of (and brief discussion of the motivation for) improvements that can be made to the seismic isolation and suspension systems in order to improve performance, increase controllability / robustness, and improve systems-level interactions with the interferometer. The sections are categorized in terms of subsystem (SEI, SUS, or SYS), and within a section, they're organized in increasing order of in terms of invasiveness / expense / time-scale of implementation.

Contents

2 Seismic Isolation System Improvements

1. **Better HEPI Pump Servos** Better ADC / DAC system; Get both sites to have a system observable / controllable from the control room (like LHO) to measure / confirm noise coupling to the rest of the IFO. Helps resolve Integration Issue 1004. Likely why LLO has had so many problems with drift when they unlock their HEPIs – poorly performing pump servos who noise is contributing to platform drift and they have no ability to assess it because it's not interfaced with CDS.

2. **Improve UGF on feedback for ISIs** Get more feed-back gain at 10 [Hz] to reduce HEPI crossbeam/boot amplification. Current UGFs are at 30 to 40 [Hz]. What's the current limitation? Is it phase loss from filtering, is it mechanical bendiness of the plant, is it noise re-injection?

   - ☐ **Update digital / analog AI filters to optimize for phase loss at ISI's UGF** The current design of the digital-to-analog uses Zero-padding (instead of sample-and-hold) to gain phase, but filters to get rid of the high-frequency noise, which in turn negates all the benefit from using zero-padding. We should improve the phase loss of the DAC process by optimizing the product of up-sampling and filtering the noise.

3. **SPI between HAM5 and HAM6** To reduce relative motion between the chambers to mitigate scattered light. Investigate whether between the HEPI piers is good enough, or if we have to go in vacuum. See P1300043.

4. **Evaluate 18-bit ADCs to improve ground STS/T240 compromise between noise performance and saturations during earthquakes** Current GND STS interface chassis have a gain of 40 to get above the current 16-bit ADC noise. Studies have shown that if we could reduce the gain by a factor of 4 because the ADC noise has improved by the same factor, then earthquakes would rarely if ever saturate the ADC. See G1300962, G1301124, G1400239, G1400784, G1400811

5. **Better sensors on BSC-ISI**

   - ☐ **More Ground Beam Rotation Sensors**. Use to combat windy conditions at LHO. Is it needed at LLO, can it help against microseism? Dependent on PEM study of ground tilt vs. wind using current ground STSs vs PEM wind anemometers.
   - ☐ **Install ST1 Compact Beam Rotation Sensors** See latter pages of G1500241 for sneak peak at proposed design.
   - ☐ **Better displacement sensors on ST2 to improve re-injected sensor noise from isolation loops; perhaps Euclid?** Believed to be the broad-band limit to the performance above 1 [Hz] for the BSC-ISIs.
   - ☐ **Better 10 [Hz] inertial sensors** HEPI boot resonance limits the performance between 5 and 10 [Hz]. Currently we use HEPI L4Cs in a Feed Forward scheme to reduce the contribution, but the sensors are not good enough to reduce the coupling to below the ST2 CPS sensor noise.
   - ☐ **Hook up low-frequency rotation to some very stable reference** Rotation in RX/RY and RZ seem to be a constant battle. We seem to be winning, but one idea would be to hook the rotational control at low-frequencies to an ultra-stable reference. What could that reference be?

6. **Fix HEPI Boot Resonance a.k.a. "Pier Amplification"** We've identified that what has long been called the "HEPI Pier Amplification" that limits the SEI performance between 8 and 13 [Hz] to instead be the common-mode resonance of the HEPI boot and spring system in all four corners; see SEI aLOG 542 and LHO aLOG 13505. It should be possible to fix this, either mechanically or by mounting additional sensors and actuators that are better coupled to this motion and reduce it.

7. **HAM ST0 FF L4Cs for HAM2/HAM3** Does having different isolation in the SRC than in the IMC and PRC between 5 and 20 [Hz] matter? We've got the bolt holes and the channels, should we install them? We should wait for definitive results with HAM4/HAM5 with HEPI unlocked – whether FF works better with the ST0 L4Cs or the HEPI L4Cs.

3 Suspension System Improvements

1. **Improve controllability of the Beam Splitter Triple Suspension (BSFM)**
   - ☐ Add sensors and actuators to the bottom stage / M3 / optic Increases the control bandwidth for length control, and allows for symmetric control of MICH, PRCL and SRCL from the M3 stage, which is helpful for angular control.
   - ☐ Reduce the strength of the penultimate stage / M2 / PUM While actuating on M3 stage will help reduce the amplitude of lock acquisition impulses, we should also consider reducing the M2 stage actuators as well.
   - ☐ Evaluate addition of a reaction mass Does not have to be an identically shaped chain; can just be a double suspension behind the M1 and M2 stages, for example.
2. **QUAD UIM Blade Spring Dampers** Reduce the Q of the UIM blade springs in order to reduce coupling to ambient electromagnetic background noise. See Integration Issue 954.
3. **Vertical sensors / actuators on lower stages of QUAD and BSFMs to add fundamental controllability of final-stage Vertical and Roll modes** These modes have proven problematic for control of DARM (saturating the OMCs DCPDs, otherwise huge sidebands/shoulders with polite the spectrum in regions well outside just the fundamental frequency), and especially the Roll modes damping relies on available dirt coupling between Roll and Pitch which changes from initial alignment to initial alignment.
4. **Improve vertical isolation on HAM Triple Suspensions using blade springs** Vertical isolation for the HAM triples will reduce the frequencies of the highest bounce and roll modes, which currently live right around where the PRCL and SRCL UGFs need to be, therefore limiting the performance. In addition to increasing the global control band-width, adding blades also couples the highest bounce and roll mode to the top mass, which means they can be locally damped. See E1400418, T1400450, and T1400290.
   - ☐ **Better bracketry design for HAM Triple suspensions vs. their OSEMs – specifically the lowest stage** Boot-strapping of OSEM bracket and EQ stop design should be reconsidered if ring heaters and lower-stage blade springs are considered.
5. **Better displacement sensors on top mass to improve re-injected sensor noise from damping loops; perhaps Euclid?** Current limitation of performance at 10 [Hz], and compromises made to reach where we are limit the amount of damping that can be done which limits the complexity / bandwidth of global controls that need UGFs in the resonance forest between 0.4 and 5 [Hz]. See P1300051.
6. **Improve degeneracy of L / P / Y control at the top mass of every suspension type**

- ☐ For QUADs and BSFMs, add an addition "FACE 4" OSEM below the centralized "FACE1" OSEM to allow for butterfly actuation and coil balancing
- ☐ Increase the lever arm of F1 OSEM to increase pitch sensitivity, and decrease L to P degeneracy
- ☐ for HAM Triples, and OMC, add two more sensors such that *any* L to P decoupling can be done
- ☐ Align horizontal actuation plane with suspension point "d" (or "lower zero moment plane", or "center of percussion") instead of center of mass to reduce mechanical L to P coupling.

4 System-level Improvements related to SEI/SUS

1. **Remove digital / analog anti-imaging filters from select suspensions to improve phase loss in DARM loop** The QUADs should be spectacular, at least $1/f^2$ mechanical filters, for imaging noise, which occurs at several [kHz]. Why not make the compromise of removing the digital and analog anti-imaging filters entirely and gain back 1/3rd of the phase loss from these two filters? Discussion subject to further analysis. See
2. **Ring heaters or other TCS for SR3 and PR3** See G1500372.
3. **Improve the thermal noise of the IFO via the SUS** See G1500233.
    - ☐ Longer Suspensions
    - ☐ Heavier masses
    - ☐ More stress on the fibers
    - ☐ Optimize the necking of the fibers

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