SEI Roadmap, T1900768-v3

Sebastien Biscans, Anne Baer, Edgard Bonilla, Sam Cooper,
Jenne Driggers, Chiara di Fronzo, Jeff Kissel, Brian Lantz,
Rich Mittleman, Conor Mow-Lowry, Arnaud Pele, Hugh Radkins,
Michael Ross, Eyal Schwartz, and Jim Warner, for the SEI team

December 20, 2019

Contents

1 Introduction

On Nov 12 and 13, the SEI team had a planning meeting at LHO. This roadmap captures the broad range of current thinking about ways we can improve the LIGO detectors. The meeting was wide ranging; some of the items will have direct impact on detector noise and stable operation, but many topics are more fundamental - better modeling, better monitoring, publishing results, etc. The items discussed here are technical, and the target audience is the seismic team (for our own planning), the LIGO Lab (for detector planning) and the LSC. Never-the-less, this intended to be is a public document.

2 Summary of Current Control Options

We find it useful to have a list of the control paths we currently have in use. This table is not complete, Jim and Arnaud will be updating it as they find omissions.

1. Local Feedback - Sensor to Actuator
   - Blended CPS / T240 / L4C on ST1 BSC
   - Blended CPS / GS13 on ST2 BSC and ST1 HAM
   - Blended IPS to L4C ST0 HEPI
2. Local offloading of global feedback control
   - Global Length (Tidal) to QUAD Top or UIM (Tidal Frequencies)
   - "LSC Offload" [Global ISI control] to ST1/ST2 BSC (0.1-5 Hz)
   - Top mass SUS offloading to ST1 HAM or ST2 or ST1 BSC
3. Local sensor to adjacent Local Sensor correction
   - STS/T240 GND to ST0 HEPI
   - STS/T240 GND to ST1 BSC and ST1 HAM
   - BRS to STS/T240 GND
   - Blended ST1 T240 (with L-4C) → ST2 CPS on BSCs (X&Y, RX→Y, RY→X)
   - HAM1 Table L4C to REFL WFS (for CHARD P)

4. Global IFO Sensor to local Sensor Correction
   (e.g. https://dcc.ligo.org/LIGO-G1902077)
   - Corner / Ends STS X and Y arm motion to local STS/T240 GND.
   - Cavity Length motion (PRCL, SRCL, MICH) measured by IFO to local ST1 HAM CPS
   - Cavity Length motion measured by CPS to local ST1 CPS ("CPS Diff")
   - "MICH Freeze" MICH Motion measured by ITM and BS ST1 CPS fed to ISC control to BS SUS. (It seemed easier at the time, may be replaced by CPS DIFF)
5. Local Sensor Feed forward to Local Actuator
   - ST0 HAM L4Cs to ST1 Actuator, HAM4&5 (5 - 30 Hz)
   - HPI L4Cs to ST1 Actuator, BSC & other HAMs (5 - 30 Hz)
   - ST1 T240 & L4C to ST2 Actuator
   - ST2 on BSCs to QUAD TOP Mass "ISI FF" (L2L, L2P, L2Y?)
6. Local Control DOF Diagonalization (oft needed because of our large drive signals)
   - STn to STn CPS ALIGNMENT (DOF diagonalization)
   - ST2 drive signal to ST1 Actuator (1-10 Hz) "drive compensation" (all six DOFs) https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=40258
   - SUS PUM L2A filtering
   - SUS PUM A2L filtering

3 Happening now or very soon

3.1 Wind Fence Studies

At the end of O3b, we should write a paper which evaluates the performance of the wind fence. The goal of the fence is to reduce the tilt of the end station slabs which is generated by wind loading on the buildings. To evaluate the performance, we need to collect the BRS data and the ground STS-2 data from both end stations and compare it to the wind speed as seen by the free-flow anemometer. We should also compare this to the PEM anemometers on top of the buildings. Other interesting comparisons are the flow fluctuations, the IFO duty cycle, corner station motion.

This paper is useful in its own right as a result, but will also be useful for the design work ongoing for the 3G buildings. We also need to evaluate the impact of the gap, the height, the partial coverage, and the ground vibrations from the fence.

ITMY seismometer as corner-station tilt-proxy - is this an issue?

We also need to publish the fence design and predictions from the FEM. This could be in the same paper, or in an earlier one. (Gerald B)

Jim / Hugh / Robert / ACTION: make sure there's good functioning anemometers for "before vs. after" studies, and revisit sensor array to better characterize the wind.

Interesting note: At LHO, the tilt corrected LHO End X vs. LHO HAM 5 and ITMY. Tilt corrected signal is smaller. ITMY in beer garden. HAM5 is by ITMY. After the fence is installed, the corner station may be the worst tilt issue. We need to monitor this.

3.2 Wind - Tree maintenance at LLO

The trees which protect End-X, and partially protect EY are probably the best wind protection we can get. Maintaining this wind block is very important to maintain the performance of LLO.

We should be proactive about this. Richard Oram and Joe Giaime are the contacts on this. Land purchase is stalled at LSU. Not sure what we are waiting for. Google map picture seem pretty accurate for current tree size. We should deal with this **before** the trees get harvested.

3.3 Beam Rotation Sensors

3.3.1 Automatic mass adjusters for ground BRS

(see SEI log 1531 by M. Ross)
The Beam Rotation Sensors (BRS) are 1-m long beam balances used to sense the ground's rotation. The rotations sensed by these devices are used to remove the tilt contamination of the ground seismometers that are part of the sensor correction path within the seismic isolation system.

Due to a not-well-understood temperature dependence of the equilibrium angle and other long term drifts, the BRSs occasionally hit the edge of their dynamic range. To account for this, a small mass is connected to the bottom of the beam balance which can be manually moved via a rod connected to a vacuum bellows. The procedure of shifting this mass is very tedious and time consuming. Additionally, if one wants to install a BRS on the isolation platforms then this process must be automated.

To achieve this, we've developed a mass adjuster, shown in Figure 1, which consists of a small nut placed on a threaded rod which is free to rotate. The edge of the nut rests against a flat which forces it to move laterally when the rod is rotated. The rod is spring loaded to keep it's center of mass stationary and is rotated via a nearby motor. The coupling between the rod and motor is designed to have a lot of backlash which allows us to decouple the motor from the beam balance by driving the motor in reverse.

This prototype will be installed and tested on the compact BRS soon. If the tests go well these could be installed on the ground BRSs by attaching to the same hole which the manual adjustment rod is currently attached to. There is also pre-existing electrical feed through which we can utilize for the motor. The only unknown about this procedure is whether the BRS vacuum system will function normally with the motors that we are currently using. If not we may need to purchase vacuum compatible motors.

3.3.2 Long term support for the BRS

The BRSs are designed to have an inherently long life span with very minimal maintenance. The ion pumps have a set lifespan but the pumping rates are low enough that we believe that they will last > 5.7 years. If any of the electronics fail, replacements can be purchased through commercial vendors. Lastly, if, due to unforeseen situations, the flexure brake replacements can be machined at University of Washington. The re-suspending of the beams can be done by either the Eöt-Wash group (Michael) or the on-site seismic team (Arnaud and Jim suspended beams during the LLO BRS install).

Concerning software, bug fixes and tweaks have been necessary every few months since the deployment of the BRSs. Barring any software environment changes on the BRS computer, we don't expect the software to need much support. The Eöt-Wash group will continue developing bug fixes and providing remote support as long as we're funded to do so.

3.3.3 Add a BRS to the platforms

With the success of the BRSs, the Eöt-Wash group is developing a compact version to be installed onto the seismic isolation system. More information will be contained in Michael's dissertation

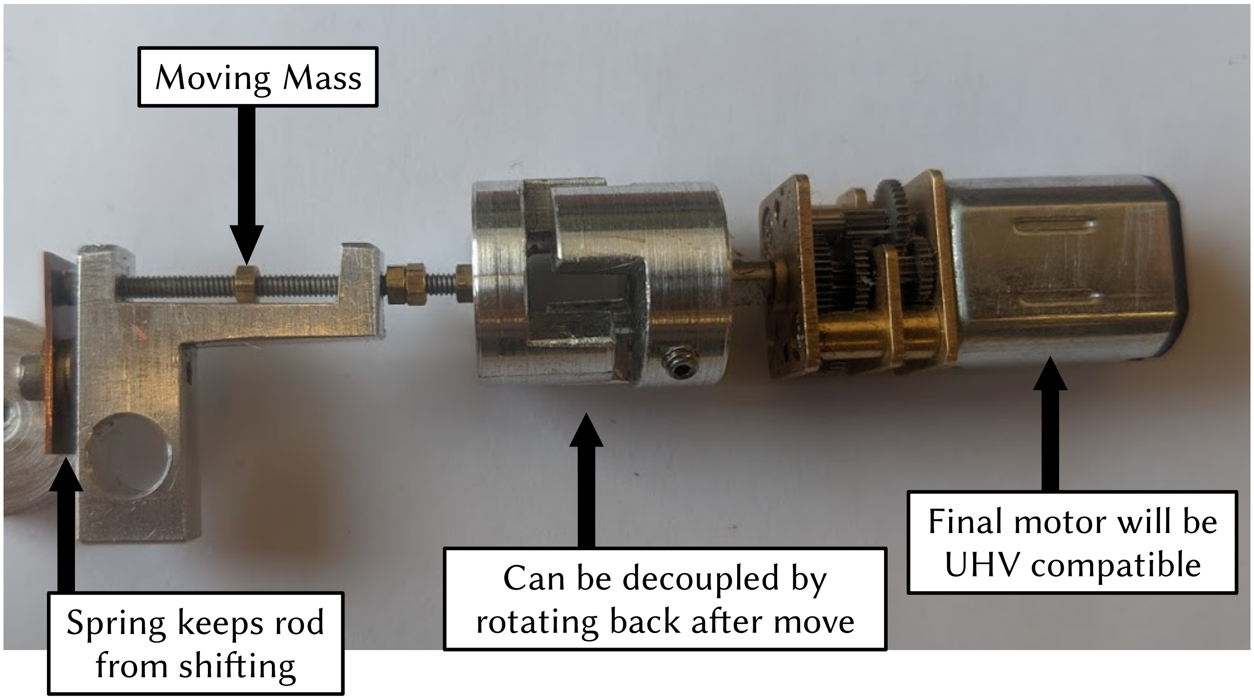

Figure 1: BRS remote mass adjuster

(March 2020).

The compact BRS will be ready to install on a test platform at Stanford in early 2020. Once installed, we will develop a control scheme to utilize this new sensor and show the ISI performance with and without the cBRS. If this test goes well we can begin to finalize the design for future install at the observatories

The models of the performance of the ISI with a cBRS installed on stage 2 (SEI 1372) show a significant improvement in residual rotation, Figure 2, which also decreases the translational motion, Figure 3, due to tilt horizontal coupling. The filters in this model were tuned to sacrifice performance at 10 mHz to gain performance at the microseism.

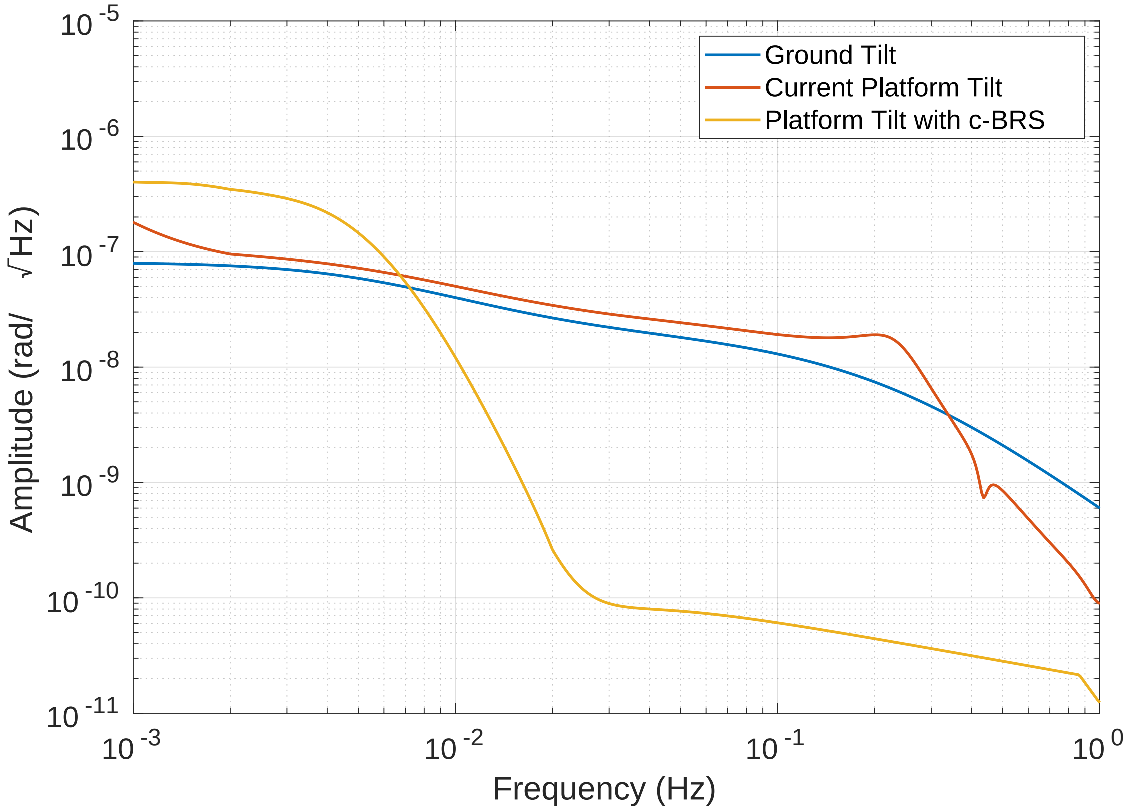

Figure 2: Projected stage 2 residual rotational motion with and without the BRS for windy conditions.

Thanks to Hang Yu, we can now model the predicted ASC noise in DARM assuming the ISI performance shown in Figures 2 and 3. With the decreased residual motion, the UGF of the ASC loops can be shifted from 3.72 Hz to 2.44 Hz while maintaining a low-frequency test-mass RMS angular motion of 1 nrad/$\sqrt{Hz}$. This then decreases the noise bleed-through into DARM which can be seen in Figure 4.

This model is a work in progress and needs further investigation before solid conclusions can be drawn. Once finished, we will make a seismic alog with the results.

3.4 Microseismic Performance

The isolation performance at the microseism is good, but the relative motion is not as good as we expect, and it is not as good as we want - especially at LLO.

3.4.1 Understanding the performance limits at the microseism

We're isolating well, because the BSCs are doing OK. The biggest problem is likely of HAMs. The extra factor of 3 is likely this difference between the HAMs and the BSCs. See, for example Brian's log entry about the SRCL motion at `https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=1393`

For the BSC tables, the excess is probably related to vertical motion causing tilt. The factor of three that we suppressed in 2010 likely found that thing, and suppressed it. In 2010, we used

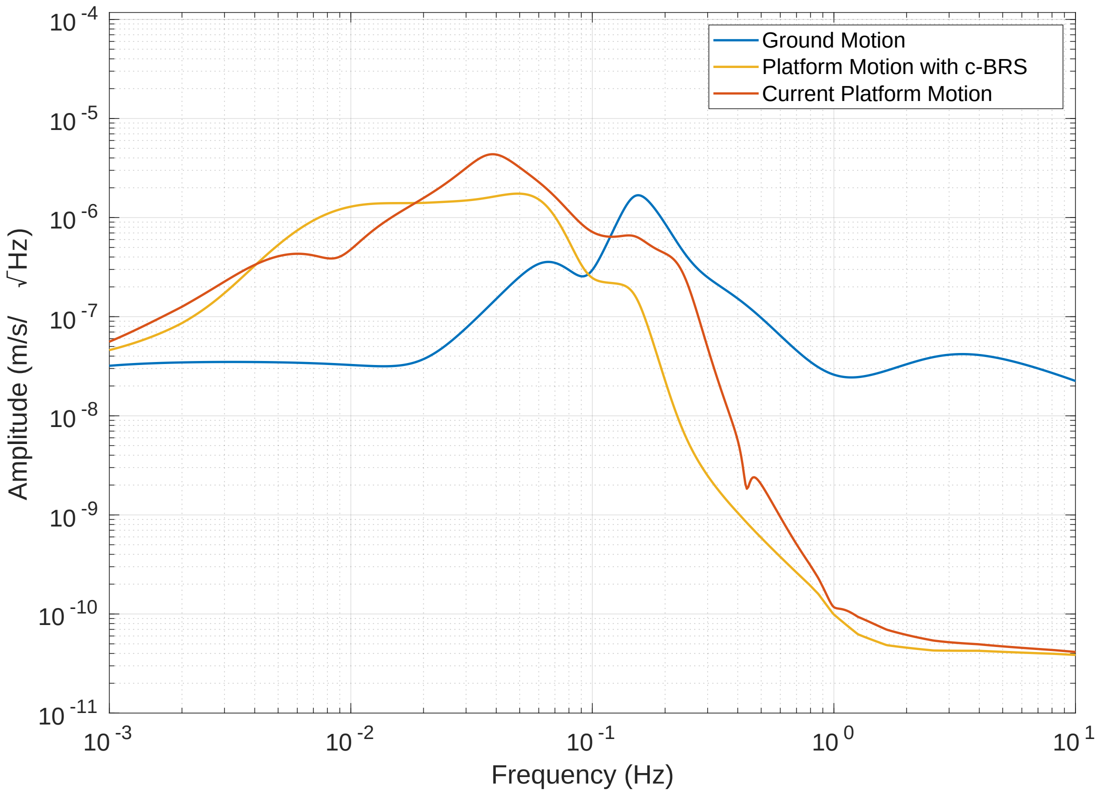

Figure 3: Projected stage 2 residual translational motion with and without the BRS for windy conditions.

the wiener topology to start putting non-intuitive DOFs together, such as STS GND Z to IMC / PRCL / DARM beam line motion. Brian also has an example of this in the DCC, although this document is focused on performance of the differential-mode earthquake isolation:
Residual X motion of the BSC seems correlated with the Z motion
`https://dcc.ligo.org/G1902038`

The ground microseismic peak is still an issue for locking, particularly at Livingston. The current thresholds for locking are ∼2.5-3 μm/s in the 0.1-0.3 Hz BLRMS band, and 1-1.5 μm/s in the 0.3-1Hz blrms (these are velocities, so the acceptable displacement is still slightly higher in the 0.3-1 Hz band). Those thresholds should be refined and used for operators as a baseline for when they should or should not try to lock. A slight increase of the tertiary microseism (0.3 Hz peak) seems to be even more problematic than for the secondary (ie main peak), (see problematic spectra at `https://ldas-jobs.ligo-la.caltech.edu/~detchar/summary/day/20191031/sei/ground_asd/`. We notice during those times, high coherence between the corner cavity control signals and the Z motion of the ground and the platforms. This has also been noted in the past by Rana et. al. (`https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=32639`).

Without including this Z-Horizontal coupling, the noise budget for both the LLO HAM and BSC stage 1 suggest the platform motion is still limited by ground noise at the microseism, although in medium to high wind conditions, the tilt noise contribution from the GS13 or T240, is close, see figures 5 and 6 from `https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=44245`.

To understand the cause of the performance limit, we need to start making noise budgets which

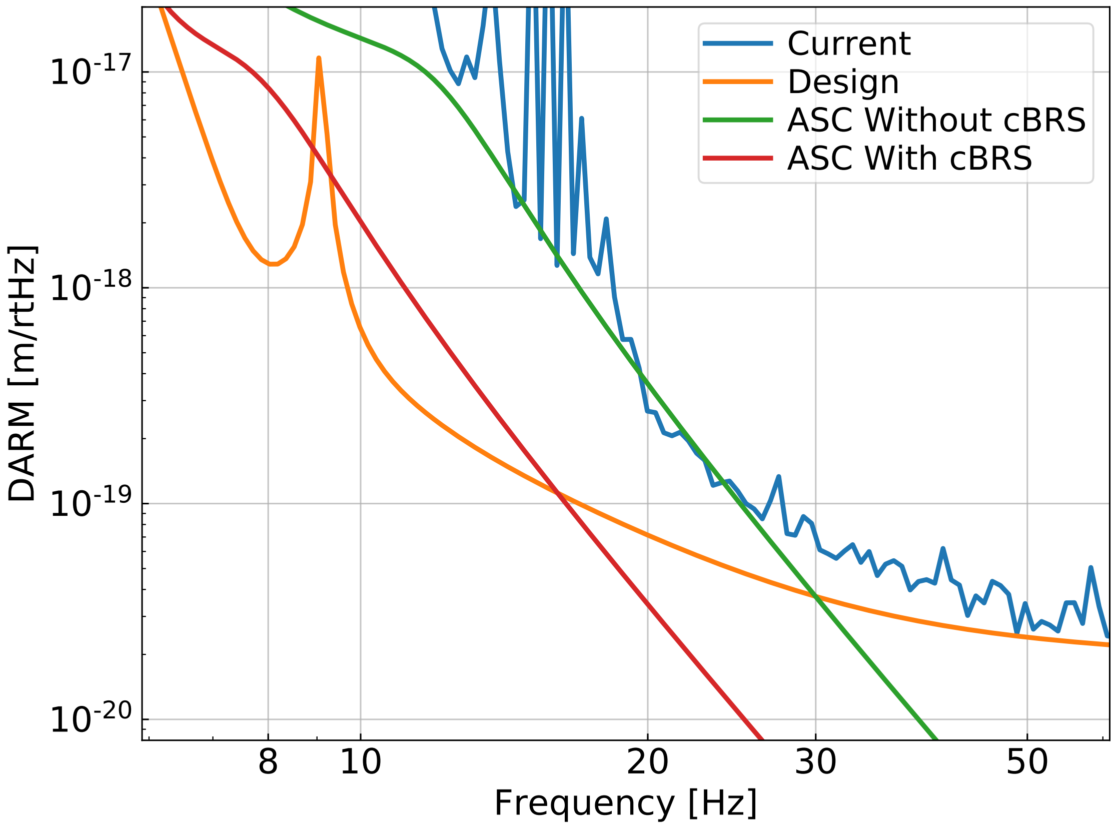

Figure 4:

show the relative motions and not just the individual platform motion. We note that a direct measure of the relative motion, e.g. an SPI (see section 4.4) would make this analysis simpler and much more accurate.

Looking at the noise budgets in figures **??** and **??** it seems that the motion of the platforms at the microseism is driven by ground motion. However, recent tests indicate this is not actually the case. If the residual motion were limited by ground motion, then the residuals should be correlated; if the control filters match, then the residuals should also match. However, when Jim carefully matched the blend filters between the HAMs and BSCs, in order to match the residuals and hence reduce the relative motion, there was no improvement seen in the SRCL drive - `https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=50483` (XXX actually, this log entry just describes setting up the system, it doesn't describe the lack of improvement - ask Jim for link to result.)

There are a number of issues which may be causing the excess motion. Based on experience, Brian expects that it is somehow related to small tilt couplings of the platforms. Here is a list of things to think about:

- Stage 0 bending,
- Stage 1 twisting

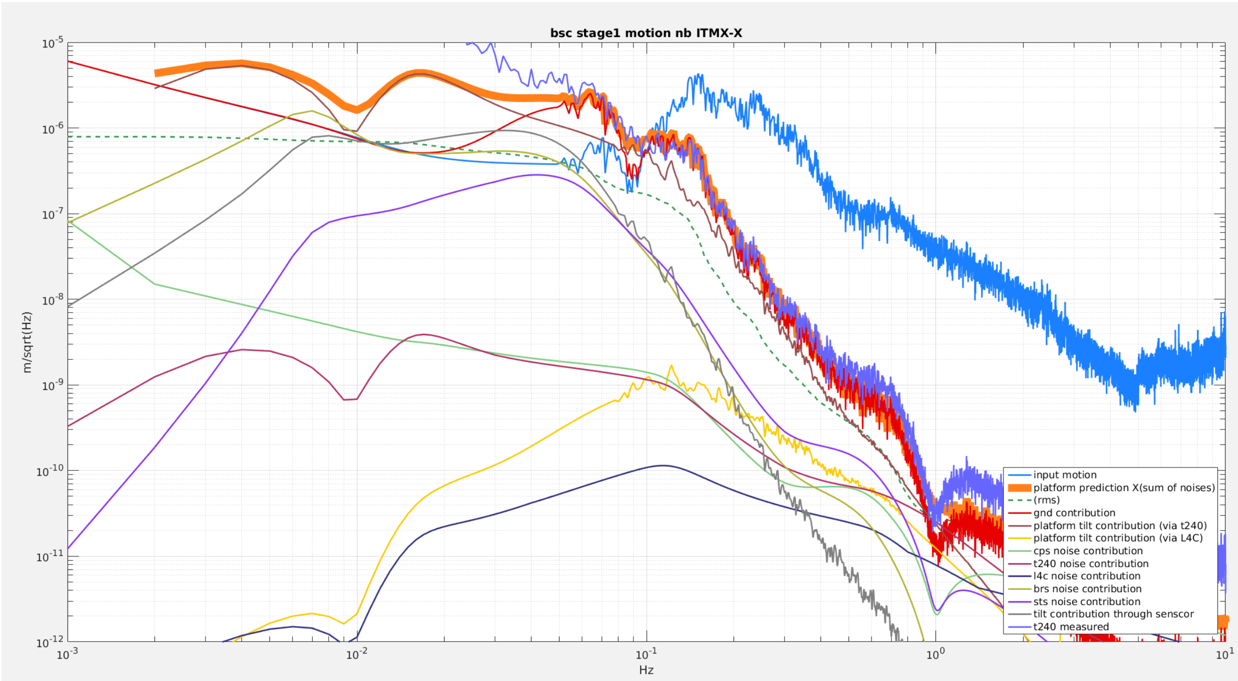

Figure 5: Noise Budget for the BSC at LLO during high wind, from LLO log 44245 A. Pele.

- T-240 Z mis-calibration
- CPS Z mis-calibration
- External structure (e.g. HEPI) deformation
- BUT maybe the HAMs are worse than the BSCs (see Brian's plots of Oct 2018), so maybe we should look more for mis-calibratied GS-13s
- HAM stage 0 bending
- Magnet coupling to inertial sensors
- Ground tilt (I don't think this is it, since it shows up between HAM2 and HAM3)

3.4.2 Improving the performance at the microseism

It is important to continue improving the microseismic performance, but these improvements will not be simple or without cost. A few methods to improve the platform motion at the useism are:

1. Decrease the blend frequency, which comes at the cost of damaging performance in windy and earthquake conditions. This would certainly not be a problem if the platforms were tilt-free. We have not tried to do tilt sensor correction with the BRS : has anyone looked at the data from the corner BRS to ISI tilt ?
2. Increasing the performance of the sensor correction. This seems possible, although we seem to be limited. We should post results showing if there is a difference in performance using more aggressive filters. We should try to use MCCS2 and compare the ground seismometer with the ST1-T240 during damp-only. Current sensor-correction subtracts all translation at the microseism down to the uncorrelated tilt 'floor' (maybe not, see the noise budgets?).

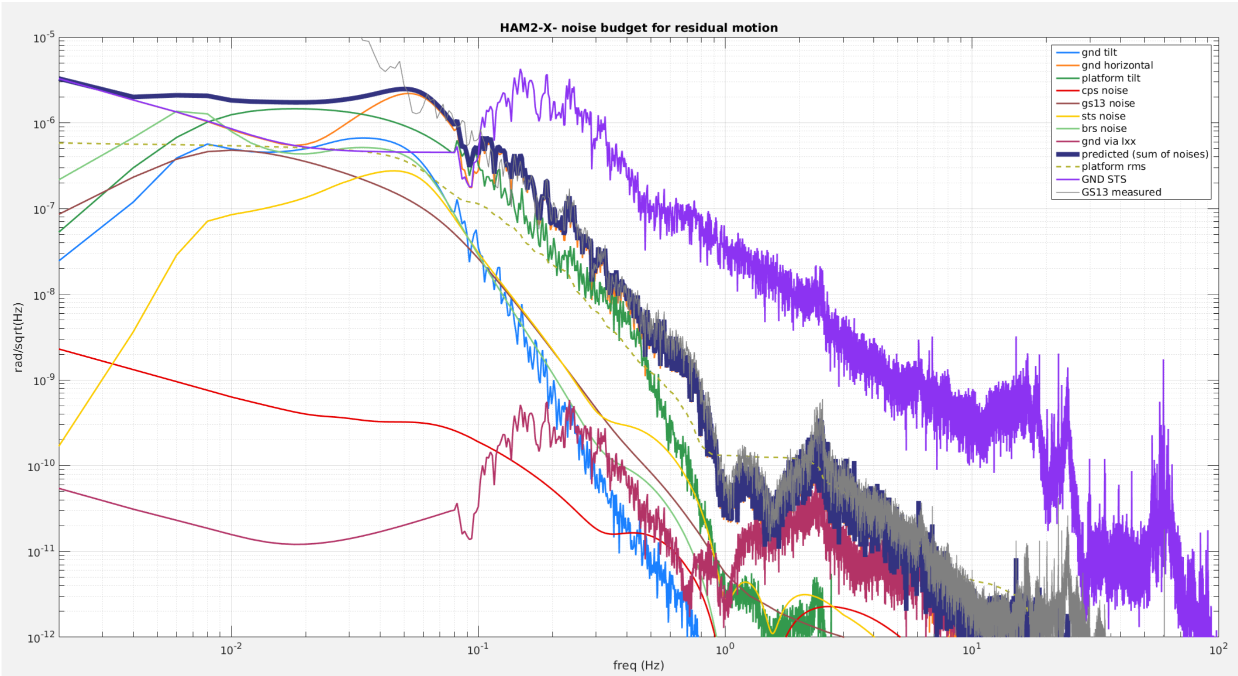

Figure 6: Noise Budget for the HAM at LLO during high wind, from LLO log 44245 A. Pele.

That's one reason why it's so hard to win anything, even with 'optimised' filters from particle-swarming (Conor).

3. Can we lower blends with global control ?
4. Try wiener ? Esp z -¿ beamline directions. This cost is that this method seems 'fragile', so changes to any of the control loops will probably require re-calculating the correction filters.
5. Tilt is a limiting factor in the beam direction in the 0.1 to 0.5 Hz region, especially during windy times. This is not limited by suppression of ground motion, it's sensor noise / issues (though that's contradictory to the statement about "when it's windy"). What do the rotational DOF blend filters look like? HAMs vs BSCs? Are we rolling off the rotational inertial sensors fast enough?

There was a fair amount of discussion of the microseismic control:

Q: Is the microseism a problem for LHO?

A: Yes – medium longer term good – it'll help reduce the ASC bandwidth. The RMS of the ASC is dominated by tilt that is induced from longitudinal ISI problems. But not urgent. Caution, though, the crossover may be a challenge because of the dynamics of the suspensions. 0.15 crossover is pretty easy to achieve, but we want 0.3 Hz crossover. Goal to have an increase in performance of "few" at the useism. It would be interesting if arm DOFs are coherent with the corner station motion.

Q: Do they have LLO filters in place to increase isolation at the useism in case they need it? In December 2018 seems like it was tricky to lock.

A: Need to check.

3.5 CPS control and Offload

3.5.1 Performance

The idea of the CPS control is to reduce the relative motion between ISI platforms by controlling the relative CPS signals. The CPS offload is similar; it actuates the platform based on the IFO drive to the suspension. Both of these techniques are intended to reduce the drive on the suspensions. A great deal of progress was made on these techniques during the O3 commissioning break, driven by Chiara and Sebstien, and assisted by many others. An overview of techniques can be seen in the document *Reducing differential motion using CPS sensors* , `https://dcc.ligo.org/LIGO-G1902077`.

CPS sensors can be used to stabilize ISI motion: this will help to reduce the differential motion between chambers at low frequency, improve the length drive and possibly reduce the locking time of the IFO and improve stabilization during wind and earthquake conditions.

The project we are going to present is to reduce differential motion of internal seismic isolation platforms (ISIs). Studies on the CPS projections to the suspension point of HAM and BSC chambers in the Corner Station (CS) are showing that CPSs are reliable witnesses of differential motion between chambers. Will will show how it is possible to use the CPS sensors to stabilize the ISI motion and improve the LSC signals at frequencies below 0.5 Hz.

This project has been performed during an LSC fellowship program between June and November 2019. Results shown are primarily from LIGO Hanford Observatory, but similar results have been obtained at LIGO Livingston observatory. Where is this being used? At LHO:

- HAM3 is following HAM2
- HAM4 is following HAM5
- The ITMs are tied to the beam splitter. This will be changed so that the Beam splitter is following the ITMs.
- ETMs are tied to the ITMs

3.5.2 Suggestions:

Instead of using raw CPS for "CPS diff," consider using "sensor corrected CPS" instead for the arm cavities. May be better. This requires some thought, is this double counting the sensor correction if so? This depends on corner station vs. arms. CPS only diff is fine enough for the corner, because the ground motion / sensor correction is the all same in the corner).

We might also want to reference the HAMs to their respective ITMs. This should reduce the relative motion for PRCL and SRCL, but in the first trial it did not work well.

There is also a potential issue of cascading model trips. If one ISI trips, how can we keep the other ISIs from following suit?

3.5.3 Plans for the future

(w/ and w/o Chiara)
It is tough to keep up momentum without being on site. Best to transfer to the next fellow? Chiara come back in April 2020 to finish further testing? "Remote" / "At-home" Modeling performance and future benefits of this between now and April 2020. We only have 6 hours a week for commissioning during the run. One model for LHO is for Jenne to take the data and implemen model changes, and Chiara to provide remote support and analysis.

3.6 Earthquakes

We have developed a way to help the sites operate during teleseismic earthquakes. We use SeisMon to predict the arrival of the surface waves, we use PeakMon to watch the wave amplitude at the sites in realtime, and we use the Differential-mode earthquake control to control the seismic system during the events. This system improves the robustness of LHO, and is in the final commissioning steps at LLO.

There are several projects underway to improve the earthquake systems. We have 3 projects underway to improve the quality of the seismon predictions, we have 1 project in mind to improve the detector control based on better predictions, and a new project in starting at LHO to rapidly react to local earthquakes.

3.6.1 Earthquake Predictions

On Wednesday, Nov 13, 2019 we had a call with Paul Earle, Head of the National Earthquake Information Center at USGS in Golden CO and Jascha Polet, a professor at CalPoly - Pomona and an expert on surface waves. Paul reminded us of these slides from 2017 - `https://dcc.ligo.org/LIGO-G1701524`.

Rapid Alerts for P-wave motion from nearby events
Bob deGroot (rdegroot@usgs.gov) is the manager for the Shake Alert system and Margaret Vinci (vinci@caltech.edu) is the regional coordinator for CA. Since Caltech is in CA. Brian and Jim are working with Margaret. She is helping get LHO set up as a beta test site for ShakeAlert, the EQ earling warning system for WA and OR. ShakeAlert is in production in CA (Brian has it on his phone). The prediction system is based on p-waves and is "Network based". The system for WA and OR could alert LHO to local events, similar to the Montana EQ of 2017, except currently the network being used is only in WA and OR, so that particular quake would not have set an alert. Having active users would probably help expand the system.

Rapid Responses to ShakeAlert. We do not yet have any response set up. Any reaction would need to be quick - maybe 10 seconds? Ideas include:

- Change the damping parameters for the suspension damping.
- Engage damping loops at the lower stages of the suspension.
- Hold the SUS and SEI watchdogs on so that the damping loops stay engaged around the event time.
- Disengage the GND feedforward.
- Adjust the isolation loops of the ISI. This is tough based on the short time. It might be a smooth shutdown, or turn off boosts to ensure stability, or hold the output of the isolation portion of the loops?

Better predictions for the amplitude of surface waves from teleseismic events
LIGO sees that if the vertical motion is more than 300 nm/s than we need to turn on "earthquake mode", but it is difficult to make predictions for this amplitude.

Discussed two methods to improve our knowledge of incoming surface waves. *USGS Picket Fence* Watch, in near-real-time, a set of USGS stations about 200-400 km from the sites, and use the data from the picket stations to predict the motion at the site 50-100 seconds later. Note- surface waves at the LHO site move about 4 km/sec. For example, the site in Corvallis, OR "IU.COR" is a good station, see `https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=1526`. It's part of the global seismic network. Preliminary test show that the surface waves are are similar, see `https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=1542`. Jascha Polet says that the correlation between surface waves at the picket station and at the LIGO observatory should be good if if the EQ is a long ways away. We asked why the surface waves were usually 20 sec-30 sec period. She says this is just because of general mantle structure of the earth, but that larger events often have more power at lower frequencies.

Paul Earle says that it ought to be possible to get information from IRIS sites in low latency, and that we'll have to see. Latency of OR stations is of order 1-2 seconds. Other stations may be a bit slower, but most everything will be under 30 seconds, especially if they are in the continential US.

We asked where to find a list of the good instruments. Paul said that the network called "GSN", and that he can help find local network. He suggested sending a visitor to Golden to learn about the seismic network and how to pull data. There is a python tool called obspy which is used to pull EQ data from the stations. Note - Anne Baer, Grace Johns, and Brian Lantz are planning to visit Paul (USGS in Golden, CO) in Jan. 2020.

Synthetic seismograms and the global propogation model. This should be good for teleseismic events past 60 degrees. It relys on centroid moment tensor modelling. Jascha Polet is the expert on this! The idea is to use the information from NEIC to make a model of the EQ event (a synthetic seismogram), then propagate that though a pre-computed global propagation model to predict what the waves will look like when they arrive at the LIGO/ Virgo sites.

Follow up with Jascha to see if we could make better predictions of peak ground velocity here at the sites. Hopefully using historical data and source physics. Long period surface waves (100 seconds) or longer are easier, because there's no 3D velocity structure to deal with. 20-30 sec is more important for LIGO, we think.

The mechanism will play a part.

Is a sophisticated code using a synthetic seismogram. Uses 3D Earth maps.

The global propogation model uses a 1 degree grid of potential sources around the planet, and then predicts the surface wave at a single given site. This is useful if you know the "mechanism" type of faulting. Focal mechanism . Reverse-faulting, strike-slip EQ etc. NEIC can do it within 15 minutes. This probably will / can be faster – 7 to 12 minutes. This is for reviewed material.

Gavin has matrics on W-phase. Once hits metrics, will go out automatically

For the propogation model, the calculation is time consuming, but OK to do ahead of time and once.

Just do a bit of work to find out the mechanism. 20 minutes before we get a mechanism from the USGS network data. With just a location and magnitude. You can calculate the maximum, worst case scenario.

How much does the depth matter? Once you get below 50km or deeper, it's pretty well constrained early on. 10-30 km has some difference, but hard to know the depth early. You'l see much less complicated surface wave stuff. In that region between 50-10 km, it's difficult to get right, especially in an oceanic environment.

Predicting the size of the surface waves

1. Magnitude and distance are obviously important
2. Shallower earthquakes produce large surface waves.
3. Shallower EQs are much more common, unfortunately.
4. Amplitude is related to orientation of the subduction and direction of slip relative to you. Subduction events make the largest surface waves.

5. This is possible: “Typically EQs in the region are this kind of mechanism.” So history can be useful.
6. Hence, you should be able to use recent history of earthquakes from a region to predict the surface waves from about 80% of followup events.
7. Is it possible to use the P and S to predict the R? Jashca says probably not, but you can check the prediction in real time by comparing measured P and S to the predicted P and S.

On level of effort by Jascha and Paul - Jashca says that a few hours are ok, but more than that will need some additional support.

Paul and Jascha can dedicate 4-5 hours per week.

`https://dcc.ligo.org/LIGO-G1901122`

Q. From cycle to cycle – why are the amplitudes different? Would it be better to predict total power, rather than peak velocity?

A. Jascha says that mixing and interference is the cause of the variation. 3D models are the best. Power won't give you a better results.

Longer quakes have more energy at lower freqs. Highest amplitude surface waves are from crustal structure. Pure oceanic structure can lead to significant (what !?)

How to get the low-latency data EQ early warning 2-10 sec. Packet of data. Global seismic network. BB sensors, 1 borehole, 1 surface 120 about the planet. Really good, not useful for the nearby idea.

NOTES: Install a beta test for “local earthquakes alert system in WA and OR” in the event of a future “montana EQ”. Work in concert with USGS. Jim / Brian working on making LHO a beta test site for this. PAUL EARLE (head of NEIS at USGS golden colorado.) Jenne “future work” action: Create a response to that alert. Turn off sensor correction. Update seismic watchdogs to allow for more motion More damping / cooling. (Simple middle stage damping / optical levers / etc) Other things?

USGS is working on making rapid moment tensors and focal mechanisms for EQs. (It has been noted that this is the current missing information.) It is thought that this can improve the prediction of surface wave amplitudes on site. Says PAUL: “As the EQs get closer to the surface, the surface waves get bigger.” “as the slip direction gets more aligned with the site, the surface waves get bigger.” He has also invited Jascha Polet who has expertise in surface-wave modeling. She is interested in joining the discussion.

USGS is working on a system that creates a “future time” surface wave prediction before it arrives on a given site. Anne Baer and Grace Johns have taken on this project: get real-time monitors of USGS stations, 200-400 km away and use the peak amplitude there for the peak amplitude here. See `https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=1526` for additional discussion. Analysis and Design of several EQ control configurations for large vs. small events

The SEI team should design at least 2 different control filter sets. The ground motion generated by teleseismic events is quite variable and difficult to predict. Currently the control filter set is designed for earthquakes with peak vertical motion of a several microns. These filters give up significant tilt coupling and have mediocre performance at the microseism. As such, there is often reluctance to engage them if the predicted earthquake motion is not too big. Many of the teleseismic event generate less than 2 microns of peak vertical velocity - which can be enough to lose lock, but not necessarily. We should design filters for events where the motion is expected to be moderate (maybe 300 - 2000 nm/sec peak). These should have better microseismic performance, and less tilt coupling at very low frequencies. In addition, operators can be more aggressive about engaging the filters before the surface waves arrive. Diff mode EQ control (Eyal & Jim)

Problem: LIGO requires an unprecedented level of isolation from the ground. When in operation, the interferometers are expected to measure motion of less than 10^{-19} meters at 100Hz. Strong teleseismic events like earthquakes disrupt the operation of the detectors, and result in a loss of data until the detectors can be returned to their operating states. A variety of seismic control strategies have been studied to reduce downtime due to earthquakes. At higher ground velocities, the interferometer becomes unstable and loses lock. The standard seismic control mode at the LIGO sites suppresses motion at frequencies above 100mHz which results in amplification of ground motion at lower frequencies, specifically in the range of 30 and 100 mHz. Earthquakes induce a large surface wave component peaking at 50-60 mHz.

Progress: An earthquake mitigation scheme was developed and implemented at LHO, in the commissioning period of 2018, to limit the extra disturbance induced by earthquakes. Similar scheme is currently being implemented at LLO. The goal is to maintain operation at the expense of sensitivity. The basics of the scheme is to try and reduce platform motion during earthquakes by redesigning the sensor correction filters to stage 1 CPS while removing common motion that is dominating the control signals and drive during high ground motion.

Things to do:

Understand (see) the effects on the optical cavities. Classify earthquakes. Diff motion deviation/ Incorporate tilt into the models. Optimize filters and train operators at LLO. Write up paper.

There are many different kinds of EQs. As we move forward, a goal would be to generate a variety of responses based on the improved prediction of the EQ. This could include, for example, different responses for the X and Y arms. Different responses based on the EQ magnitude, depth, distance, orientation etc. – i.e. what will be the resulting amplitude and orientation on site. Microseismic prediction Operationally it is useful to know several days in advance when there will be no chance of locking (owl shifts, when to do planned maintenance).

Nick Harmon ¡N.Harmon@soton.ac.uk¿ says that it's possible to predict microseismic activity some time in advance. He also had suggestions for EQ early warning: Talk to Richard Allen or John Vidale about earthquake early warning .

And Fabrics Arduin about predictive microseism prediction or me.

3.6.2 Earthquake Response

Brian Analysis EQ controllers for big vs. small events.

Thoughts on quick response to ShakeMon alerts

3.7 New monitoring channels/ displays/ metrics

Discussion led by Jeff Kissel.
The isolation performance of the Seismic tables and optic suspensions is very good. Further improvements should focus on the global motion of the platforms and the performance of the interferometer systems. There are many existing monitors which server this end, and others are considered here. These are typically digital combinations of local channels which are compared with interferometer DoFs. These are essential as metrics for performance. We need to have a better understanding, documentation, and display of the existing sensors and metrics.

The current monitors are:

- A primitive version of the interferometer DoFs can be found in `https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=775`
- The SUSpoint motion is the motion of the ISI tables, measured by the GS-13s, at the suspension point for each optic.

- Predicted motion of each optic calculated by projecting the SUSpoint motion through the modelled transfer function of each optic.
- Motion of the SUSpoints projected to the IFO basis.
- Motion of the optics projected to the IFO basis. @3 need to make sure these are properly whitened, and should reconsider sampling rate / storage rate.
- ISI platform motion, as seen the CPS, projected to IFO basis. This allows analysis like whats in SEI aLOG 1489 `https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=1486`. Need to check if these are installed yet or still pending.
- The seismon system needs good maintenance, and upgrades to the amplitude predictions. This is discussed in the earthquake section 3.6.

There are several new monitors which would be useful.

- GO/NoGO Thresholds of"when we can / cannot lock the IFO". There is a simple level which is currently manually assigned by Arnaud based on historical data. These could be integrated with the ground BLRMS or with the table motion BLRMS.
  Academics might say"good opportunity for machine learning!" Engineers on site say "what can you do that is 'good enough' right now?"
  The IFO control systems are improving all the time, so we should consider how to regularly update these thresholds. Also, again, highly dependent on input motion.
- "In case of emergency" Offsite/Onsite/Quick SEI/SUS state monitoring. This would be a way to help off-site (at home, on vacation) commissioners work with the operator to quickly diagnose why an ISI is not working. This is an excellent suggestion by Arnaud, but it's not clear how to implement it.
- Easy-to-read, and machine ingestible "nominal" performance metrics, or acceptable performance limits. These would be useful for operators and for guardian. An example is the ISI performance BLRMS matrix. Jim and Arnaud felt this was the right idea, but not quite what was wanted.
- Better ways to connect the variations in Ground motion to the variations in ISI and IFO performance. We have the ground BLRMS and the EQ PeakMon. Conor suggested that we watch the velocity ASD / RMS in addition to the displacement metrics we have now. Conor also suggested scaling the low frequencies by sqrt(f) which gives better RMS behavior. This is something not well calculated in realtime. We would also like better access to modifying the summary pages, or faster turn around.
- We need a person to maintain Seismon.

3.8 Performance Modelling of the ISIs

We need to finish the modeling tools for the ISI performance. We have several HAM-ISI models, the most complete is the one by Sam Cooper. There are also several BSC-ISI models. The oldest is the one by Hua used for ISI design. This is rarely used, now. Navita and Jim started a BSC model and Arnaud also has a BSC-ISI model. The plan now is to use Sams HAM model, and complete Arnaud's BSC model by completing the modeling for stage 2.

There is a good model for SUS performance, which is maintained by Edgard Bonilla.

There are lots of interesting questions which should be looked at. Many have been examined before, but things are changing as the controls are updated:

- Explain the ISI performance.

- Evaluate the contributions to optic motion from ISI motion and OSEM noise. Optic pitch is particularly interesting. Arnaud & Edgard are following up on this.
- Model the differential motion (see earthquake section 3.6 and the microseism section 3.4).
- Impact of better OSEMS (= reduced cross-coupling?)
- Impact of optical levers and full SPIs.

Concatenation of performance models Sam is working on connecting the ISI and SUS models, GND → ISI → SUS → Optical system.
Sam's note collecting references is here:
`https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=1528`

For the model connections, the idea is not to truly "integrate" the SEI → SUS, but rather to just multiply transfer functions.

The SUS models have the capability to include back reaction as a force on the seismic platforms, and Hua's models had the capacity deal with the torques generated by moving the cg of the SUS model. The SUS models also have the ability to move the drive side of the OSEMs, allowing a reasonably good model integration. True integration is not a priority at this point.

Model connect we have in mind is mostly syntactical stuff, nothing fundamentally new. Multiplication of displacement-to-displacement TFs. These must be mindful of the phase, since some displacement input may add (subtract) linearly. We must know the consistent ordering of degrees of freedom.

Brett Shapiro and Zach Patrick (and Jim warner and Nairwita mazumder) worked on creating a state space model for the HAM and/or BSC:
`https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=956`
`https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=858`
`https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=873`
`https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=672`

Advantages of the "current" (Sam's) HAM model in that it has the ability to include Feed forward. That's not hard to include in a state space model. We need to be able to extract a system model from from modeling system so that we can also do time-based simulations.

What don't we have?

1. MIMO model of the HAM-ISI. Ability to extract system for time based simulations.
2. A complete, user friendly BSC model.
3. We need better user communication such that we, as a group, stop writing our own models every time.
4. Easy, user friendly switchability of bringing in and out filter / control paths (i.e. turning on / off sensor correction path)

Move seismic models to gitlab We should move the models to gitlab. This is a fine idea, but if you do so, you've signed up for "a year's" worth of maintaining it. All agree that this is fine. Kissel's human reminder: the reason we are continuing to write our own models is because the humans we have writing the models find it easier to write their own model than to learn svn or git well. Conor adds: also, people write their own model to understand existing models. But, we should agree to have the discipline to *stop* with their training wheels model once understanding is acquired. Brian: get some instructions on how to use git.

Sam to make a presentation to Jim and Arnaud and Brian to remind us how to use the HAM model.

3.9 Operation Monitoring of the ISIs

3.9.1 Health Monitor

We have been discussing adding realtime health monitors to the ISIs for some time. Would be a realtime model of the plant, which runs on a front end and accepts ground motion and actuator drive signals as inputs and calculates sensor signals as outputs. One then compares the calculated sensor output to the real sensor output to assess the system health. Look up Brett's work on this.

For health monitoring, this does not necessarily need to happen in real time. This could be done on stored data to check the function of a plant. We might try this on LHO-HAM2. This could be an interesting project to use the IIRational fitting on the initial TF data for another HAM, and see if we can demonstrate what's up.

3.9.2 Realtime Noise Budget

A closely related topic would be an online noise budget for the ISIs. This could help understand the performance limits on a day-to-day time scale, and also check that things are working as expected. When there are troubles locking the IFO, can we confirm that the ISIs are working correctly, and is the ISI motion and ground motion too big to lock.

Jamie Rollins has offered to help use the existing noise budget tools to do this. We can pull time series from NDS and use models of measured transfer functions to make live noise budgets for each ISI. Jenne had some concerns about the computing infrastructure - we might need some more compute power/ or maybe data access.

Arnaud and Jamie will follow up on this, and Brian will also contribute.

There was general acclaim for the noise budget from everyone working at the sites.

3.10 Ground motion models

It would be useful to update our set of ground motion models. This is a few days of work to find the various things we have now and up them into an format which is easy to find and easy to use. It would also be valuable to do some updates for the statistics, similar to what Ed Daw and Jan Harms have done. No one is currently following this up.

3.11 Control Development

1. Improve switching by putting the EQ switches into SEIproc.
   Jim is leading this issue, with help from Dave Barker.
   This is slightly different than the 'Fader Switch' issue which was fixed by the gain=1 trick. That fix helped, but Guardian switches still not simultaneous. This issue is an example of a more insidious problem with idiopathic 'Fail to Compile' problems, see FRS `https://services.ligo-la.caltech.edu/FRS/show_bug.cgi?id=13715`.
   The fix is still progress. Rolf's explanation of the RCG:
   "In this case, it appears that the gcc optimizer is causing the problem. The initial error message had to do with undefined symbol pow. This is a math library function, unavailable in kernel space. So it appears the gcc optimizer is replacing the Tramp * Tramp * Tramp, etc, with a pow() call. To test this theory, I removed the optimizer setting from the RCG

Makefile, and the code compiles successfully. Still a mystery as to why the optimizer in one case substitutes the pow() and other times not ie apparently not when code changed as done by Thomas."

For the moment, we will try to work around the problem. This is a serious development issue which CDS needs to get fixed.

2. Put blend-switching into format like Sens-corr switching. Operators strongly support this. Brian Lantz will push this.

3.12 Blend Switching

A long-standing desire of the seismic team is to speed up and smooth out the blend-switching. The new switching for the earthquake mode which is used for the Sensor correction is the prototype for this change. This new switch will have all the possible filters running all the time, and one just switches the outputs. The current blend filters have only one filter running, so the system has to engage the new filter and wait for the initial transients to settle. The update is somewhat complex to implement in the models, although it should be nearly invisible to the operations on site. There are 3 benefits to this update.

1. It will improve the speed of the switching.
2. It will reduce the glitchiness (currently small) of the switching.
3. It will allow more complex filters to be used in a simple way. The current method is meant to switch between single filter modules, but the new one can use all ten modules if desired without additional complexity.

We would like to install this update during the break before O4.

3.13 Feedforward

We should look again at the ST2 ISI to SUS M0 FF (Edgard).

Right now there is some feedforward from the SUSPOINT GS13 L motion → M0 Pitch feed-forward to cancel pitch motion at the test mass.

The original idea was to do L2L (ISI2SUS). This did not work, because it was unstable. This was because of coupling from back reaction to the platform tilt, and stage 2 ISI is not running the isolation loops. The L2L and L2P scheme was tried at LASTI, but it made the Yaw worse. This might be because of L2Y coupling from osem actuator misbalance.

Summary is written up here:
`https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=1529`.

If this is to be tried again, we need to do 2 things. We need to figure out how to run the stage 2 isolation loops for pitch, and we need to include the measured yaw coupling of the SUS.

3.14 Paper on SEI performance

This is long overdue. We need to write this up so people can see how well these systems are working. The goal is to "Describe the performance of the current isolation systems."

Important points to include are:

- "How well are we doing" (last update is P1200040) ASDs of how much the table is moving. SUSPOINT motion. Table motion in XYZ RX RY RZ. Emphasize optical table motion / suspoint motion, NOT how the interferometer is doing.

- Summarize control topology to get there.
- Current limits on BW and performance.
- "BW" is traditionally referring to the feedback bandwidth. Make sure to talk about the feedforward limitations, since that's what gets us a good fraction of the performance above 10 Hz.
- Talk about the feedback limitations, i.e. that cranking up the loop gain won't help, because we're at the sensor noise. The GS13 feed back is limited by the signal processing and anti aliasing filters.
- Global control improvements are out of the scope of the paper.
- Be sure to include performance the HAMs and the BSCs.
- Differentiation between operational requirements and low noise performance. Debunk the belief that the "seismic" is the limit of the low frequency end of the detection band.
- Describe how seismic performance relates to the overall IFO function.
- 3 driving requirements for seismic
  - Performance in band
  - All the auxiliary DOFs and scatter (the myriad ways that auxiliary noise coupled to DARM) [reducing the control requirements on the optics]
  - Lock acquisition / alignment
- impact of out-of-band noise from the sensors.
- The sensors on the seismic table are an excellent monitor for the environment (the vibration that gets to the optic).

Plots that we should show:

- Control diagram (or diagrams) that show the topology, perhaps at various levels of detail
- "Stick figure" model guiding the reader through what limits the performance and feedback bandwidth (mechanical dynamics and sensor noise limit the feed forward band width)
- "We use these sensors in these frequency bands." (sensor correction, feed back, and feed forward sensors) recast as a "complimentary blend filter" like plot:
- Recreate the "walk through steps of seismic isolation" for both a HAM and a BSC
  `https://dcc.ligo.org/LIGO-G1900949`
- Show performance of ALL DOFs. Show our "best" platform
- Show multiple tables and/or some interferometrically interesting ASD that demonstrates all of the tips and tricks.
- Also consider showing interferometer signals propagated back up through the suspension model to say what the optical table is doing, and compare against what the GS13 says (which is what is traditionally displayed as the "table performance) Show how seismic makes one robust against transient seismic inputs (see G1600349).

Papers that already exist (Where have we left off?)

- Seismic Isolation of Advanced LIGO: Review of Strategy, Instrumentation, and Performance (CQG 2015)
  `https://dcc.ligo.org/LIGO-P1200040`

- Dynamics Enhancements of Advanced LIGO Multi-Stage Active Vibration Isolators and Related Control Performance Improvement
  https://dcc.ligo.org/LIGO-P1200011
- Advanced LIGO Two-Stage Vibration Isolation and Positioning Platform - BSC-ISI Paper (PRE 2015)
  https://dcc.ligo.org/LIGO-P1200010
- S. Wen, R. Mittleman, et. al., "Hydraulic External Pre-Isolator System for LIGO", Class. Quantum Grav. 31 235001 (2014), P1400058
- Sensor fusion methods for high performance active vibration isolation systems.
  https://dcc.ligo.org/LIGO-P1400022
- Seismic control strategy to limit the impact of earthquakes on the LIGO gravitational-wave detectors duty cycle.
  https://dcc.ligo.org/LIGO-P1700163
- Brett Shapiro SEI log about bsc model https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=858
- Sam's manual/description of the HAM model:
  https://dcc.ligo.org/LIGO-T1800092
  (related) possibility for performance improvement:
  https://dcc.ligo.org/LIGO-G1801759
- Predicting surface wave velocities at gravitational wave observatories using archival seismic data - Nikhil Mukund
  https://dcc.ligo.org/LIGO-P1800312
- Tilt correction paper
- Windproofing LIGO: Improving low-frequency active seismic isolation using rotation sensors.
  https://dcc.ligo.org/LIGO-P1800038
- Sensor fusion methods for high performance active vibration isolation systems
  https://dcc.ligo.org/LIGO-G1901936
- New methods to assess and improve LIGO detector duty cycle
  https://dcc.ligo.org/LIGO-P1900222

3.15 Fix LHO-HAM2

We need to replace HAM3 V2 GS13 (pre O4) - (task for Jim) https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=46600 . The alog showing v2 GS13 is possibly bad is https://services.ligo-la.caltech.edu/FRS/show_bug.cgi?id=11740. There is a FRS ticket for ham3 excess lsc coupling.

3.16 Software Tools Development

1. Build the swarm optimizers into ISI codes.
   https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=1527
   Conor is pushing this item.
2. Build the sys-id IIRrational into ISI codes. This needs an advocate. Everyone is for, but no one is pushing it.

4 Near-term and Future Hardware Upgrades

4.1 Lower noise CPS

We have been approached by Microsense, the makers of the CPS, with a possible readout replacement with 5x lower noise. This is an excellent opportunity, and would immediately improve the platform performance (this plots exist, link to them). We have expressed our interest, and Rich Mittleman is following up. This seems to be a development project by Microsense; we don't have any cost or schedule information.

4.2 HAM1 Instrumentation

Summary: The optical table in HAM1 is on a passive stack, and motion of that table is linked to noise in ASC. One action underway now is to add eddy current dampers to the blade springs for the tip-tilt mirrors. The table at LHO has 4 L-4Cs installed, but the one at LLO has only two. We need to work with ISC to determine the right sensing scheme (ie Arnaud should discuss with Valera and Marie). We expect that making LLO match LHO is the right path. This should happen at the break before O4 .

Discussion: There is a spurious coupling from HAM1 table vertical motion to the REFL WFS signals, polluting the ASC control signal, which is close to DARM from 5-15Hz, see the injections from alog 41621. A feedforward scheme from HAM1 motion witnessed by recently installed vertical L4Cs to the error point of the CHARD control was commissioned and reduces the control signal by up to a factor of 2 between 10-15Hz, see alog 34905. A decision for not building additional HAM-ISI was made because of the low impact of those frequencies on sensitivity, described in note M1900052. Currently we do NOT plan to install additional sensors on HAM1. On Dec 18, 2019, Arnaud and Peter confirmed that the the plan is to NOT install additional sensors into HAM1.

The 6.1 Hz bounce mode from the RMs which are used as steering mirrors to the REFL WFS is still seen in many ASC control signals, and dominates the RMS motion. Adding passive damping on the RMs to reduce this motion seems like a reasonable thing to do. We are also commissioning additional feedforward from the tip-tilt osems. We have seen at LLO a reduction of DARM in this band, post- October 2019 vent, see the blue vs orange DARM curves on the summary page from 2019-11-06. We should try to understand what changed. Arnaud is working with Bram on adding eddy current dampers to the blade springs for the tip-tilt. Testing now at Caltech. Expect to install at both sites when it works.

LHO Chard noise dominated by other things, not using the FF. - have 3 vert. L4C and 1 horz. LLO 2 vert L4C, feedforward now helps - ISC should consider if additional sensing will improve this situation.

4.3 Performance of the ISI from 5-30 Hz.

So far, this does not seem to be a performance limit. Improvements here could come from:

- Elimination of input environmental sources (good idea, ongoing effort w/ PEM and Detchar).
- Reduction of the stage 0/ HEPI resonance via FF or structure changes (there is no plan now for structure modifications).
- Broad improvements will require improved GS-13 noise (hard).
- Broadband improvement would be helped w/ more bandwidth. (hard)

- Higher bandwidth also requires careful consideration of the performance of all the payload. Resonances of the payload can limit the control bandwidth. All items on the table should be lightweight structures with high natural frequencies which are well damped.

4.4 SPI

4.4.1 Introduction

Development of Seismic Platform Interferometers (SPI) has strong support by everyone in the SEI team. This is a key technology for improving stable operation of the detectors and is also a key technology for improving the detector noise by lowering the bandwidth of the interferometer control loops. There has been work by the groups at Stanford, MIT, AEI, and Birmingham on this technology, but its development is resource limited.

4.4.2 SPI discussion

There is a good outline/ tree of SPI efforts in `https://dcc.ligo.org/T1900110`.

1. What's being done at the AEI. Sina thesis: `https://dcc.ligo.org/P1800282`
2. Global seismic control part 1: offloading cavity signal: `https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=1479` Global seismic control part 2: CPS differential between platforms: `https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=1482`
3. Relative motion of ISIs dominates the SRCL bandwidth, HAMs 4 and 5 are biggest contributors. `https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=1393`.
   The SRCL bandwidth, in Oct. 2018, was set by the inertial motion of HAM4 and HAM5 between 0.7 and 4 Hz. Some improvement can be achieved with bend filters (done), better vertical displacement sensors (planned for HAMs 7 & 8). Further improvements can be the angular sensing of an SPI system.
   The second largest BW limit was the relative motion at the microseism. The length sensing of an SPI is ideal for this issue.
4. There is a nice noise analysis on optical levers by Chiara and Conor at:
   `https://dcc.ligo.org/LIGO-T1900778`
5. Using optical levers to control RX motion in HAM4 and HAM5:
   - Some thoughts on Controlling SRCL: `https://dcc.ligo.org/T1900107`
   - Optical levers' noise budget: `https://dcc.ligo.org/T1900105`
6. Length control could be nice as well to reduce tilt reinjection and acquire lock more easily (especially during high-wind): Interferometric sensors in the corner station: `https://dcc.ligo.org/G1900371` HAM/BSC noise budget with high winds: `https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=44245`

Sebastien has also done the calculation to examine how much improvement can be seen in the HAM2-3 motion by using various sensors: Better CPS, CPS offload, SPI.
`https://alog.ligo-la.caltech.edu/SEI/index.php?callRep=1524`

- In Seb's calculation, CPS offload has a bit of gain peaking at 200 mHz, 3 x better below 100 mHz, slight differences at 1 Hz.
- For fine CPS and 5x better CPS, we see that you get improvements above 1 Hz, and below 150 mHz. It is slightly better in mid-band. The Fine-CPS is a bit better than the coarse CPS

with a 5x improved readout, but not much. The improvement is limited by Ground motion and the noise from the GS13. In this case, the 5x better coarse CPS is probably the easiest improment operationally - since the in-vacuum hardware is unchanged; the sensors heads are not changed and the motion limits are not impacted.

- SPI - pure sensor for differential x between platforms. This calculation uses the SPI noise from Sina thesis, fit by eye. It calculates the impact assuming an SPI at the error point, ie take SPI signal and send to CPS control point. The impact is seen in figure (xxx include figure).
  Green curve - assumes the filter in the log entry. The noise is lower, measurement is the one we want - Result is "way better" up to 600 mHz, with some gain peaking at 800 mHz. This SPI curve assumes the current CPS, better CPS would make it better.
  Blue curve - Sending the SPI signal into lowpass on HAM3 INSTEAD-OF the CPS, to lock HAM3 directly to HAM2 with a much higher blend freq, 900 mHz. With this, we might achieve differential motion of $<$ 1e-8 m/$\sqrt{\text{Hz}}$. The length noise of the SPI is 2e-11 m/rt$\sqrt{\text{Hz}}$. This shows that the SPI can dramatically improve the relative motion.

4.4.3 Optical levers and tilt sensing.

Performance of the optical lever will likely be limited by the z motion of the tables between 0.1 and 1 Hz. During low wind, it is reasonable to assume the ground tilt is small, so CPS rx is a good measure of inertial tilt. (0.15 - 0.8 Hz). For the HAMs, the optical levers must be very low noise to make things better. The AEI oplev noise at 0.1 Hz is about 3e-9 rad/$\sqrt{\text{Hz}}$.

We need to show that this noise level can improve the noise below 0.3 Hz. The limiting noise is differential Z. How does the compact BRS compare to this noise?

Should we make the in-vac tilt system into something better? According to M. Ross, LIGO-G1901599, at 0.1 Hz, the current noise (pg 6) is 2e-9 rad/$\sqrt{\text{Hz}}$, and has not reached the design noise of 8e-11 rad/$\sqrt{\text{Hz}}$. Development of this instrument needs to be well supported. This noise could be significantly lower than the differential vertical noise of two T-240s, as installed on the BSC-ISIs.

For the HAM tables, the tilt noise is differential GS-13 signals on one table (roughly a 1 meter baseline for rx and ry). If the absolute angle noise of the optical lever is set differential translation of the HAMs, then one can see the potential of the optical lever when you realized that the signal is limited by differential motion of tables separated by 10 meters.

This scaling roughly agrees with our observations. Tilt noise on the HAMs is about 1e-8 rad/$\sqrt{\text{Hz}}$ when windy - Arnuad's noise budget. (from the ground). Tilt noise for the differential GS13s at 0.1 Hz 2e-8 m/$\sqrt{\text{Hz}}$, and at 50 mHz it is 2e-7 m/$\sqrt{\text{Hz}}$, ie GS13 sensor noise. So the optical lever should be at least 10 x better than the differential GS-13 tilt measurement.

One issues with sensing tilt by subtracting agencent translations is that the translations are usually large, so small errors in the scale-factors or frequency responses can result in large errors. Jim suggests that we check the gain and plant-inversion matching of the vertical GS13s by looking back at the CPS tilt-decoupling measurements, and look carefully at the diff vertical signals. When these measurements were done originally, the matching was done at the resonance and at higher frequencies (ie at and above 1 Hz). This might be a simple way to get a bit more performance.

Actions:

- Chiara - add GS-13 tilt noise to figure 5 of T1900788.
- Sam - In the noise budget for HAMs - Make motion budget with improved angle noise. Note - the noise at the microseism is not sensor noise, it is more subtle, and may require some

more complex modelling or some clearly-stated assumptions.

- Arnaud - is the differential motion of the HAMs at LLO bigger or smaller than for the BSCs? (is the noise on the HAMS bigger or smaller than the BSCs at microseism) Locking together in length HAM4-5 can reduce the 4-5 motion, but won't be enough to improve SRCL because both platforms still moving wrt the BSC (better, but not fixed) Improved angle can reduce abs. Motion at microseism and make things much better.

4.4.4 Moving forward with SPI

Brian has been talking extensively with Sina. Brian is proposing to build an AEI-style SPI at Stanford with a new CDS readout to make it cheaper. We could then run the Dan Clark system next to the AEI system and have good out-of-loop performance measurements.

Conor thinks HoQI can be a cheaper option. BHam making some HoQis for A+, could be installed on M2 of the BS. Not on the baseline for A+, so might be available for HAM testing, which would be very interesting.

4.5 New sensors / DOFs that wish we had

Some of the sensors we wish for are better versions of what we have now, and some are ways to measure motions which we don't have direct sensors for now.

textbgImproved/ additional sensors

- Addition of ST0 L-4Cs sensor onto PRCL HAMs (maybe also on HAM6), maybe also onto the BSCs. These are a good way to reduce the translation motion around 10 Hz.
- Inertial sensors on HAM1
- Lower noise CPS.
- Lower noise OSEMs (on L2 or L3)

New Sensors to measure things that can't be provided by digital recombinations of existing channels.

- Optical lever, SPI, cBRS (there have already discussed).
- Better local angular sensing of the mirrors, so you don't need an IFO to measure good performance.
- We need a (low noise) way to reduce the optic motion (locally / differently globally that WFS) of cavities under the influence of radiation pressure (i.e. sigg-siddles instability).

However, there is a clever way, currently under investigation at University of Birmingham, to measure angular displacements of the benches very precisely (10^{-12} rad/$\sqrt{\text{Hz}}$) and to actively control them. This is done by Optical Levers.

5 Hardware Priorites

Here is a sense of how we feel about the best way to move forward.

1. 5x better CPS. Vertical on HAMs 2, 3, 4, 5, and 6. We could try it on HAM6 for all 6 DOFs. Someone should put the new CPS noise in the BSC model (Arnaud) and look at potential BSC-ISI improvements. This is appealing because you get clear improvements with low effort, medium cost.

2. SPI. This is the highest priority for R&D. The benefits are clear and compelling, but it needs more work before it is ready.
3. Compact BRS. This R&D is ongoing, and needs to be supported.
4. HAM1 sensors and Feedforward L4Cs for stage 0. These could probably improve the 8-30 Hz motion of the platforms, but it isn't clear that there is a benefit to the detectors. It is straightforward and relatively inexpensive upgrade, provided we have the leadtime to coordinate with a long, planned vent.
5. Optical levers. These could be cheaper and faster that the full SPI (length + optical levers), but only get you part way to where you want to be on improvements auxiliary length control. Only seems worthwhile as a separate project if the SPI dies.

6 Far Future Hardware upgrades and Design Suggestions

Remember that there are several "next time, we should do this" documents already.

For suspensions, see `https://dcc.ligo.org/LIGO-T1300993` And related documents.

One point that is NOT on there. We should increase the Pitch/Yaw moments of inertia of the suspensions, and hence stiffness, in order to reduce length to angle coupling physically. This will probably also improve Roll. The idea is that, if you increase the moment of inertia, you can keep the same natural frequency while increasing the rotational stiffness, but not the longitudinal stiffness. Currently the length to pitch coupling at the SUS top mass is very large, changes a bit from time-to-time, and is quite different from SUS to SUS. Quads are the worst. This could reduce the cross-coupling.

We should fix the load lines through the BSC ISI structure. (Part of the Z to RZ coupling). The suspension holding up stage one, and actuator pushing on stage one are not colocated. Thus pushing on the stage with a vertical direction, you also twist it, and the T240 is sitting on the place that you are twisting.

BSC ISI blade springs should be flat when loaded. (also any new suspension design – see OPOS suspensions.)

Fix HEPI Crossbeam foot so as to not bend at 10 Hz.

The current LIGO noise budget, in band, is severly compromised by ISC control noise. The largest impact we can have is to make changes which impact the ISC control.