# Final Report: Characterising Behavior of LIGO Subsystems through Noise in the Seismic Environment

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*ALIGO's seismic isolation system aims to attenuate seismic noise that affects the sensitivity for gravitational wave detections. This system needs to be tested and to have each of the installed systems characterized in such a way that problems can be quickly found. By tracking coincident non-Gaussian transients (glitches) through the subsystem's chambers, various statistical analysis including coincident glitch rates and average signal to noise ratios can be compared to determine which chambers are glitching most and which are not successfully attenuating noise. Problematic areas can also be found by finding which chambers are creating glitches most often and how these glitches propagate through the system. This information can be then used to localize problems for aLIGO's commissioners at the detectors in order to aid in their mitigation.*

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## Introduction

Advanced LIGO's (aLIGO) new seismic isolation (SEI) subsystem is one of many systems aiding in the detection of gravitational waves (GW). Specifically, this system detects various types of seismic disturbances using sensors placed in and out of each vacuum chamber. As shown in Fig. 2, each chamber contains various pieces of aLIGO's interferometer. The core optics of the interferometer are located in the basic symmetric chamber (BSC) while the auxiliary optics are located within the horizontal access modules (HAM) [1].

In short, both chambers use isolation stages to attenuate various forms and the locations of seismic disturbances. These isolation stages consist of, in a simplified sense, STS-2 seismometers to sense ground motion, a hydraulic external pre-isolatior (HEPI/HPI) to measure motion of the test mass and suspension supports, an internal seismic isolators (ISIs) to determine and isolate motion within the chamber of various components such as optics, and, finally, a suspension (SUS) stage of isolation to measure motion and actuate to reduce the motion of the suspended optics. There is another type of HAM chamber: the signal recycling cavity length (SRCL) HAM. The primary difference between these chambers are the number of sensors available in each isolation stage, and that BSC and SRCL HAM ISIs have 2 stages of isolation instead of the one for regular HAM ISIs [2]. While this list covers the sensors placed throughout the SEI subsystem, there are also actuators in each stage listed which reduce the motion for each subsequent isolation stage.

The SEI system has changed considerably since initial LIGO (iLIGO). Initially, there was no active, only passive seismic isolation on LIGO's mirrors, which meant that no actuation to counteract the seismic ground motion could be done. A HEPI was added during the S5 data run in order to deal with nearby logging at the Livingston interferometer and has since been upgraded for aLIGO. By upgrading the overall design of the SEI system with better and more sensors, aLIGO can yield much more precise measurements than its predecessor. This results in a significant decrease in the displacement noise that aLIGO observes, and, as can be seen in Fig. 1, this difference of noise is especially pronounced at frequencies on the order of 1-100 Hz [1]. At these frequencies, noise is reduced by up to 7 orders of magnitude and at higher frequencies (100 to 1000 Hz), the noise is still reduced by two or three orders of magnitude due to improvements in the shot and thermal noise of the detectors. All these improvement lead to the expectation that aLIGO will be able to make around 40 GW detections from binary neutron star mergers per year with a range of 0.4-400. [2].

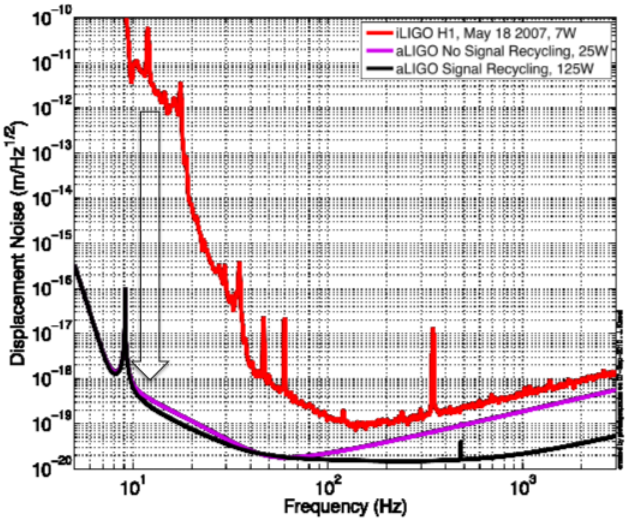


**Figure 1:** Predicted aLIGO displacement noise levels with and without signal recycling compared to observed iLIGO noise levels [2].

With the new aLIGO SEI subsystems online, it is necessary to determine whether and how each optical chamber's isolation stages glitch. Glitches are transient noise (non-Gaussian) events within a system. Optimizing detection systems requires mitigating or eliminating glitchy behavior. Consistent glitchiness within systems need to be characterized by their source and nature in order to be mitigated. This project will focus on characterizing these glitches. Eliminating these glitches is necessary because the seismic ground motion is coupled with the gravitational wave data channel directly if it is in band or by upconversion [3]. This detector characterization will be done by recording each system's behavior with an event trigger generator (ETG). In particular, Omicron is an ETG which has a high trigger generation efficiency at lower frequencies in comparison to other ETG's [4]. This is ideal since the majority of seismic events occur at low frequencies (1-100Hz). The trigger data will be used to track disturbances through each optical chamber's isolation stages.

By tracking the disturbances from ground stage channels to the optic stage channels, it will be possible to determine the percent of glitches mitigated at each stage. This will also determine the amount of glitches that transfer from the ground to the optics and possibly correlate glitchiness with frequency for each channel [4]. This project will aim to determine whether and how the new SEI system glitches. In particular, I will look for glitches which transfer from the ground isolation stage to the optical suspension stage or are produced by actuator motion.

## Methods

### Running Omicron and Channel Selection

In order to characterize the SEI systems, trigger data for each isolation stage and relevant degree of freedom (DOF) are necessary. A data channel corresponds to the digital output of specific sensors placed around and within the subsystems. The channels chosen for this study needed to be representative of the motion of the isolation stages for each chamber and can be broken down by individual DOFs. By Jessica McIver's recommendation, approximately 87 channels were chosen. The subsystems and chambers corresponding to the recommended channels can be seen in Fig. 2 as they are introduced throughout the rest of this section.

Breaking the selected channels down by their isolation stage and DOF, the first set of channels consist of 3 STS-2 seismometer channels (one for each DOF) to measure ground motion. The second set of channels are the HEPI/HPI channels. Each platform consists of 8 DOFs and each chamber has a HEPI platform [2]. Third, there are the ISI channels. As noted earlier, there are three types of ISI systems: the standard HAM ISIs, which are in the HAM 2,3 and 6 chambers; the SRCL HAM ISI's located in HAM 4 and 5; and the BSC ISIs located in the BSC chambers. A standard HAM ISI consists of one isolation stage with 6 DOFs (6 channels). A SRCL HAM ISI consists of two isolation stages each also with 6 DOFs (12 channels). Finally, a BSC ISI consists of two isolation stages. The first stage is measured by two sensors and the second one is measured with one sensor. Each sensor has 6 DOFs which totals to 18 channels. Finally, there is one platform summary channel for each degree of freedom of which there are six [2]. This totals out to 23 channels for HAM chambers, 29 for SRCL HAM chambers and 35 for BSC chambers.

While all of these channels can be relevant, the data coming out of chambers which are available for Dual-Recycled Michelson Interferometer (DRMI) testing were the most important. These are the Beam Splitter (BS), Input Test Mass X (ITMX), Input Test Mass Y (ITMY), and HAM (2 and 3) chambers seen in Fig. 2.

### Characterizing Detector Behavior

With the relevant channels selected, their trigger data is analyzed in order to answer particular questions. I wanted to find whether glitches and noise can be tracked from the ground detectors to the optics. I also checked how the glitch rate changes for each stage of isolation. Finally, I determined whether the amplitudes of the observed glitches change between isolation stages. All of these questions were used to characterize the noise observed by the aLIGO SEI subsystem in order to find their origin.

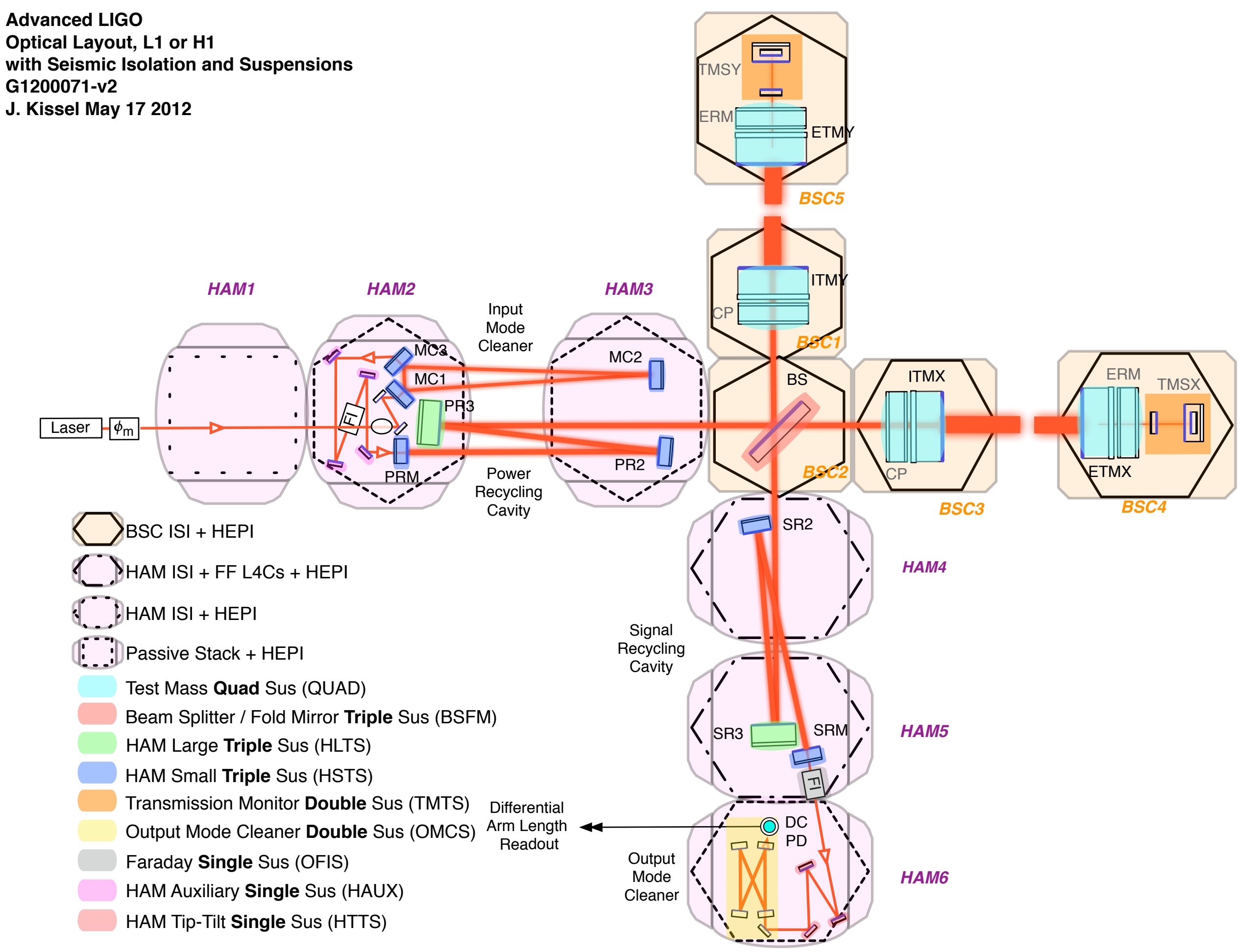


**Figure 2:** aLIGO optical chamber layout showing the stages of isolation for various chambers including HEPI, ISI and payload subsystems [2].

In order to compare amplitudes of observed glitches and their affect on glitch rates, signal to noise ratio (SNR) information was gathered from omicron's trigger data and compared using our developed plotting tools [5]. This will allow for a visual representation of glitchy behavior as a function of SNR. It will also allow for comparison of corresponding glitches in other subsystems to see how the SNR changes throughout the stages of seismic isolation.

### Data Check

In order to meet the primary goal of this project, which is determining whether glitches are transferred through the SEI system and whether any particular section is creating glitches, it was necessary to determine whether the channel pairs are operating as expected. Channel pairs are being analyzed rather than individual channels, because in order to check whether glitches are transferring through the SEI system, coincident events must be searched for in channel pairs. The first step in the process of verifying if channels are functioning correctly was determining the distribution of time differences between potential coincidences. This was done to identify a coincidence window between the two channels. Ideally, the time difference of many coincident events between two correlated channels should form a Gaussian around zero. If this is the case, then an appropriate coincidence window can be determined from the standard deviation of the resulting distribution.

By plotting a histogram of the time difference between coincident events where a coincidence window is set to a high value (5 seconds), a Gaussian fit could be created to the data. The mean and standard deviation were calculated as a check that the events are clustered near zero. The skew and kurtosis are then calculated to be sure that the distribution is at least Gaussian-like. An example of this is shown in fig. 3. Once the data were determined to be Gaussian-like and clustered around an approximately zero value, the coincidence window is taken to be six times the standard deviation of the data. Despite that this is a wider fit than would be recommended by a perfectly fit Gaussian, the accidental coincidence rate at wide time differences is extremely low. Therefore, precisely determining a coincidence window is not imperative because a large difference in the coincidence window only corresponds to a few extra coincident events. For example, in fig. 3, a coincidence window increase of a half second only increases the number of coincidences by 6 (out of an original 169). Similar background rates are observed for channel pairs that meet the criteria listed above.

Another step taken to show that channel pairs are operating as expected is showing that the distribution of triggers throughout a time interval is not random. This is important for first checking that the SNR threshold is high enough, but also to show that the events are being caused by external, non-random events. By plotting a histogram of time differences between neighboring coincidences, $dt$, it can be shown that the timing of the glitches do not follow a random, or Poisson, distribution, but instead are correlated with one another. An example of a this can be seen in fig. 4.

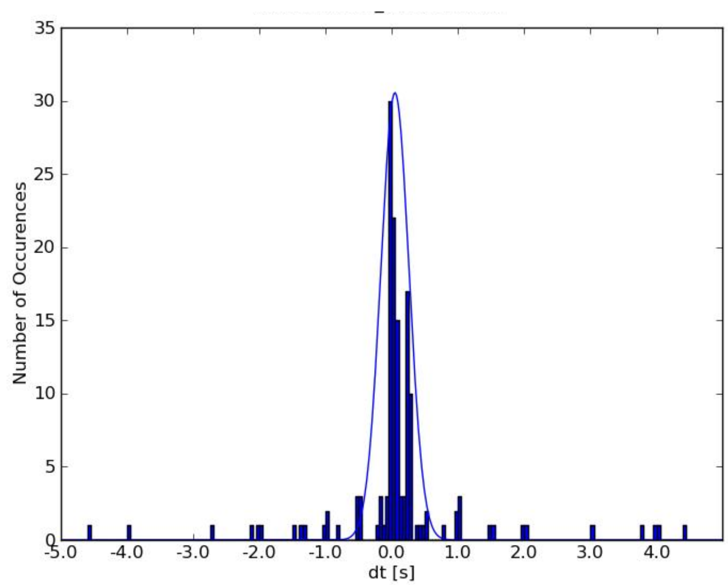


**Figure 3:** Histogram of time differences between coincident events of one HEPI channel, H1:HPI-HAM3_STSINF_A_X_IN1_DQ, and one ISI channel, H1:ISI-HAM3_BLND_GS13X_IN1_DQ, throughout a metric day in 1000 second intervals. The data were taken over GPS times 1056200000 (June 25th) to 1056300000 (June 26th).

If the glitches were randomly distributed in fig. 4, the bins corresponding to different time differences would all have nearly the same number of occurrences. However, since there is a clear probabilistic favor toward near zero values, the events are likely correlated with one another. The observed downward sloping from zero is an ideal case for our data since we would hope that most groups of events are clustered near each other. This pattern suggests that non-random events are causing highly correlated triggering.

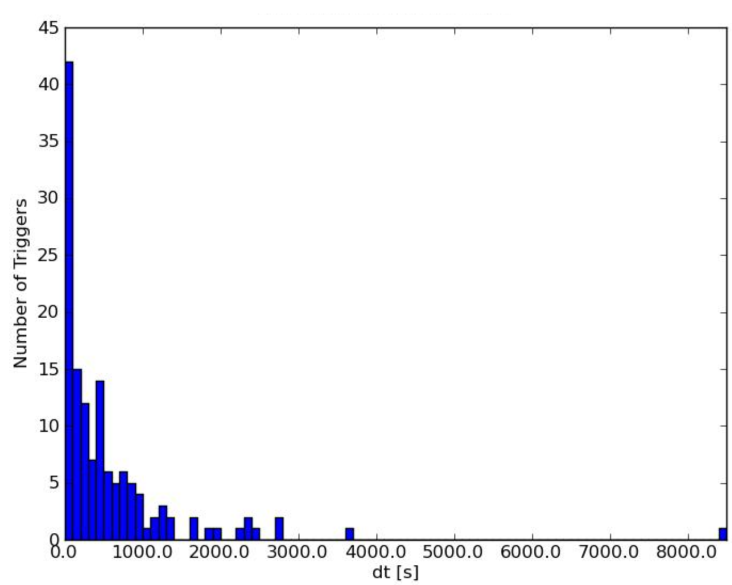


**Figure 4:** Histogram of time differences between consecutive coincidences of one HEPI channel, H1:HPI-HAM3_STSINF_A_X_IN1_DQ, and one ISI channel, H1:ISI-HAM3_BLND_GS13X_IN1_DQ, over the course of a metric day starting at 1056200000 (June 25th) to 1056300000 (June 26th).

By plotting a histogram of the number of coincident events in small sections of time (1000s), one can determine a window where a non-random trigger inducing event is occurring by looking for regions of time with higher triggering rates. This gives insight as when to search for events in my study to see how they interact with the SEI system. An example of this can be seen in fig. 5.

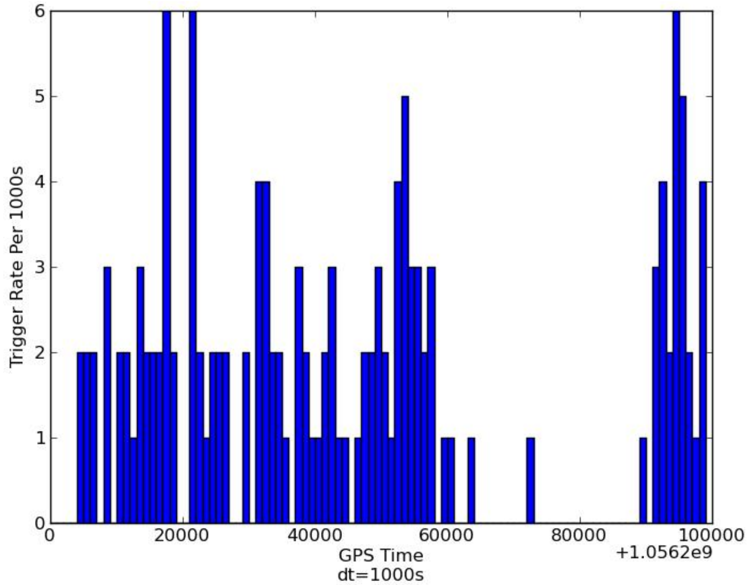


**Figure 5:** Histogram of coincident triggers per 1000s between one HEPI channel, H1:HPI-HAM3_STSINF_A_X_IN1_DQ, and one ISI channel, H1:ISI-HAM3_BLND_GS13X_IN1_DQ, throughout a metric day in 1000 second intervals. The data were taken over GPS times 1056200000 (June 25th) to 1056300000 (June 26th).

### Visualization Tools

Initially, this tool kit was written for only one pair of channels. Now, all of these preliminary mechanisms have been generalized so that they can be run on a list of channels, not simply one pair.

Once the tool kit was generalized to run on a list of channels, it was possible to test various statistics across entire subsystems and display them in an interactive way. These statistics included histograms of glitch rates throughout a time interval, glitch duration, max SNR, SNR ratios, coincidence chain length, coincidence starting channel, weighted peak frequency, and others. The visualization of this data serves two primary purposes: allowing for the easy visualization and locating of problem areas, and the ability to quickly discern interesting time segments to analyze. Because of these purposes, it became helpful to link each displayed coincidence glitch to a vertical alignment of each channels time band-passed time series around the time of the glitch. Links to this interactive display can be found in the visualization links section.

As noted earlier, Chase and I developed a vertical alignment of raw band-passed data time series plots for each channel around a particular coincident event. This was helpful to see the glitches' propagation through each isolation stage. An examples of this plot is shown in fig. 6. This plot is an example of a glitch that propagates through the entire SEI subsystem of BSC6 at Hanford. This glitch can be seen on the leftward side as a dark trend. Finding events like these is a pivotal component of this project. This plotting method is imperfect however. Because the frequency band of many glitches spans the majority of the channel's available frequencies, the band-pass filter is ineffective at discerning glitches clearly. Due to extensive problems with this method, we have decided to switch this tool to using spectrograms rather than the time series.

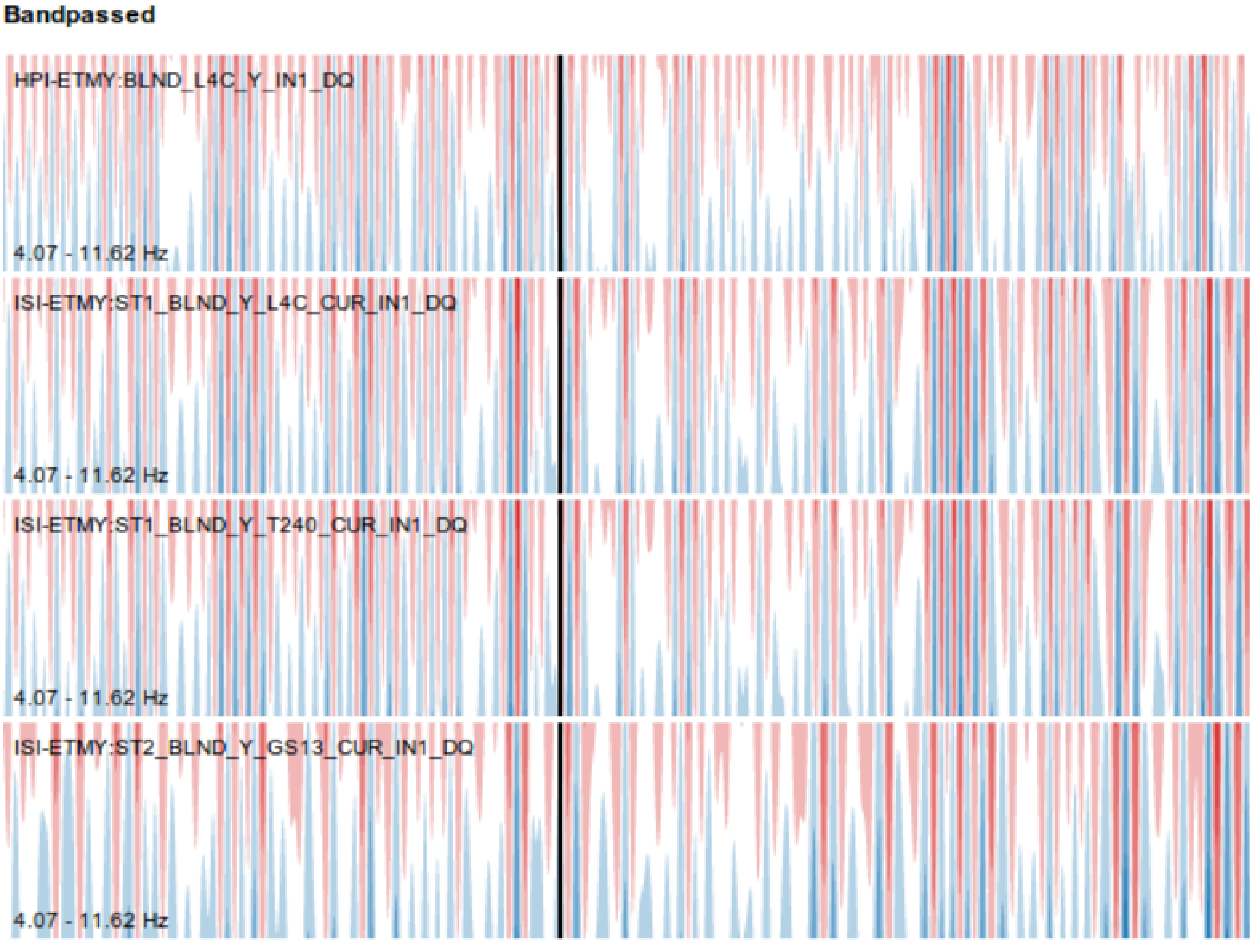


**Figure 6:** Band-passed time series of channels displayed vertically with the ground motion corresponding to the top time series and moving down corresponds to moving up the SEI chain. Red colors are positive motion and blue is negative. This plot displays darker shades as displacements that have moved beyond the vertical screen display of the graph.

Chase Kernan and I used my statistical and coincidence code as a base for us to to visually show the propagation of all glitches over any time period and other relevant statistical information in an interactive way. Fig. 7 shows an example of this interactive software, and links to the actual web pages are given in the Visualization Links section. This visualization allows for extremely fast data analysis of the many chambers and channels that are currently being looked at in the SEI and SUS subsystems. These web pages currently show the propagation of coincident glitches horizontally across the virtual map of each chamber. When one clicks on a particular glitch (line) it gives relevant information for that particular coincidence including times, frequencies and SNR. The coincidences can also be selected by SNR thresholds by dragging a particular area of the SNR versus probability plot on the right side. These functionalities have already yielded a number of interesting results.

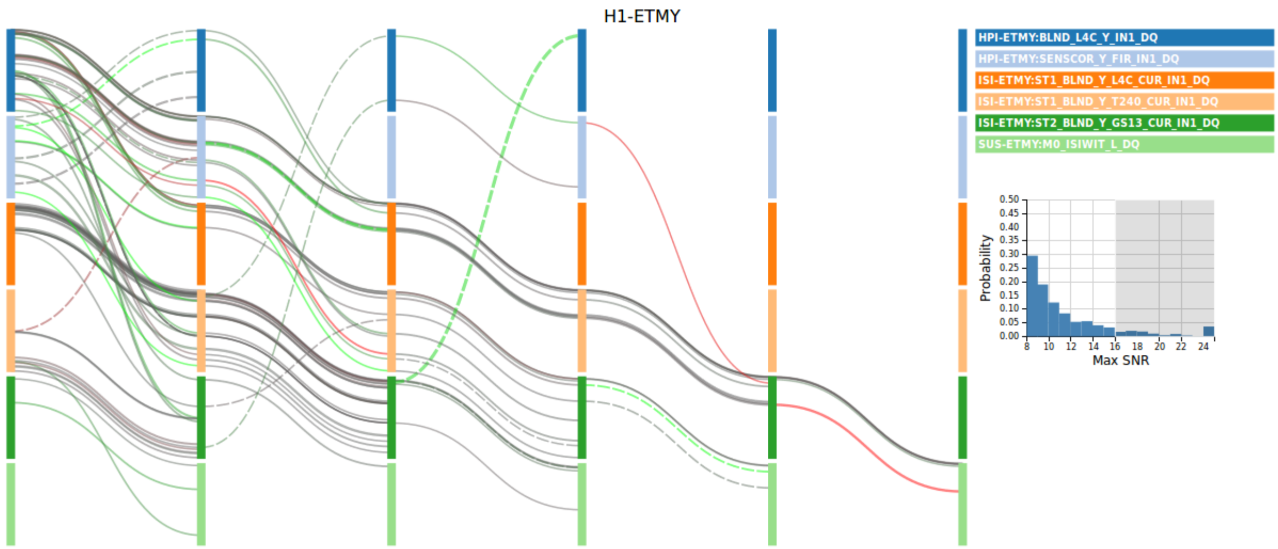


**Figure 7:** Example of still visualization for the H1-ETMY chamber for glitch data during July 27th. The vertical bars correspond to channels, and the horizontal axis is a maximum time separation of 50 ms. Each line corresponds to a coincidence and the line can be followed as to how it propagates through the chamber. By clicking on an individual coincidence (line) information about its times, frequencies and SNR will be displayed. This plot has been filtered for SNR≥16.

## Preliminary Evidence

The visualization tools developed have yielded a number of observations that warranted further investigation. First, the ISIWIT channel seems to create a large amount of glitches that are not coincident with any SEI channels. We have also found that glitches are originating at locations other than the ground and then propagating up and down the SEI subsystem then into the SUS system. This is important because we want to determine which chambers and isolation stages are doing this the most. Despite our characteristics for coincidence being met for these events, because our visualization of the raw data is not fully functional, we have not been able to check that the causality of these glitches have long enough time delays to imply causality.

We also found 3 distinct patterns among the data. Firstly, SNR is being mitigated but not always. Averaging among the chambers about 75% of glitches are being attenuated by the SEI and SUS systems. The rest are actually increasing in SNR by the end of these systems. One example of this is shown in fig. 8, where we see a case where the average SNR of the ISIWIT suspension channels is double that of the SEI channels. While the previous examples shows this is not always the case perfect, in general the systems is functioning properly.

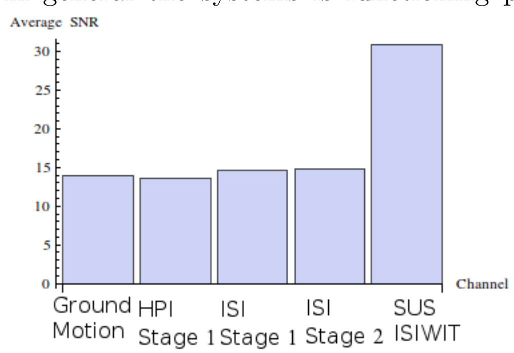


**Figure 8:** Histogram of SNR per channel as they propagate through the stages of isolation in H1-BSC6.

Another observation for only LLO is that glitches rarely span the entire chain, which also strongly supports that glitches are being attenuated. In fact, the majority of glitches only propagate one or two isolation stages beyond where they originate.

One last observation is that the number of glitches appears to decrease during the night to half the rate of during the day on average. An example of this for Hanford's BSC-6 chamber is shown in fig. 9. This pattern is expected because many anthropological noise sources are less apparent during the night.

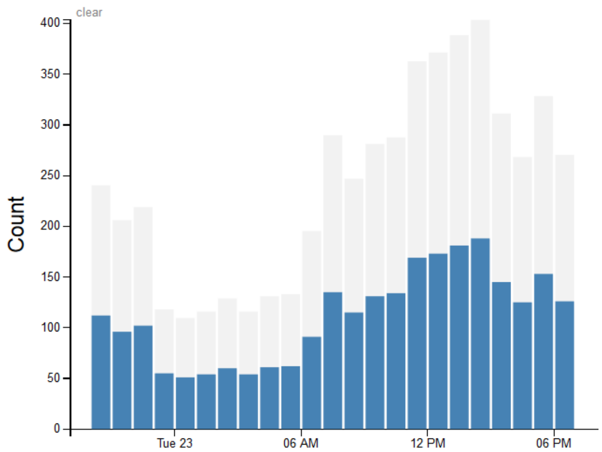


**Figure 9:** Histogram of counts/hr. of coincidence glitches over July 7th from 12am to 7pm in the Hanford BSC-6.

## Future Work

First and foremost, we plan on reworking our individual coincidence viewer (shown in fig. 6) to utilize spectrograms rather than band passed time series is order to avoid band passing issues. Once that is completed, we plan on simultaneously reworking features of the visualization software to make it more accessible such that it can be simpler to someone who does not actively work with the code to discern which chambers are problematic.

While working on the visual component of this goal, we hope to use the previous statistical tools to characterize normal behavior for each chamber and then strong deviations from these norms can be considered problematic behavior. These two parallel goals will hopefully amount to a useful tool to commissioners for optimizing the aLIGO SEI and SUS subsystems for a gravitational wave detection. We hope to have a prototype of the spectrogram based coincidence viewer in the coming weeks and the characterization of SEI and SUS for the simpler coincidence information viewer (similar to Coincidence Info Plots accessible through the visualization links section) in the next month.

## Acknowledgments

I would like to thank Prof. Alan Weinstein, Jessica McIver, and Vivien Raymond for their help in advising me during this project and for their help in understanding the project. I also would like to that Chase Kernan for his contributions to this project. I would also like to thank the California Institute of Technology and the SURF program for granting me the opportunity to pursue this project. Finally, I would like to thank the NSF for the necessary funds to carry out this project.

## References

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[2] Kissel, Jeff. *Advanced LIGO Active Seismic Isolation.* Det.Char telecon. LIGO-G1100431. April 7, 2011 (Unpublished).

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[5] Robinet, Florent. *Omicron for detector characterization.* Virgo. LIGO-G1300287. 18 March, 2013 (Unpublished).

## Visualization Links

| Chamber | Link *insert https://ldas-jobs.ligo.caltech.edu/ before each link. |
|---|---|
| Visualizer | Coincidence Tracker |
| H1-BSC6 | ~chase.kernan/cgi-bin/lsc-seis-gcm/web_main.py/coinc/group/0 |
| H1-HAM3 | ~chase.kernan/cgi-bin/lsc-seis-gcm/web_main.py/coinc/group/1 |
| L1-ITMX | ~chase.kernan/cgi-bin/lsc-seis-gcm/web_main.py/coinc/group/2 |
| L1-ITMY | ~chase.kernan/cgi-bin/lsc-seis-gcm/web_main.py/coinc/group/3 |
| L1-BSX | ~chase.kernan/cgi-bin/lsc-seis-gcm/web_main.py/coinc/group/4 |
| L1-BSY | ~chase.kernan/cgi-bin/lsc-seis-gcm/web_main.py/coinc/group/5 |
| Visualizer | Coincidence Info Plots (Same number at end of address for each chamber as above) |
| Repeat | ~chase.kernan/cgi-bin/lsc-seis-gcm/web_main.py/coinc/cross/group/ |
| Visualizer | Coincidence Time Series Viewer |
| Repeat | ~chase.kernan/cgi-bin/lsc-seis-gcm/web_main.py/coinc/group/*insert number*/time-series/ |