SFP Progress Report 1

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Introduction

As the latest generation of LIGO detectors approaches its first science run in the coming months, it is becoming increasingly important to specifically identify and target sources of noise, especially considering the many orders of magnitude improvements expected from aLIGO's strain sensitivity levels [7]. One such noise source is referred to as "scattering noise". Scattering noise can manifest itself in different ways. One specific mechanism we are looking for is when light scattered from the main LIGO beam scatters off of some element of the interferometer system that is itself vibrating at some frequency. This usually occurs when said element is not well isolated from ambient seismic noise. This scattered light is then modulated much in the same way that a gravitational wave signal would be, and if this light then recombines with the main beam and reaches the LIGO detector it can create significant noise.

In an effort to find and amend these noise sources, we are searching throughout the LIGO Livingston Observatory (LLO) for the specific sources of scattering noise. This search includes looking for the specific elements that are scattering light, and how much each of these elements' scattered light is actually reaching our detectors.

Our main methods of searching for these sources involve applying injections from various sources on specific parts of the interferometer and observing the resulting effects on the signals detected from other parts of the interferometer, especially the differential arm (DARM) signal. If we observe a large amount of noise in the DARM signal relative to the injected noise level in a certain element, then we will investigate that element further as a potential source of scattering noise. For example, we would like the effect on the DARM signal from ambient noise to be around 10-30x below the nominal noise floor of DARM during normal operation. As such, if we excite a specific system with noise around 100x above normal levels, we would hope to see noise below 3-10 times normal levels in the DARM signal. If we see larger noise levels in DARM, then those noise levels will be high enough to investigate further.

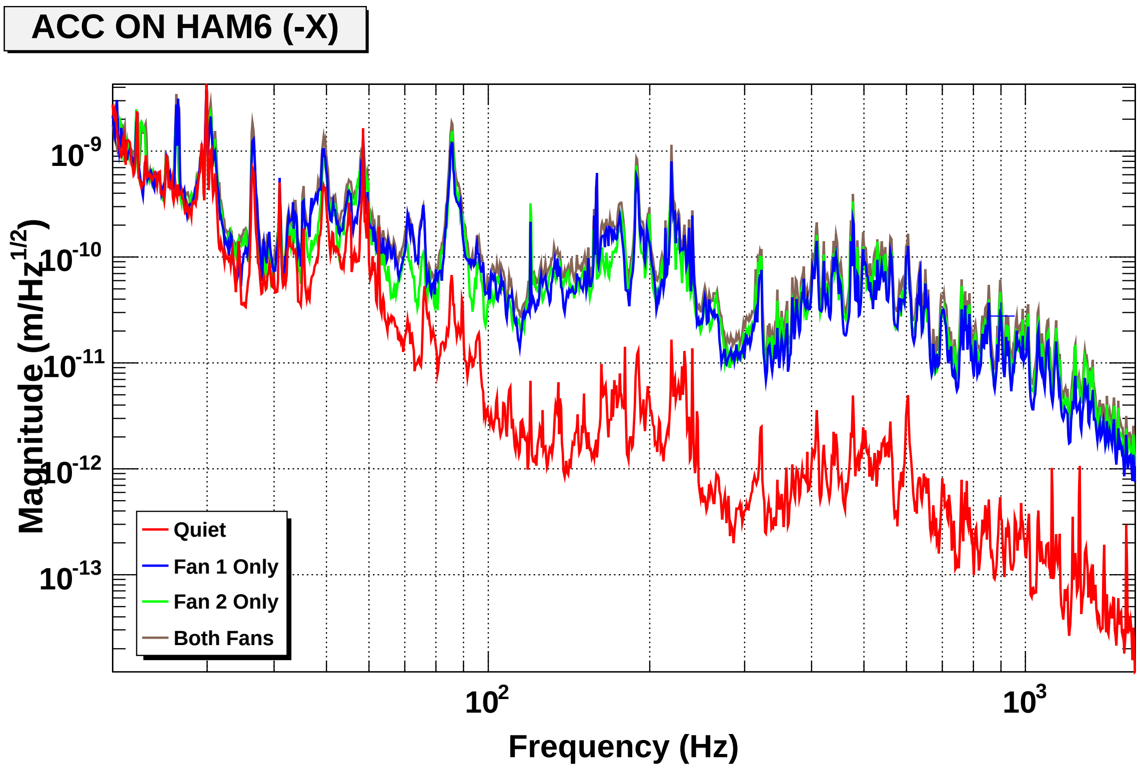
Specifically, we have two main types of injections. First are the acoustic injections, which involve pointing a speaker vibrating in a specific frequency range at a specific region of the detector. Second are mechanical injections, which directly shaking a part of the detector, which can refer to either remotely shaking a part inside the detector, or attaching our own shakers to the outside of the detector.

Previously, there have been many attempts at characterizing and modeling the scattering noise in the LLO detector [1, 2, 3, 4, 6]. We have, so far, focused specifically on the components in the HAM6 chamber as potential noise sources. Most recently, we did one large set of tests to examine how acoustic/seismic noise directed at the HAM6 chamber couples with noise in DARM, with specific attention towards the ISI table in HAM6.

Specific Tests

We've observed DARM noise when the entire HAM6 chamber is shaken by the operation of the clean room above it, and we are trying to narrow down the specific element that causes this. To that end, we shook HAM6 with two broadband sources: the clean room fans and an acoustic injection on the X side, and then investigated the ISI table in HAM6 as a potential cause of the observed DARM noise. We did not find any

Figure 1: Clean Room Injection ACC -X Spectrum



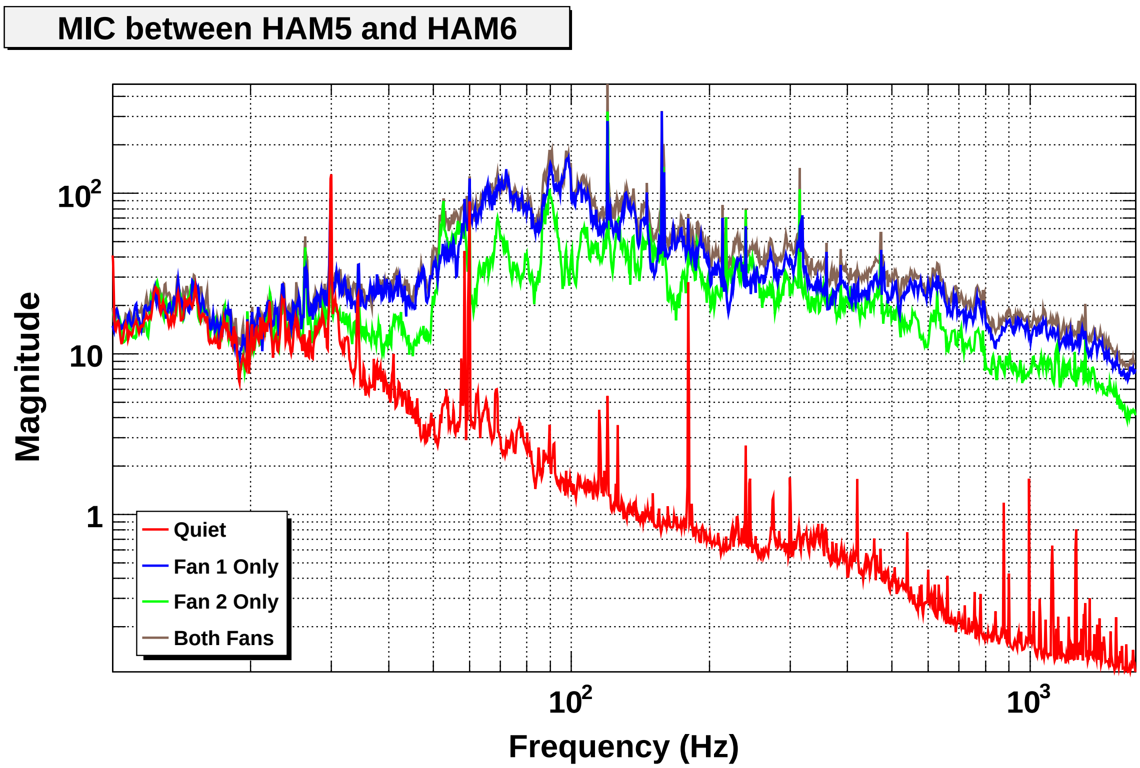
evidence to support the ISI table as a cause of the DARM noise when excited at the specific frequency range we tried, though our chosen excitation frequency band may have been too narrow to cover the entire range of response peaks we saw in the collected DARM spectra. This will warrant additional ISI table injections.

1 Clean room fan injections above HAM6

There are two fans in the ceiling of the clean room that contains HAM6 and we took environmental recordings while both fans were on separately as well as when they were on together. We took spectra from a microphone located between HAM5 and HAM6, two accelerometers located on the X and +X sides of HAM6, and sensors on the ISI table in HAM6 corresponding to all 6 degrees of freedom when needed.

We saw broadband noise on the accelerometers and the microphone at about 100x background over the range above 100Hz, but this petered out at lower frequencies and we noticed no noise below 20Hz (Figures 1 and 2). The ISI sensors showed a few specific excited regions, all at 10x background: 100-200Hz, 300-500Hz, and 800-1000Hz. Other than one very sharp peak at 25Hz, we observed no significant peaks in the lower frequencies (Figure 3). The DARM spectrum showed some broadband noise at about 2x background in the 30-170Hz region and showed three sharp peaks that may roughly correspond to the three excited regions in the ISI table spectra. There was a fairly weak peak (2x) at 130-140Hz, a stronger (10x) peak at 450Hz, and a region of a few 2-3x peaks in the 850-1000Hz region (Figure 4). Since the maximum noise injected by the clean room fan was roughly 80x background (Figure 2), noise levels of about 2x above background are just above the lower limit of acceptable levels, whereas peaks of 10x background strength certainly warrant more study. These noise levels were the main motivation for the following tests.

Figure 2: Clean Room Injection MIC Spectrum



2 Acoustic injections on -X [1] side of HAM6

Broadband Injection

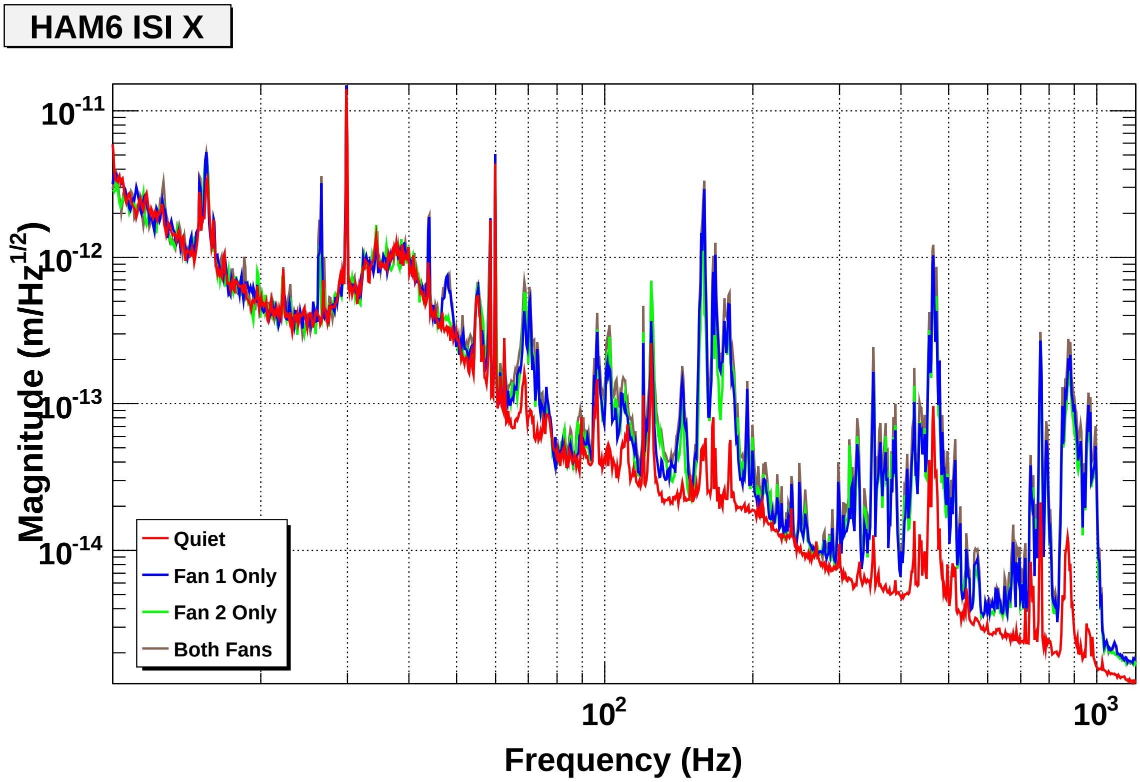
We attempted to narrow down the amount of excited elements by exciting HAM6 directly with a speaker pointed at its X side. We used two frequency ranges from the speaker. First, we tried a broadband excitation band from 100Hz to at least 4000Hz. Next, we tried a high frequency injection in the 700-1200Hz range. We used the same set of sensors as the previous injection.
DARM showed almost no response with the exception of two small peaks (3-5x background) around 320Hz and 450Hz. We observed no low frequency response (Figure 5). This may be a clue as to the source of the noise, but the speaker injections have the same problem as the clean room fans, in that they shake many parts of the chamber, including the support beam of the seismic (ISI) table and the chamber walls. Notably, this injection apparently didnt excite whatever element of HAM6 is responsible for the noise enough to show a DARM response, assuming an element of HAM6 is the cause of this noise. The mic and accelerometers showed the expected broadband noise above 100Hz and nothing below 100Hz (Figures 6 and 7). This noise was roughly of the same strength as the noise created by the clean room fans, showing that we were at least shaking the chamber with roughly the same strength as the fans. The ISI table sensors showed two regions of peaks about 10x above background: 250-600Hz and 700-1000Hz. No other peaks were observed (Figure 8). Again, these peaks were roughly the same magnitude as those seen in the fan injection spectra.

High Frequency Injection

This time DARM showed some lower frequency noise in the 40-120Hz range, which was a somewhat similar range to the noise observed in DARM from the fan injections, but about a factor of 2 weaker (Figure 5).

[1] defined by the interferometer axes shown in fig 13

Figure 3: Clean Room Injection X Spectrum

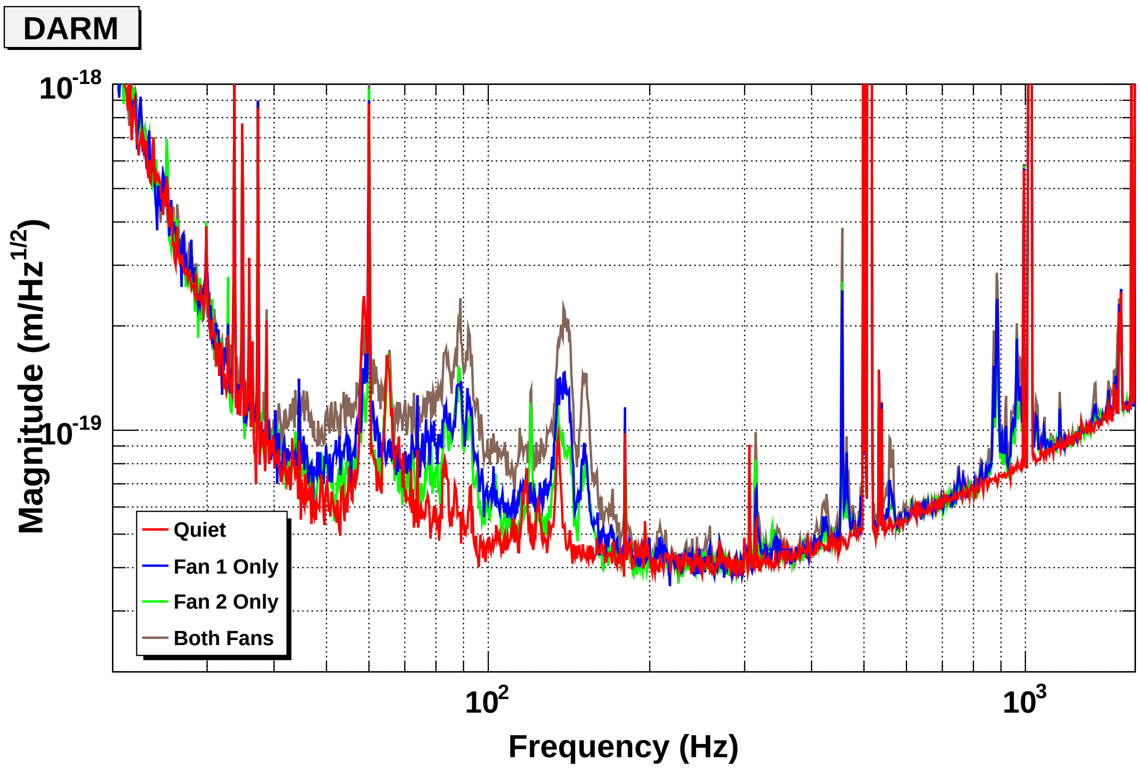


There were also some weaker peaks around 900-1000Hz.
The microphone and accelerometers showed the expected broadband noise in the 700-1200Hz range and nothing below that (Figures 6 and 7). The noise was roughly the same strength as the fan injections within the described band.
The ISI table sensors showed one region of peaks about 10x above background from 750-1100Hz, which is slightly narrower than the band observed in the mic and accelerometers. No other peaks were observed (Figure 8). These peaks were also roughly as strong as those observed during the fan injection.

2.1 Direct injections to ISI table in HAM6

Due to the constant presence of the peaks in the 800-900Hz region in the ISI table sensors in both broadband injections as well as the peaks in that region in the DARM spectra from the clean room fan injection tests, we decided to directly excite the ISI table at frequencies in the 800-900Hz range to try to detect a DARM response from the ISI tables oscillations and perhaps find evidence for some kind of causal relationship between the two. We excited the ISI table in all 3 translational degrees of freedom and recorded similar results from each.
Despite exciting the ISI table to magnitudes nearly 200x above background levels and about 20x above those we saw in the fan and acoustic injection spectra, we saw no DARM response at any frequency other than a small peak less than two times above background in the excited 800-900Hz region (Figure 8). This strongly suggests that the DARM noise seen in the broadband injections did not originate from the ISI table shaking at those frequencies. However, it should be noted that our excitation band did not completely cover the range of the peaks observed in the ISI tables sensors during the fan injections. To reach a more definitive conclusion on the ISI tables involvement in observed scattering noise, we will need to excite the table over the full observed range, about 700-1100Hz.
Figures 6, 7, 8, and 5 give a brief summary of the noise observed in all 4 tests in DARM, the microphone

Figure 4: Clean Room Injection DARM Spectrum



between HAM5 and HAM6, and the ISI table.

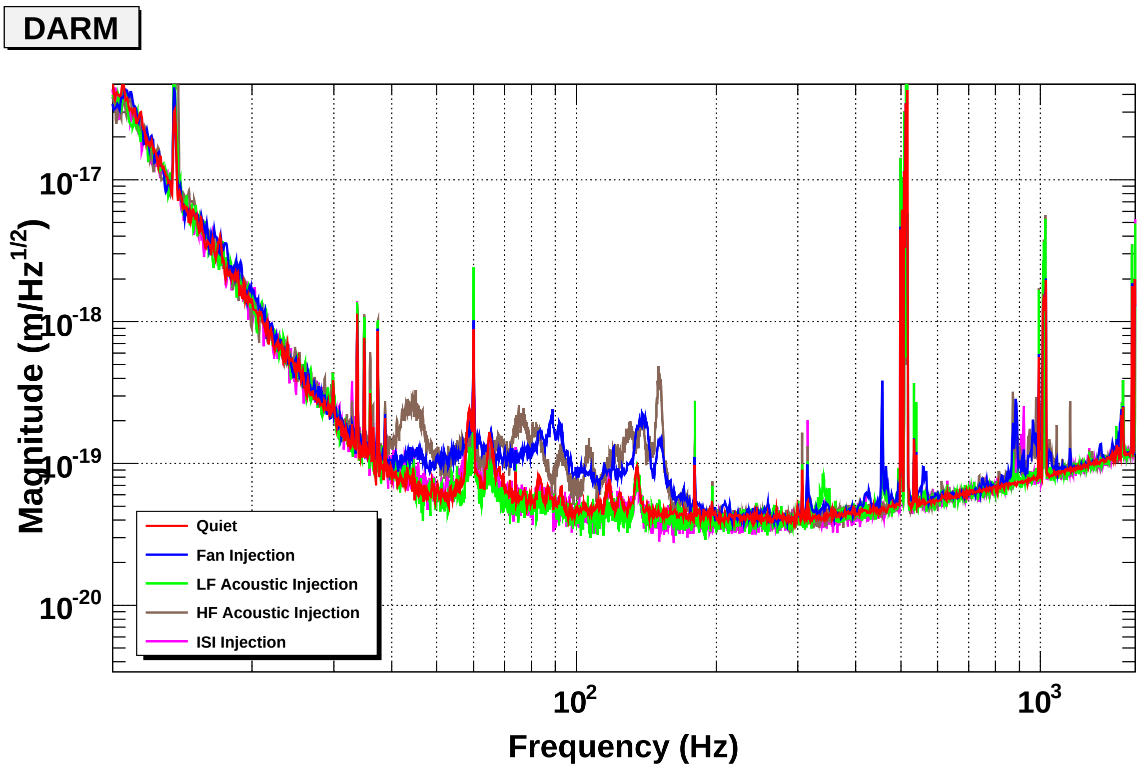
Further Analysis

After we took our initial data from the tests detailed above, we went back and looked more closely at specific regions of our DARM data that correspond to regions where others at the LHO facility had observed in a log what they thought were peaks due to resonances in the blade springs and wires in the HAM6 chamber [5].

We did not notice any peaks in the 2400-4000Hz range where the aforementioned log showed high frequency wire resonances (Figure 11), although we only excited in this band to 20x background (Figure 12) and we don't know how close that was to the LHO log's excitation levels . We, however, did notice some peaks that could correspond to the suggested blade spring resonances at around 880Hz (Figure 9). Coherence measurements between the excitation and response spectra were inconclusive, suggesting that the observed peak was not rung up directly from the acoustic injection. Also, the peak we observed was not at exactly the same frequency as the one shown in the LHO log, but this could just be due to slight differences in the resonant frequencies between the two sites.

Throughout the DARM data, the excitation levels caused by the high frequency acoustic injection (700-1200Hz) are nearly always higher than those caused by the very broadband injection. This suggests that the 700-1200Hz region is the main noise-causing region for acoustic injections into HAM6, at least at frequencies greater than 100Hz.

Figure 5: All injections summarized, as seen in the DARM signal



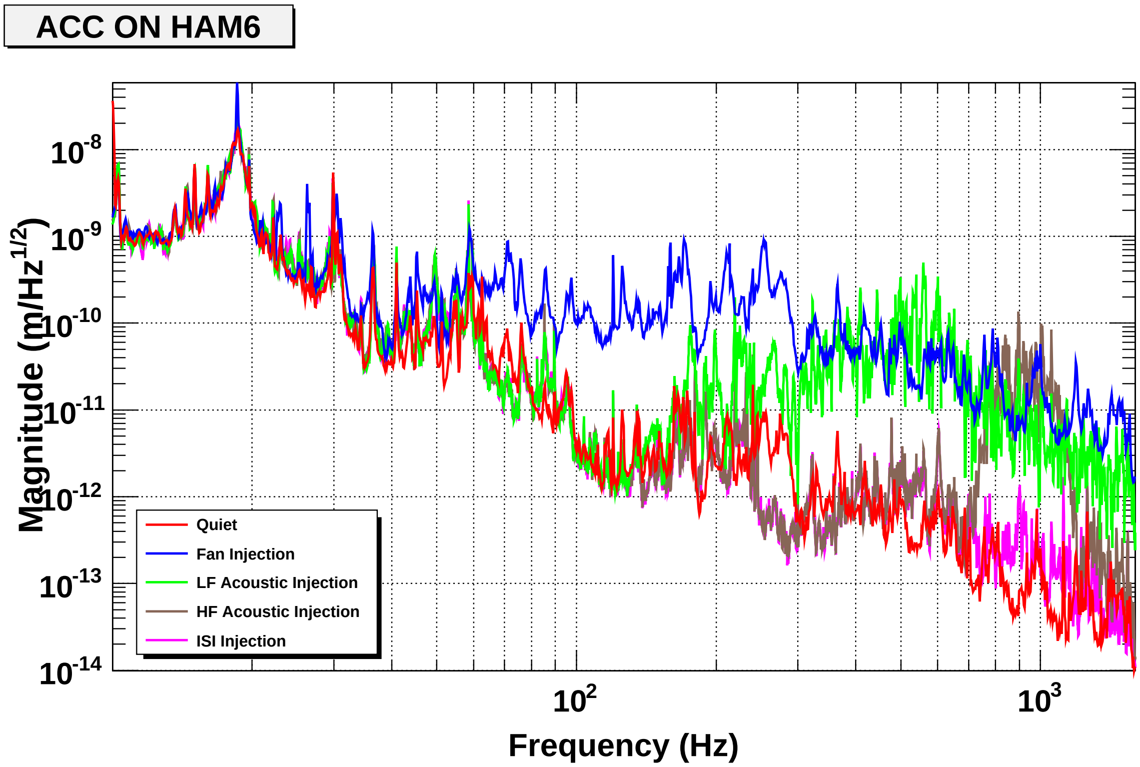
Future Experiments

We will, in the following weeks, continue our tests involving exciting the ISI table in HAM6. Frequency regions of interest include 700-1100Hz and 300-600Hz, as they correspond to the high excitation response regions seen in the ISI table data when excited by broadband noise.
We have also placed our shaker on the HEPI crossbeam under HAM6, and are waiting for an opportune time to shake that as well.
We have placed our speaker used for acoustic injections pointed at the electronics rack on the Y side of HAM6, and plan to inject the electronics rack to investigate the possibility that some noise may be coming from some coupling within the electronics themselves. Previous experiments have tried placing a shaker directly on the electronics rack, and noticed no noteworthy noise [3], so if we notice no noise after acoustic injection of the electronics rack, we will most likely rule it out as a noise source.

Predicted Difficulties

There are two main difficulties with this project. The first is the scarcity of available time to run the tests that we require. Since the vast majority of the meaning in our data is derived from comparing them with the DARM data, we require the interferometer to be in full lock to run the majority of our experiments. Since the interferometer is not always in full lock, and it is important to use such times to acquire quality data, there is generally not a large amount of time set aside for experiments that involve purposely causing noise in the detectors. Our second difficulty is that due to the complicated nature of the LLO facility, it is an equally complicated task to determine, when the majority of our injections excite multiple components of the interferometer, specifically which component is to blame for observed noise. As such, it requires multiple targeted tests for each location in the system to obtain valid conclusions.

Figure 6: All injections summarized, as seen by the HAM6 Accelerometer (-X side)



References

[1] Canuel, B. et al. 'Displacement Noise From Back Scattering And Specular Reflection Of Input Optics In Advanced Gravitational Wave Detectors'. *Opt. Express* 21.9 (2013): 10546. Web. 6 July 2015.

[2] Effler, Anamaria. *HAM6 Scatter Investigations With Shaker In Single Bounce*. Livingston, LA: LIGO Livingston Observatory, 2015. Web. 7 July 2015.

[3] Effler, Anamaria. *HAM6 Scatter/Shaker Tests Continued*. Livingston, LA: LIGO Livingston Observatory, 2015. Web. 7 July 2015.

[4] Ottaway, David J, Peter Fritschel, and Samuel J. Waldman. 'Impact Of Upconverted Scattered Light On Advanced Interferometric Gravitational Wave Detectors'. *Opt. Express* 20.8 (2012): 8329. Web. 6 July 2015.

[5] Schofield, Robert. *High Acoustic Coupling Likely Due To HAM6 ISI Blade Spring And Suspension Wire Resonances; Wire Damping Demonstrated*. Hanford, WA: LIGO Hanford Observatory, 2015. Web. 6 July 2015.

[6] Schofield, Robert. *Shaking study suggest beam-tube baffle scattering noise will be borderline near 14Hz, below noise floor elsewhere*. Livingston, LA: LIGO Livingston Observatory, 2015. Web. 7 July 2015.

[7] Waldman, S. J. 'The Advanced LIGO Gravitational Wave Detector'. *LIGO Scientific Collaboration* (2009): n. pag. Web. 7 July 2015.

Figure 7: All injections summarized, as seen by the microphone between HAM5 and HAM6

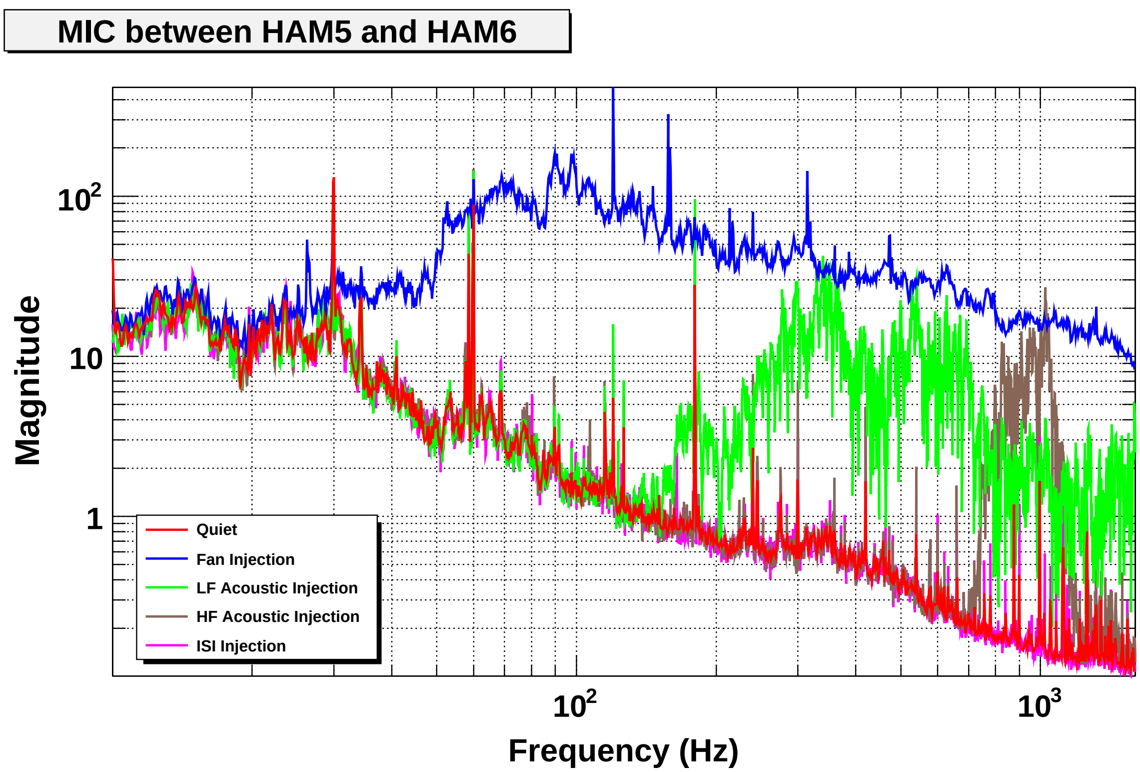


Figure 8: All injections summarized, as seen by the sensor recording the X axis movement of the ISI table in HAM6

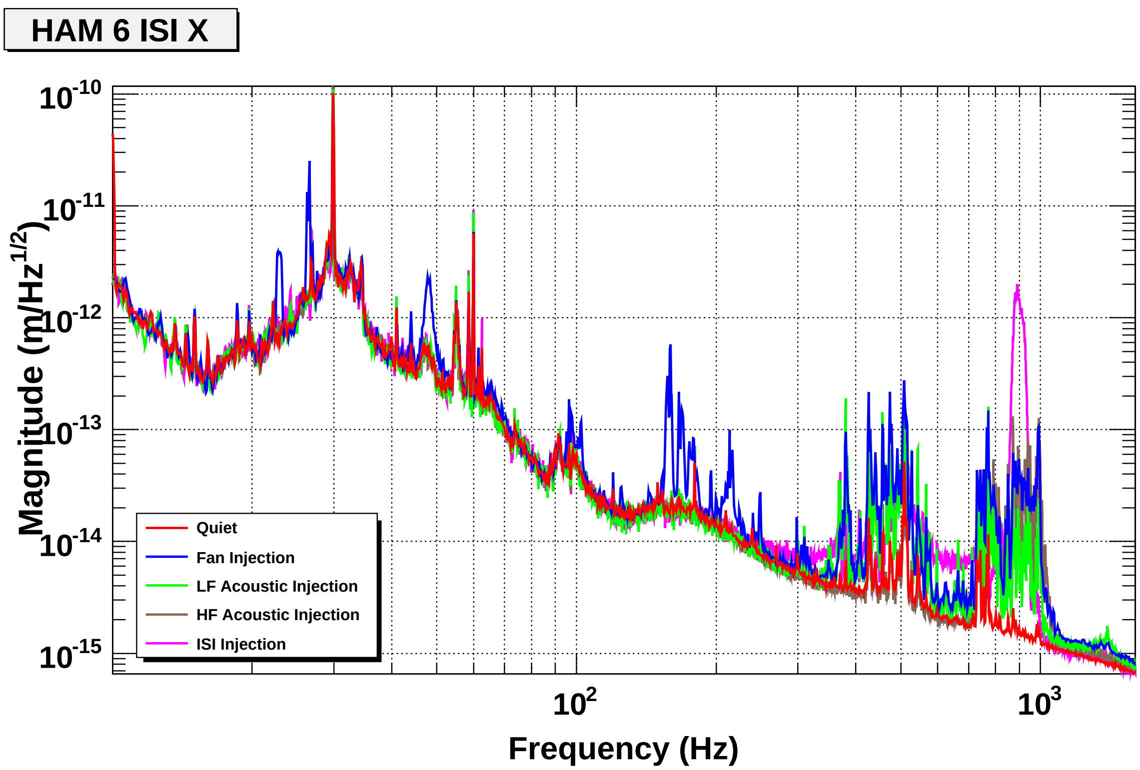


Figure 9: A closer look at the DARM signal observed during the various acoustic injections

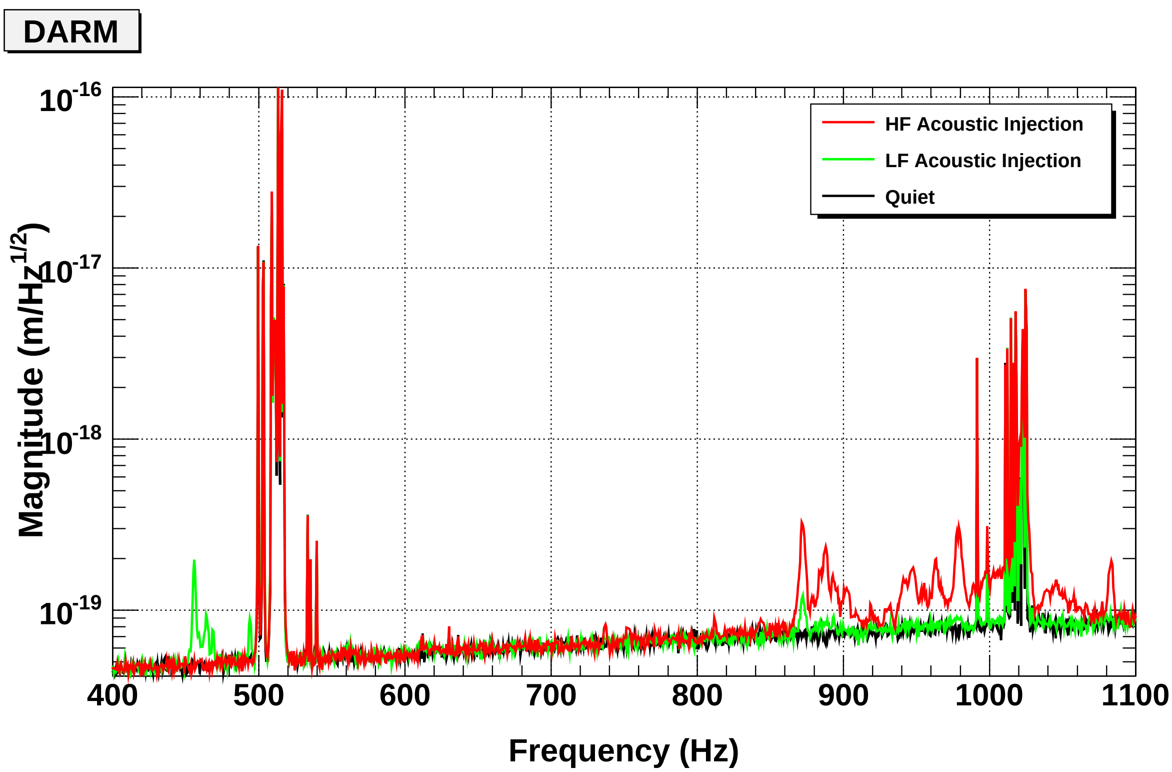


Figure 10: A closer look at the microphone signal observed during the various acoustic injections

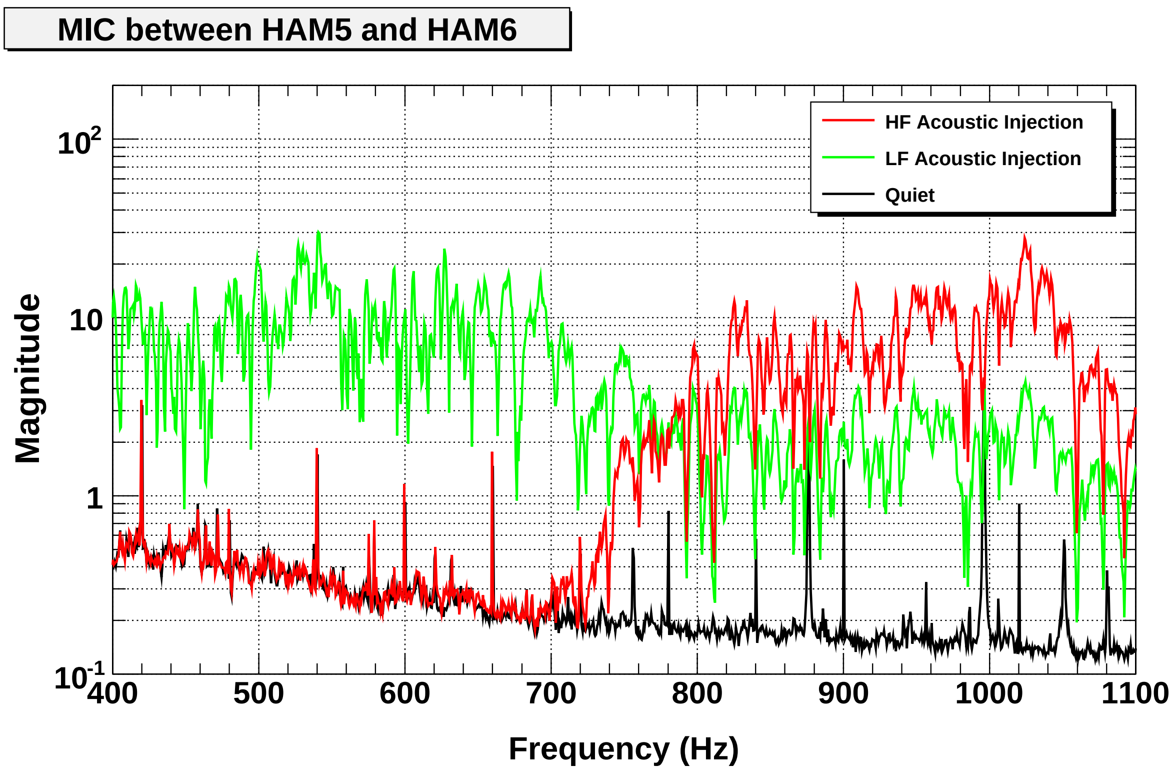


Figure 11: A more expanded look at the DARM signal observed during various acoustic injections

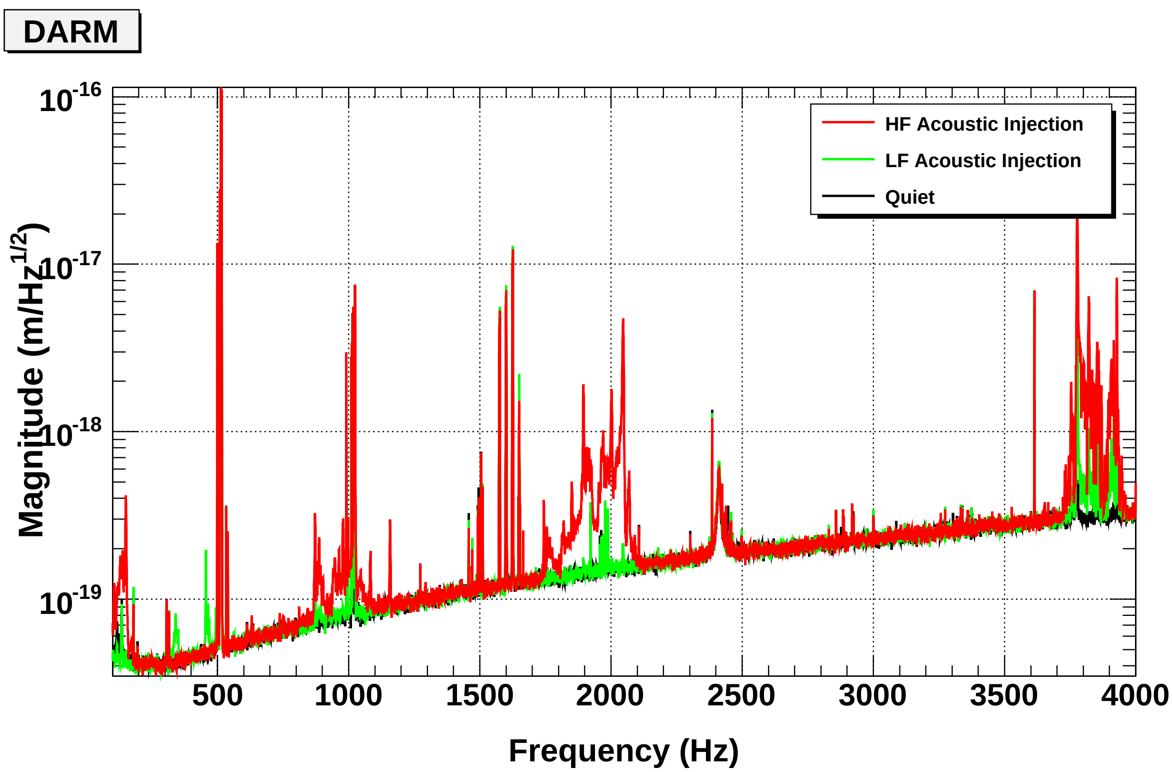


Figure 12: A more expanded look at the microphone signal observed during the various acoustic injections

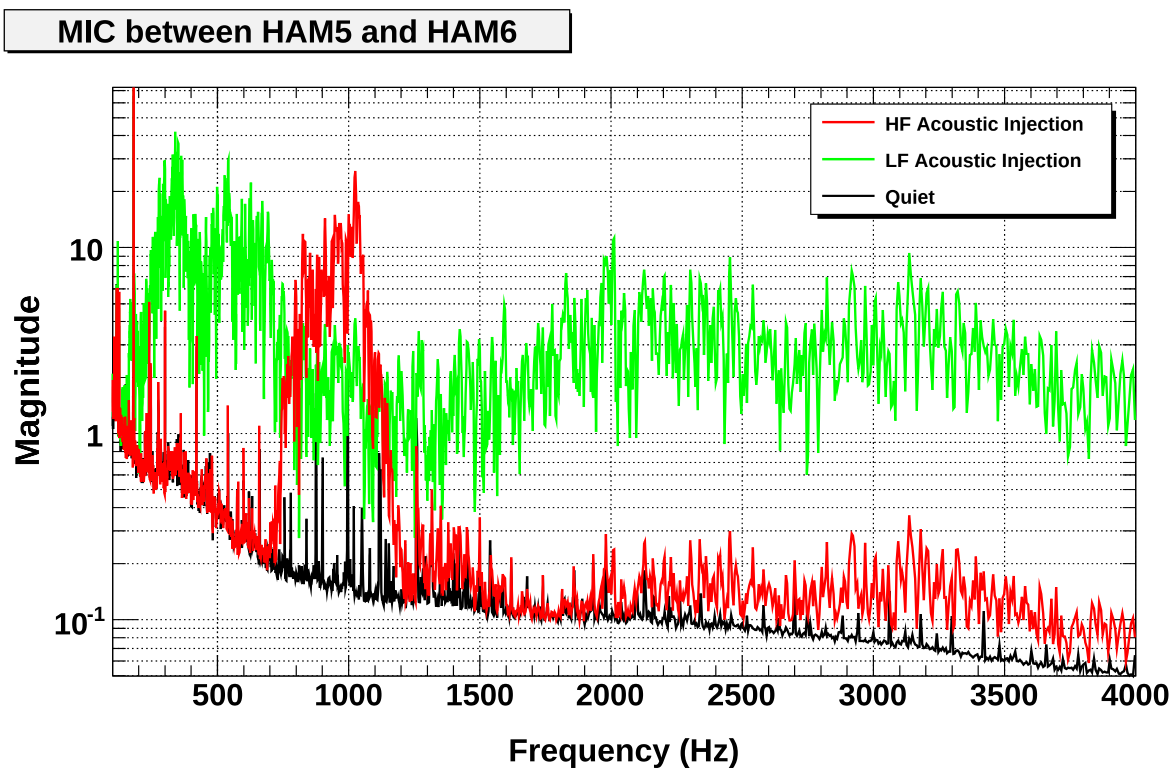


Figure 13: Diagram of the LLO facility