SFP Final Report

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Introduction

With the advent of the latest generation of LIGO detectors, it has become 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 [11]. 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 [5, 8].

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. Injections are generally defined as an introduction of pre-determined, known noise into a system, usually to observe its unknown results with some kind of quantitative measure.

We are especially interested in the injection response observed in the differential arm length (DARM) signal, as the LIGO detectors detect gravitational radiation through observation of the difference in the lengths of each detector's two arms. Due to this, it is obviously very important to eliminate as much noise as possible in this 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 the DARM signal 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 noise in the DARM signal above this threshold, then those noise levels will be high enough to warrant further investigation. The main purpose of this project is to specifically determine which elements of the interferometer system cause noise above acceptable levels.

Specifically, we have two main types of injections. First are the acoustic injections, which involve pointing a speaker that is 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. This can refer to either using pre-installed servos to remotely shake a part inside the detector or attaching our own piezo-electric shakers to the outside of the detector.

Previously, there have been many attempts at characterizing and modeling the scattering noise in the LLO detector [5, 6, 7, 8, 10]. We have, in the course of this program, focused specifically on the components in the HAM6 chamber as potential noise sources, although we did investigate some other parts of the interferometer. We spent the majority of our efforts looking at how acoustic/seismic noise directed at the HAM6 chamber couples with noise in DARM, with specific attention towards the ISI table in HAM6.

Figure 1: Image of the HAM6 Chamber and Its Surroundings

Figure 2: Simplified Drawing of the HAM6 Isolation Systems

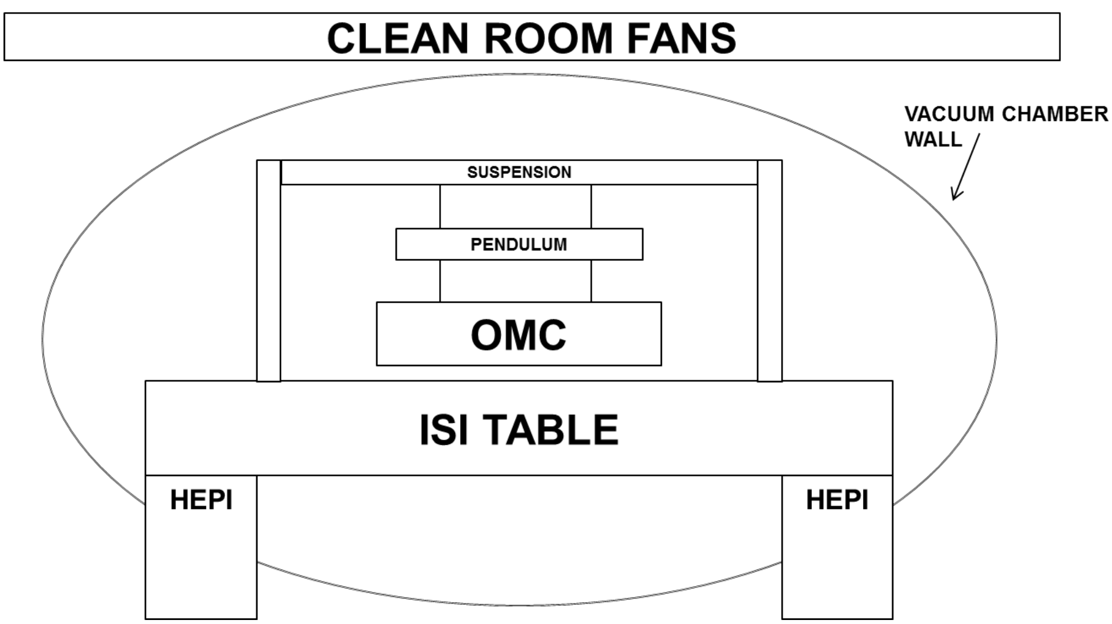
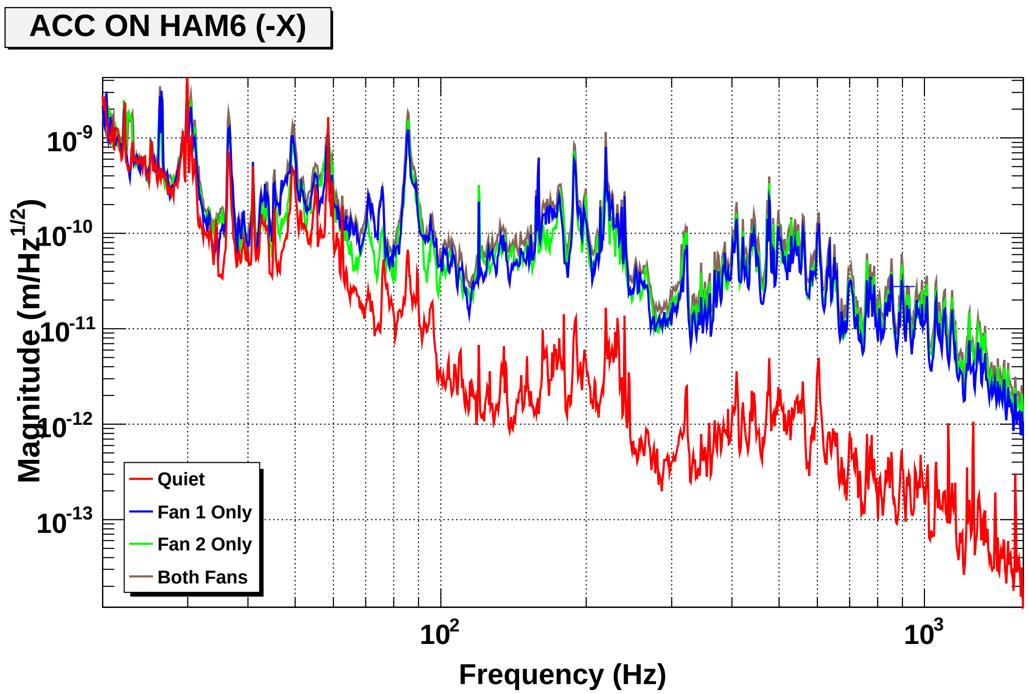


Figure 3: Clean Room Injection ACC -X Spectrum



Low Frequency DARM Noise from HAM6 Chamber Injections

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 in using injections from two 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 initially found no evidence of this ISI to DARM noise mechanism, but due to further, more specific ISI injections, a noise creation mechanism was proposed and somewhat confirmed.

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 3 and 4). 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 5). 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 6). Since the maximum noise injected by the clean room fan was roughly 80x background (Figure 4), 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 4: Clean Room Injection MIC Spectrum

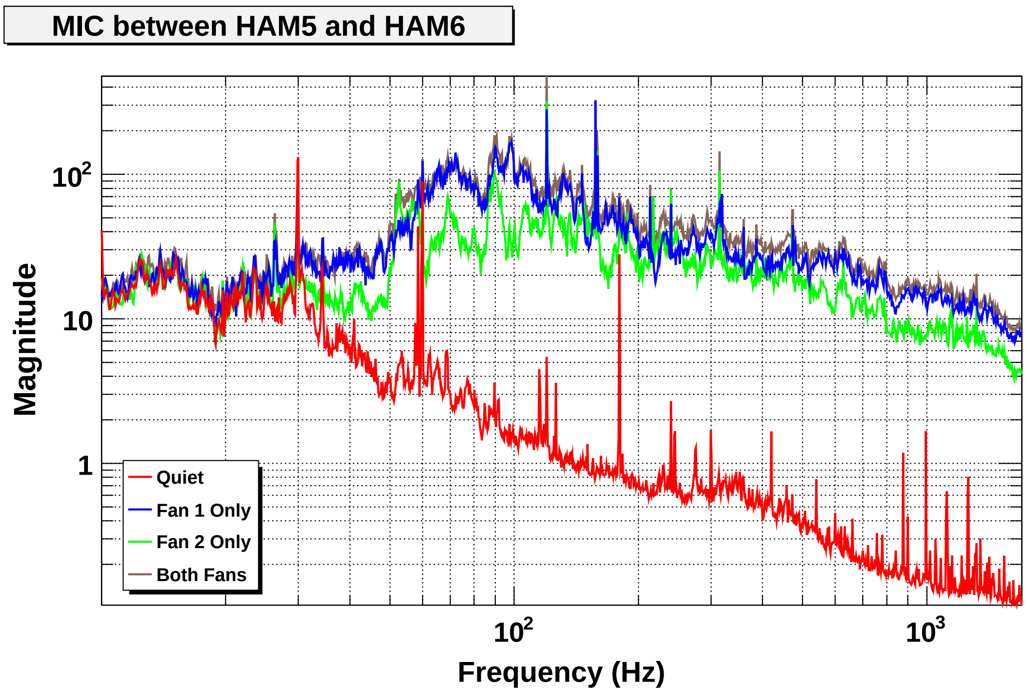


Figure 5: Clean Room Injection X Spectrum

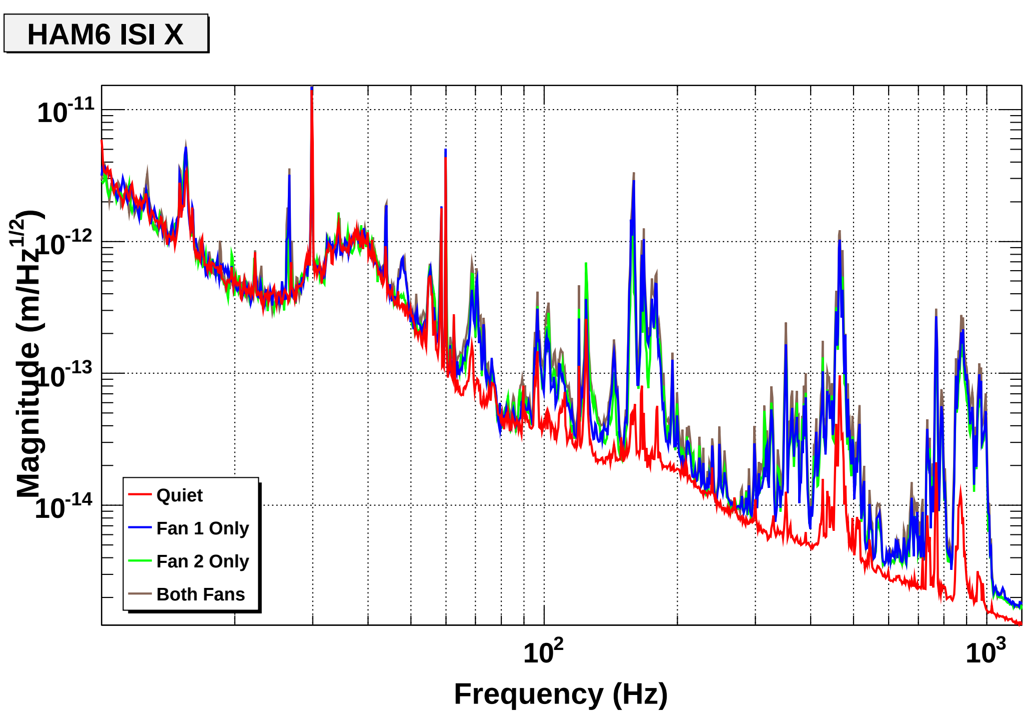
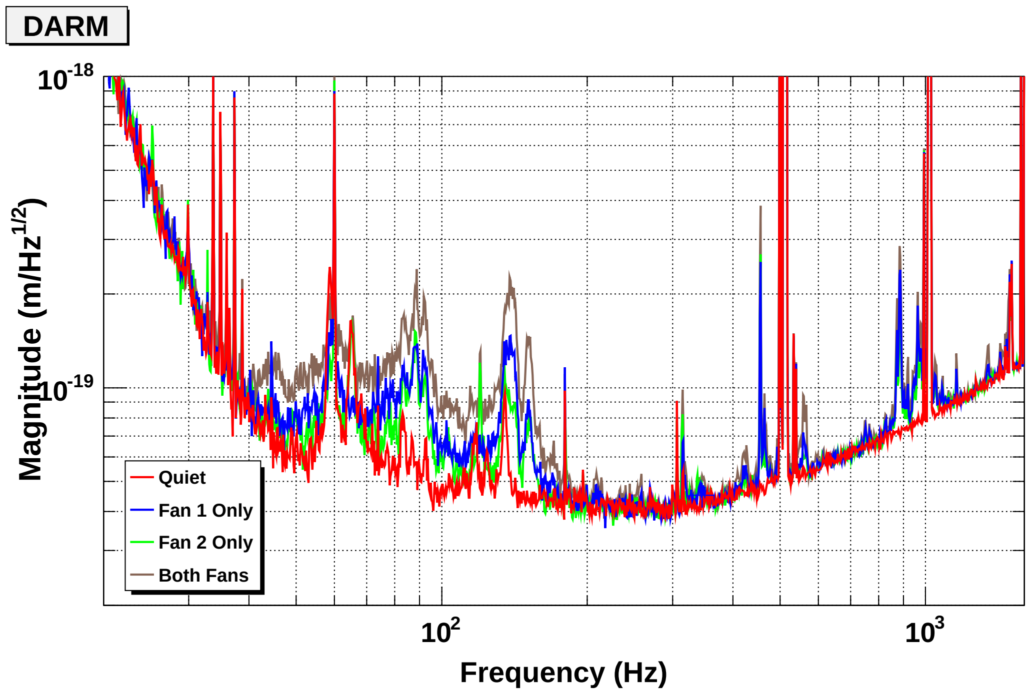


Figure 6: Clean Room Injection DARM Spectrum



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 7). 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 8 and 9). 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 10). 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 7). 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 8 and 9). The noise was roughly the same strength as the fan injections within

[1] defined by the interferometer axes shown in fig 34

Figure 7: All injections summarized, as seen in the DARM signal

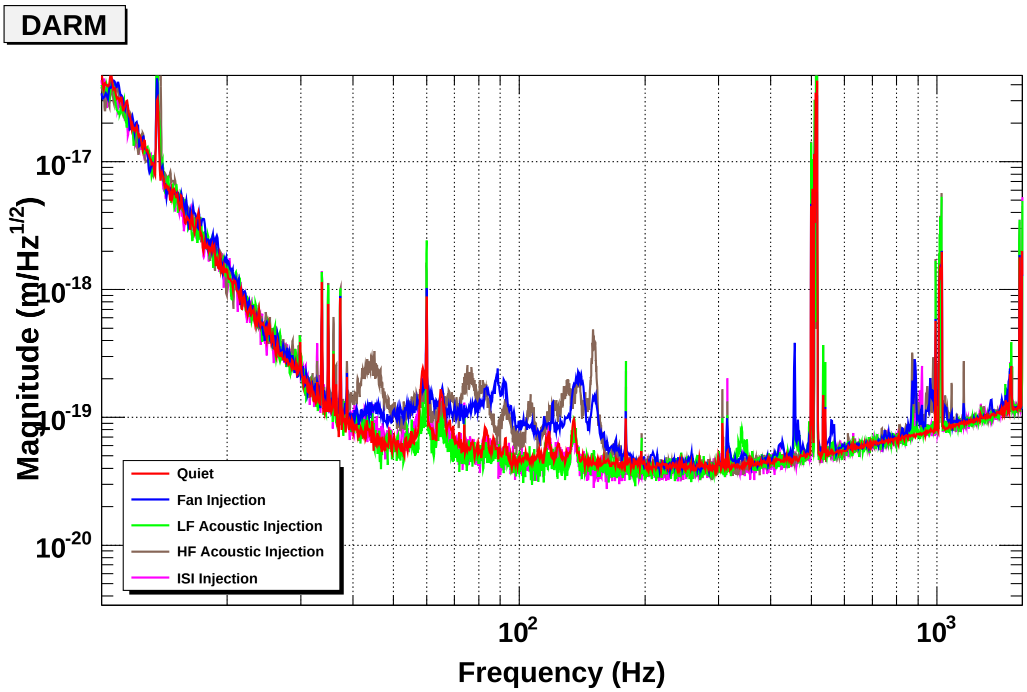


Figure 8: All injections summarized, as seen by the HAM6 Accelerometer (-X side)

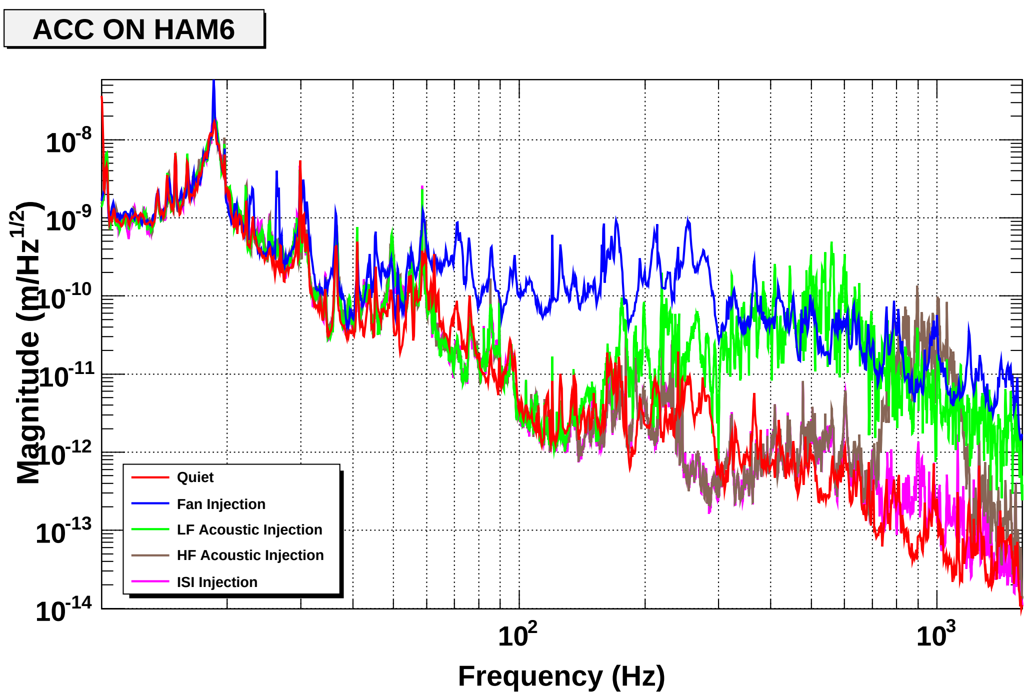


Figure 9: All injections summarized, as seen by the microphone between HAM5 and HAM6

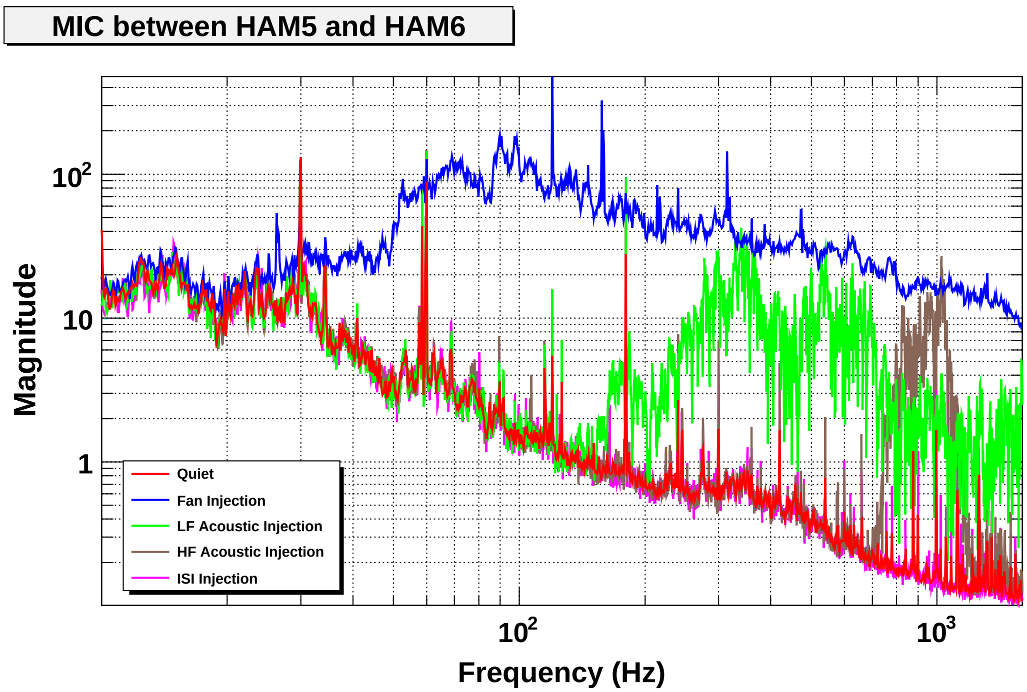
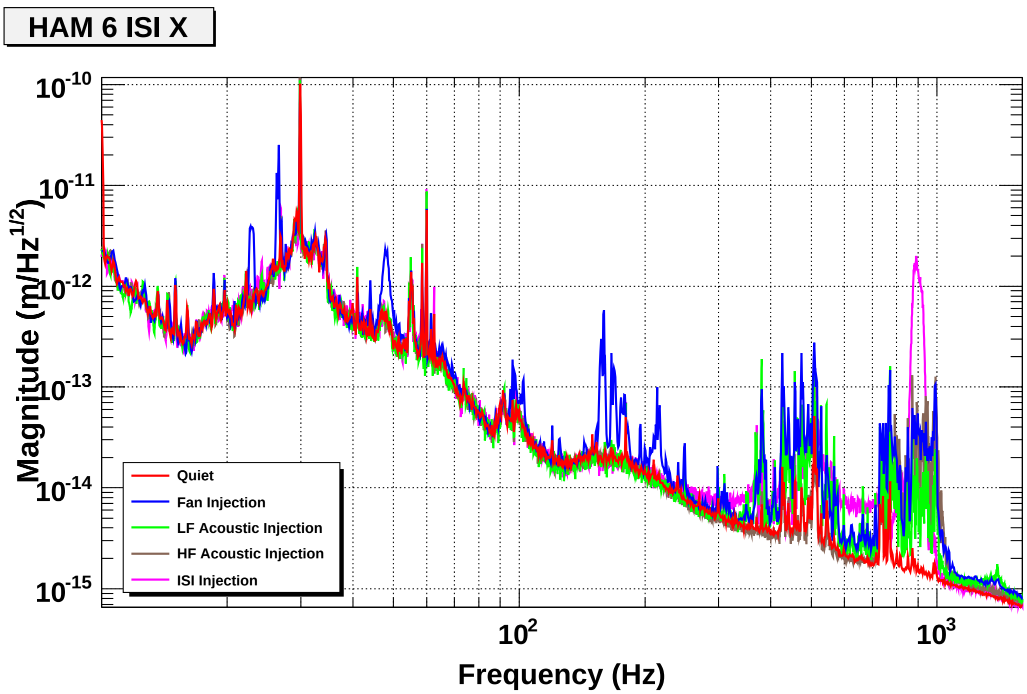


Figure 10: All injections summarized, as seen by the sensor recording the X axis movement of the ISI table in HAM6



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 10). These peaks were also roughly as strong as those observed during the fan injection.
Since we saw almost no DARM response from the strong, broadband acoustic injection, but saw significant low frequency noise in DARM from an injection over this specific frequency range, we concluded that (1) this noise mechanism is likely non-linear and (2) the 700-1200Hz range warrants further study in futher injections.

3 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 look at the DARM response to injections done directly to the ISI table in HAM6. In all ISI table injections, we excited the ISI table in all 3 translational degrees of freedom and recorded similar results from each.

Initial Injections (800-900Hz)

Initally, we directly excited the ISI table at frequencies in the 800-900Hz range, and 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 10).
These inital tests seemed to suggest that the DARM noise seen in the broadband injections did not originate from the ISI table shaking at those frequencies. However, since our excitation band did not completely cover the range of the peaks observed in the ISI tables sensors during the fan injections, we decided to inject the ISI table over a larger frequency range, about 700-1100Hz.

Figures 8, 9, 10, and 7 give a brief summary of the noise observed in all 4 tests in DARM, the microphone between HAM5 and HAM6, and the ISI table.

Broader Injections (700-1200Hz and 900-1200Hz Bands)

Later, we injected over the much broader interval between 700 and 1200Hz (Fig 12). We observed the same low frequency noise in DARM that we had seen in previous non-ISI injections, which strongly supported our suspicions about our previous injections being too narrow (Fig 11). Notably, the vacuum pumps on HAM6 were running during the acquisition of all of this data, which created additional broadband noise.
It was noticed during the 900-1200Hz injection (Fig 14) (which also created low frequency DARM noise (Fig 13)) that we observed corresponding noise in the output mode cleaner (OMC) length error noise readout (Fig 15).

Narrower Injections

Next, we injected over narrower bands that spanned the frequency range just above our previous ISI injections in an effort to isolate the specific peak or peaks responsible for the observed DARM noise (Figs 13-15). We injected over 1000-1100Hz and then an even narrower band between 1010 and 1030Hz and observed not only the aforementioned LF DARM noise, but also narrowing noise bands in the OMC length error readout. This further supported that the noise in the OMC length error readout was coming from the ISI injections. Then we briefly inspected the band just below our original ISI injection band with two injections over the relatively narrow band from 845 to 865Hz. This time we noticed LF DARM noise only around 150Hz due to this injection, and we saw noise over the injection interval in the OMC length error signal.

Figure 11: DARM readout during ISI 700-1200Hz injection

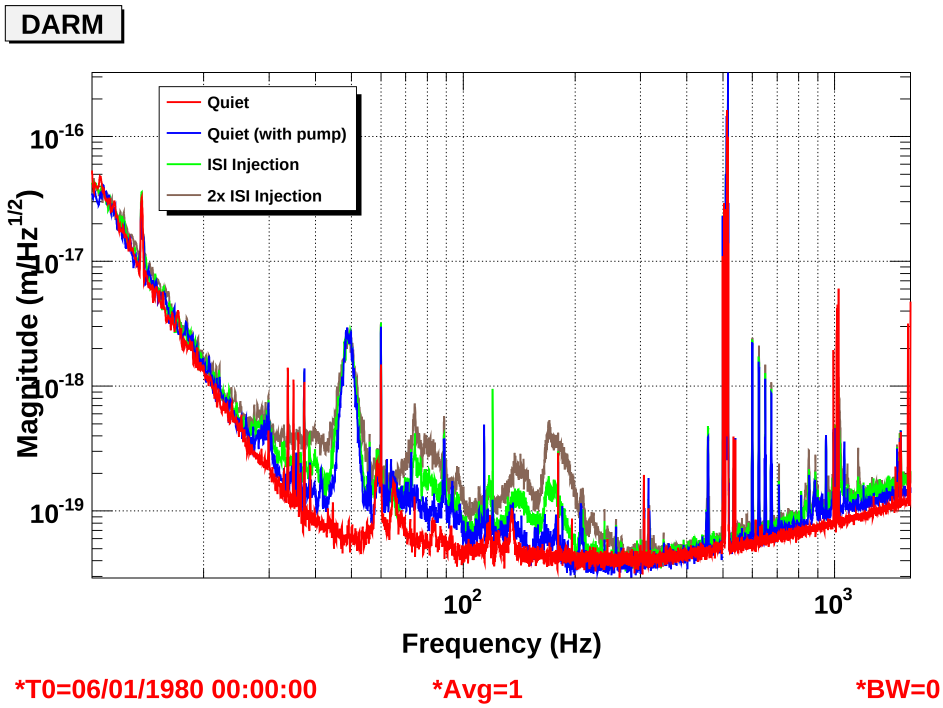


Figure 12: HAM6 ISI Table readout during ISI 700-1200Hz injection

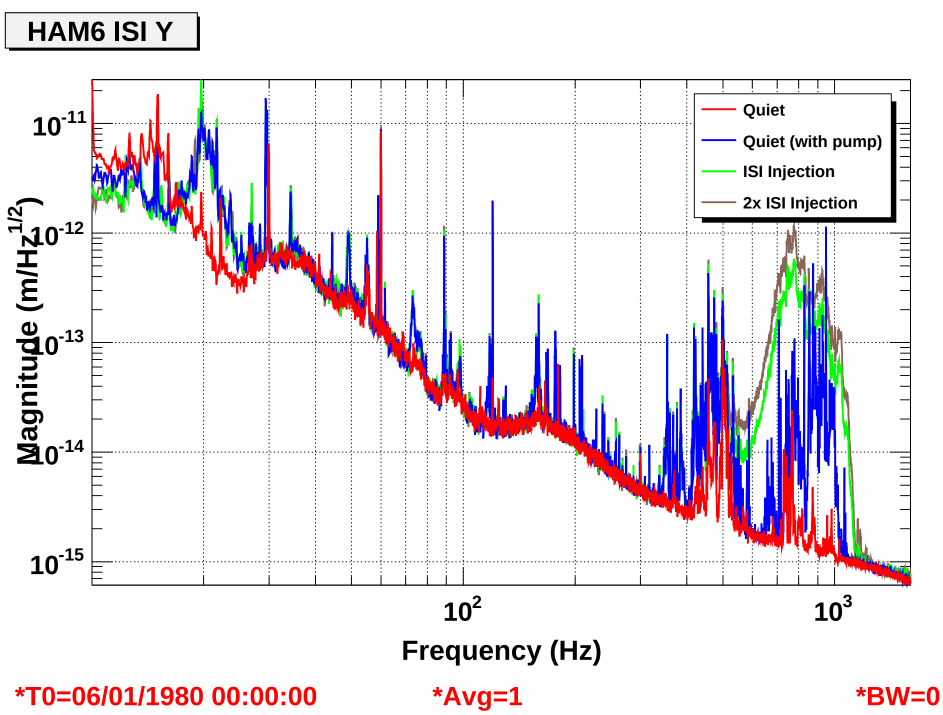


Figure 13: DARM readout during various ISI injections

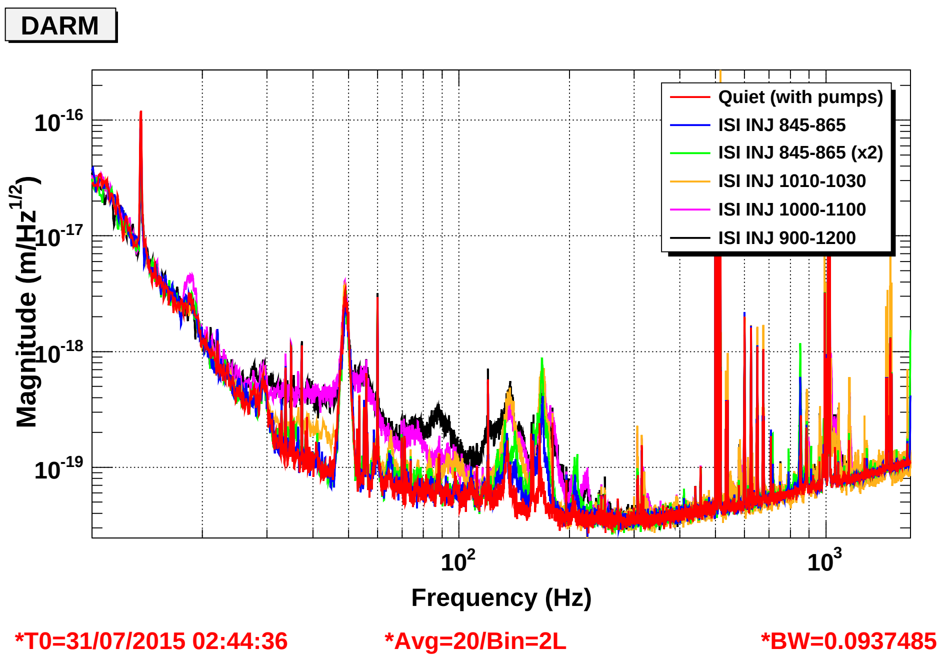


Figure 14: HAM6 ISI Table readout during various ISI injections

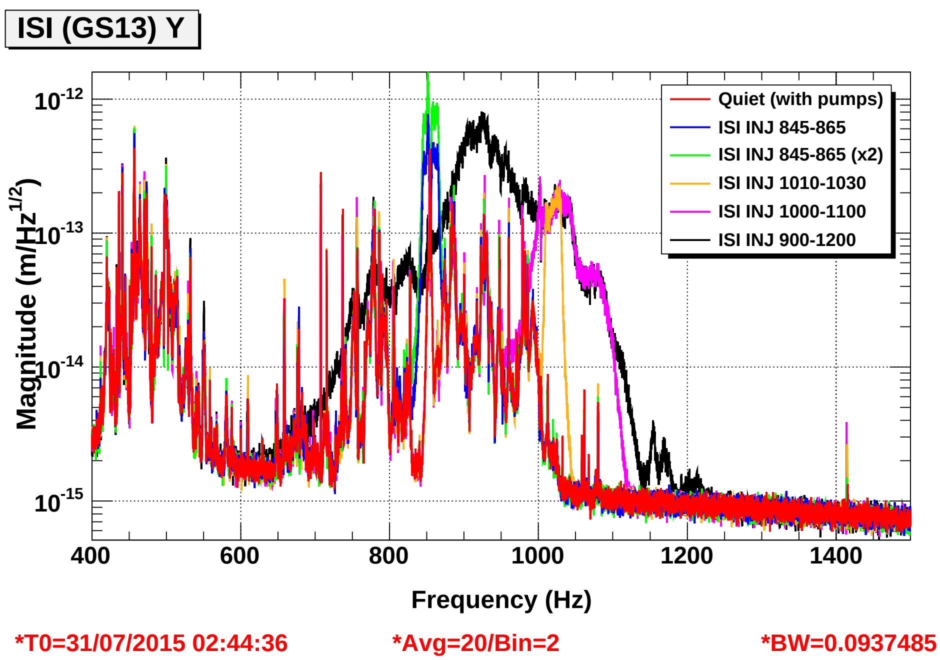
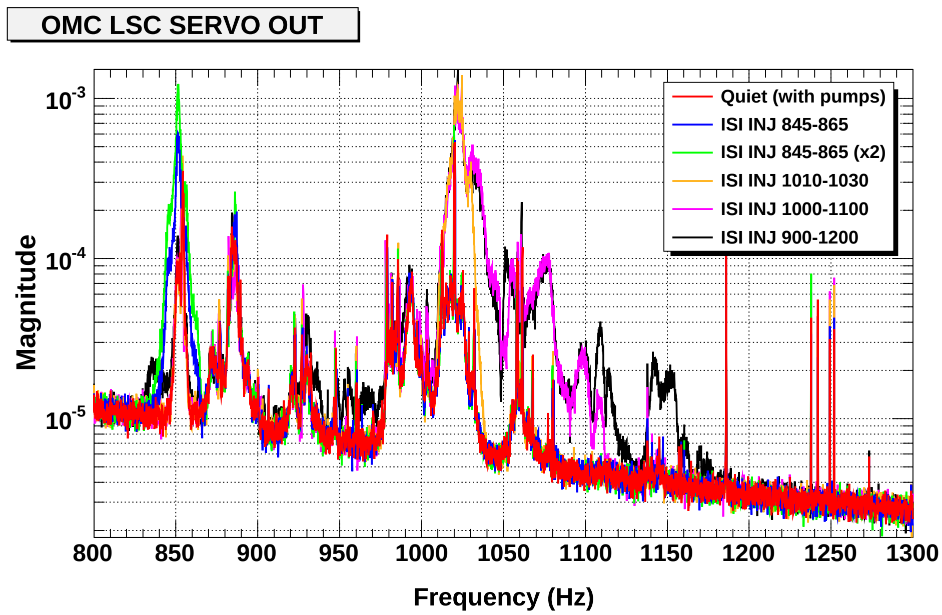


Figure 15: OMC length error readout during various ISI injections



Analysis of ISI Injections

The results of these new ISI injections led to a new theory, posited originally by Denis Martynov, explaining this LF DARM noise. We observed that the low frequency noise manifested itself only when injecting over the narrow band around one peak observed at 1020Hz in the OMC length error readout. How this peak made it into the OMC length error signal is unknown, but we theorized that the LF DARM noise could be the result of the ISI injected noise, which had somehow made its way into the OMC length noise signal, beating with this peak at 1020Hz. [2] This new beat noise, which can be found at the difference of the two beating frequencies, would manifest itself in DARM at low frequencies, since the frequencies we were injecting had frequencies within a few hundred Hz of the 1020Hz line.

The aforementioned beating occurs in the DARM signal because the DARM readout is the **power** transmitted from the OMC cavity, which is proportional to the square of the transmitted field, which is itself proportional to the length of the OMC cavity. If we imagine the OMC length error signal to be a combination of two frequencies,

$$L = Acos(\omega_1 t) + Bcos(\omega_2 t) \propto E_t \tag{1}$$

then the transmitted power that becomes the DARM signal will be:

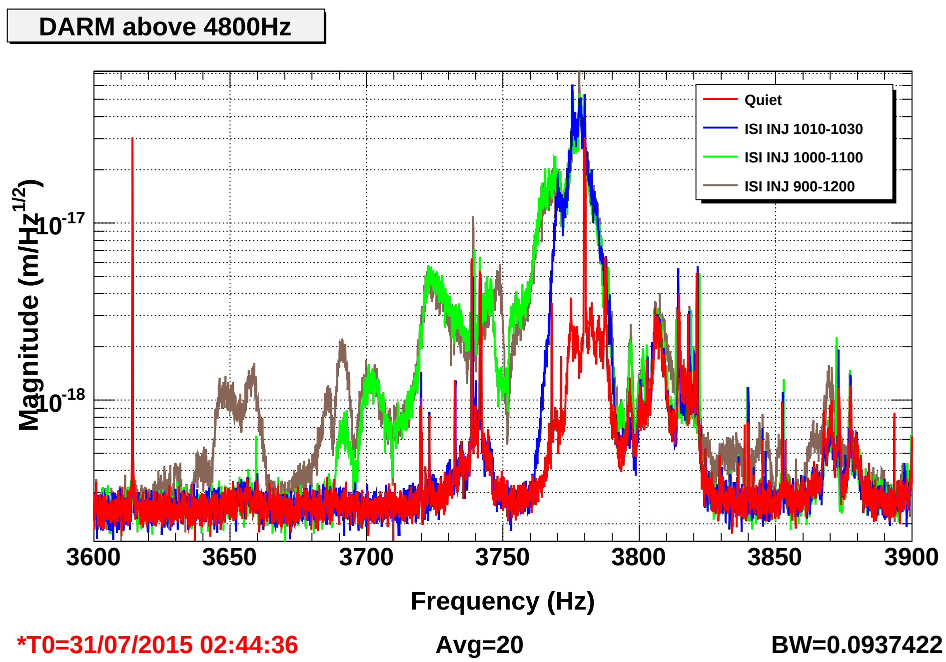
$$P = |E_t|^2 \propto L^2 = A^2cos^2(\omega_1 t) + B^2cos^2(\omega_2 t) + 2ABcos(\omega_1 t)cos(\omega_2 t) \tag{2}$$

$$= \frac{1}{2}(A^2 + B^2 + A^2cos(2\omega_1 t) + B^2cos(2\omega_2 t) + 2ABcos((\omega_1 - \omega_2)t) + 2ABcos((\omega_1 + \omega_2)t) \tag{3}$$

This theory suggests that the LF DARM noise we observe is due to this $\omega_1 - \omega_2$ signal.

Further supporting this theory, we have observed high frequency noise in DARM that almost exactly matches the noise signals we saw in the OMC length noise readout at 4800 ± 1020Hz. [show figures from log] 4800Hz is the demodulation frequency used to control the OMC cavity, and the fact that we see its signal beating (both at $\omega_1 - \omega_2$ and $\omega_1 + \omega_2$ in this case) with the noise around 1020Hz in the OMC *in DARM* means that

Figure 16: DARM readout 1020Hz above 4800Hz



this length noise we observe in the OMC is in fact showing up in the DARM signal, as must be the case if our above theory is correct (Figs 16-18).

Noise Budget Modeling

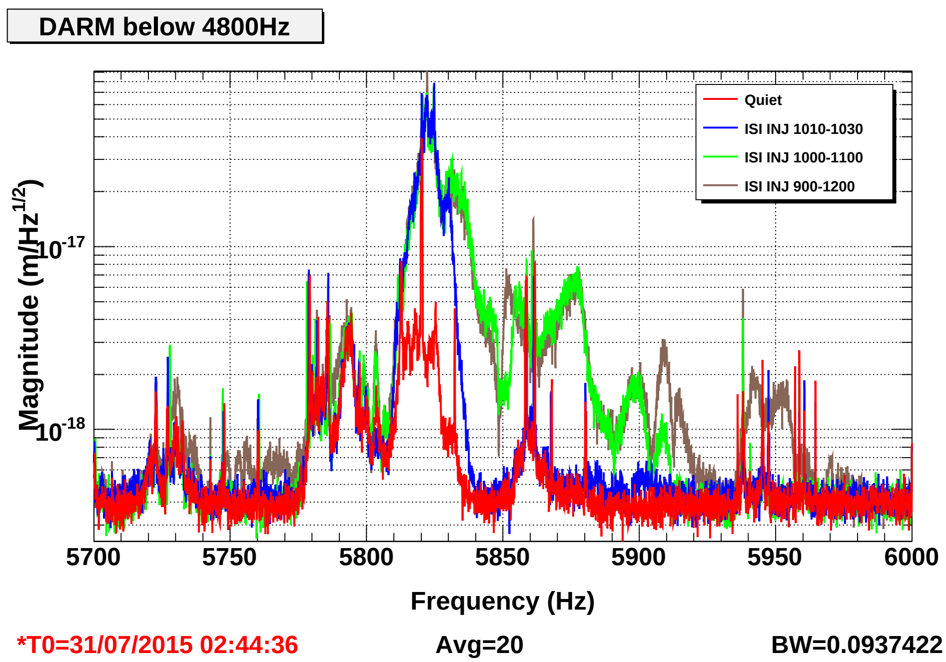
Linear Modeling

In the weeks of detector inactivity during which the HAM6 chamber was opened, we created template for a noise budget plot to demonstrate the contributions towards DARM noise of all of the elements we had injected since the beginning of the program. Our first plot naively assumed a linear system when considering the noise levels. For example, if we injected somewhere in the system at 100x background levels of noise and saw noise in DARM at 10x background, we assumed that this noise, during normal operation, would contribute 10x below the normal noise threshold. We chose to only include those noise sources that could possibly be linear in behavior, rather than those that are obviously non-linear, such as our ISI injections. The main lines come from two injection sources: the clean room fans above HAM6 and acoustic injections perfomed using a large speaker. Both of these injections are explained in depth in the previous progress report. [1] It should be noted that the clean room fans above HAM6 are not normally active, and as such they normally have zero contribution to DARM noise. However, their contribution to the noise budget is notable as an indicator of how much similar environmental effects (other things that cause both acoustic seismic noise) would affect the DARM signal.

Nonlinear Modeling

We were able to create a kind of non-linear noise budget for the low frequency DARM noise that followed our working model by simply plotting the square of the OMC length noise signal. A plot of this model is

Figure 17: DARM readout 1020Hz below 4800Hz



shown in Figure 20, along with a plot of the actual low frequency noise observed during an injection from the HAM6 clean room fans. The second plot shows the coherence between the two. Notably, while this simple model does quite accurately match the observed noise peaks at around 25Hz, 130Hz, and 170Hz, it misses another low frequency peak at around 90Hz. This 90Hz peak could simply be from another noise source, or the simplicity of our model may be missing some critical detail. Either way, reconciling this model with the observed data is another open question to be explored in further research.

Effects of HAM6 Chamber Improvements

During the second half of this program, the HAM6 chamber was opened, and several improvements were made to the in-vacuum system in an effort to reduce noise. Two improvements that were especially notable for our studies were a set of dampeners attached to the ISI table suspension wires and a “shroud” that was placed around the OMC in an effort to reduce the amount of scattered light that could contaminate the cavity. After these changes, we noticed a significant improvement in DARM low frequency noise (Figure 21), although we do not yet know which of the two aforementioned improvements is responsible for this change. Investigating this would be quite useful, as it would provide some information regarding the HAM6 ISI table-to-OMC coupling mechanism to which we attribute the majority of this low frequency noise. It should also be noted that these HAM6 improvements also appeared to reduce the 90Hz peak that was unexplained by our current model for this noise mechanism.

Vacuum Tube Investigations

As an additional investigation of potential noise sources, we looked at a portion of the vacuum chamber that is enclosed on both sides by flexible bellows between HAM4 and HAM5. Due to this configuration, the

Figure 18: OMC length error readout during various ISI injections

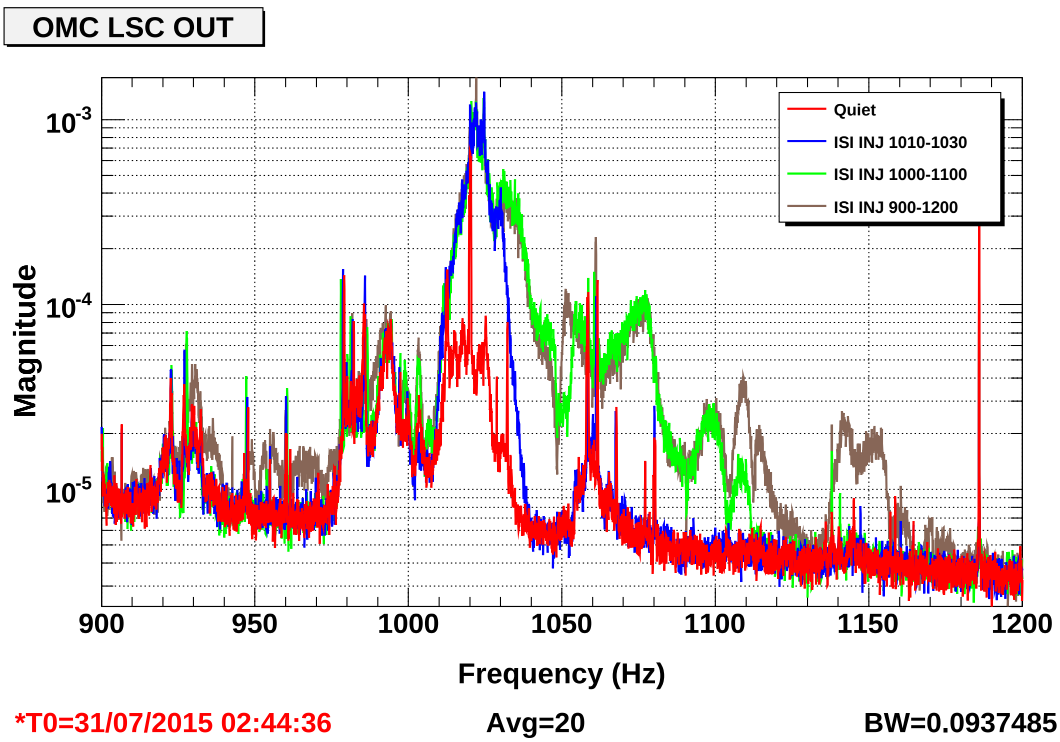


Figure 19: Linear Noise Budget Plot

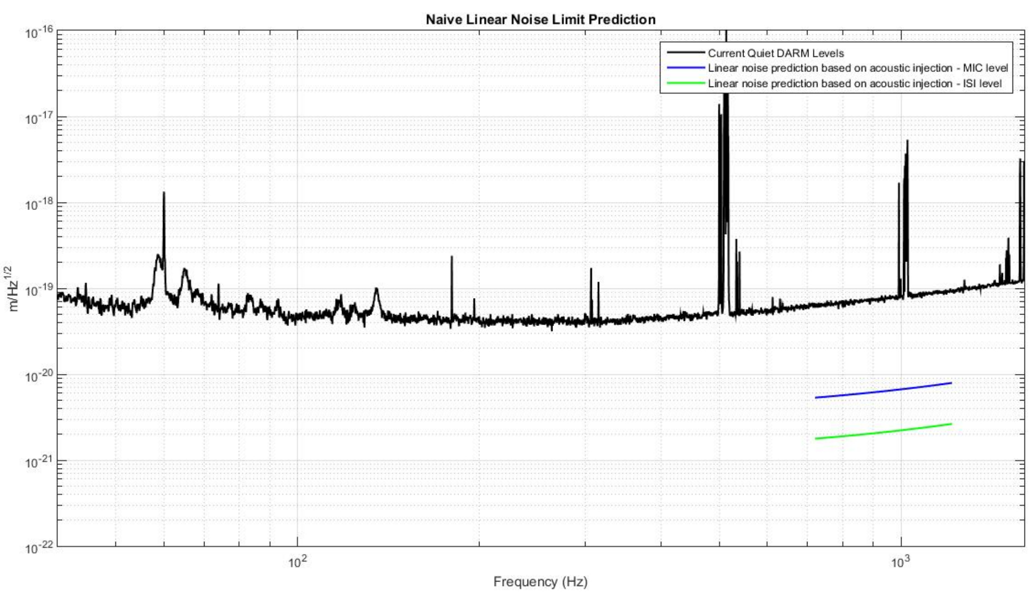


Figure 20: Non-Linear Noise Budget Plot

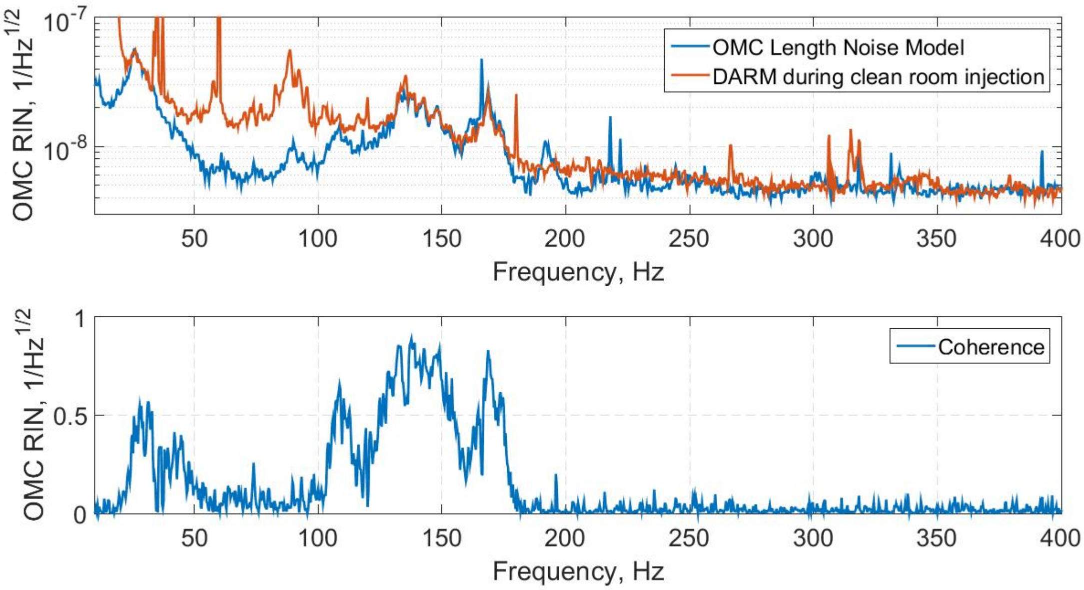


Figure 21: Comparison of low frequency DARM noise from clean room fan injections before and after the HAM6 internal improvements

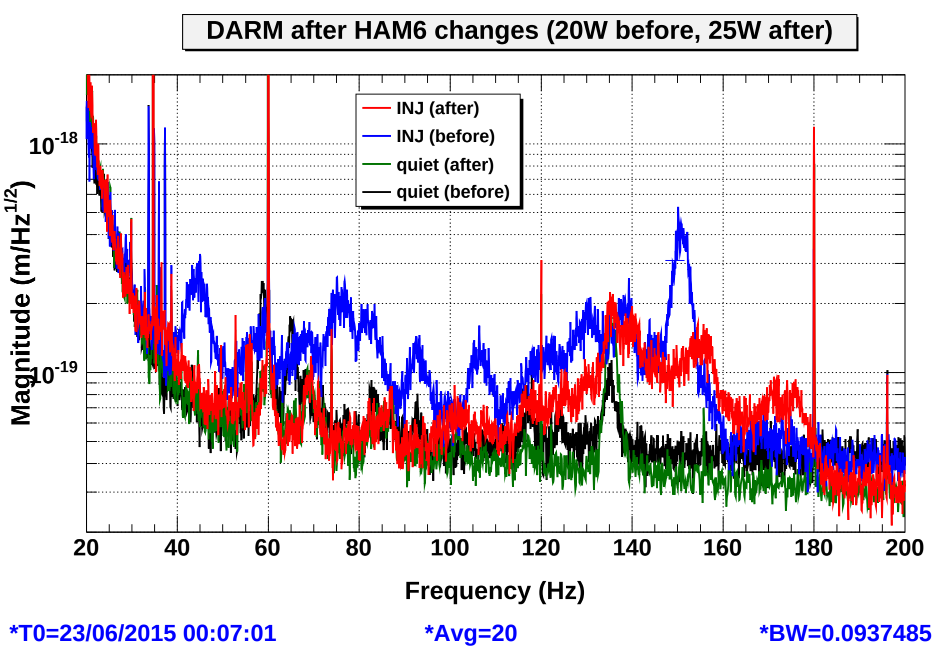
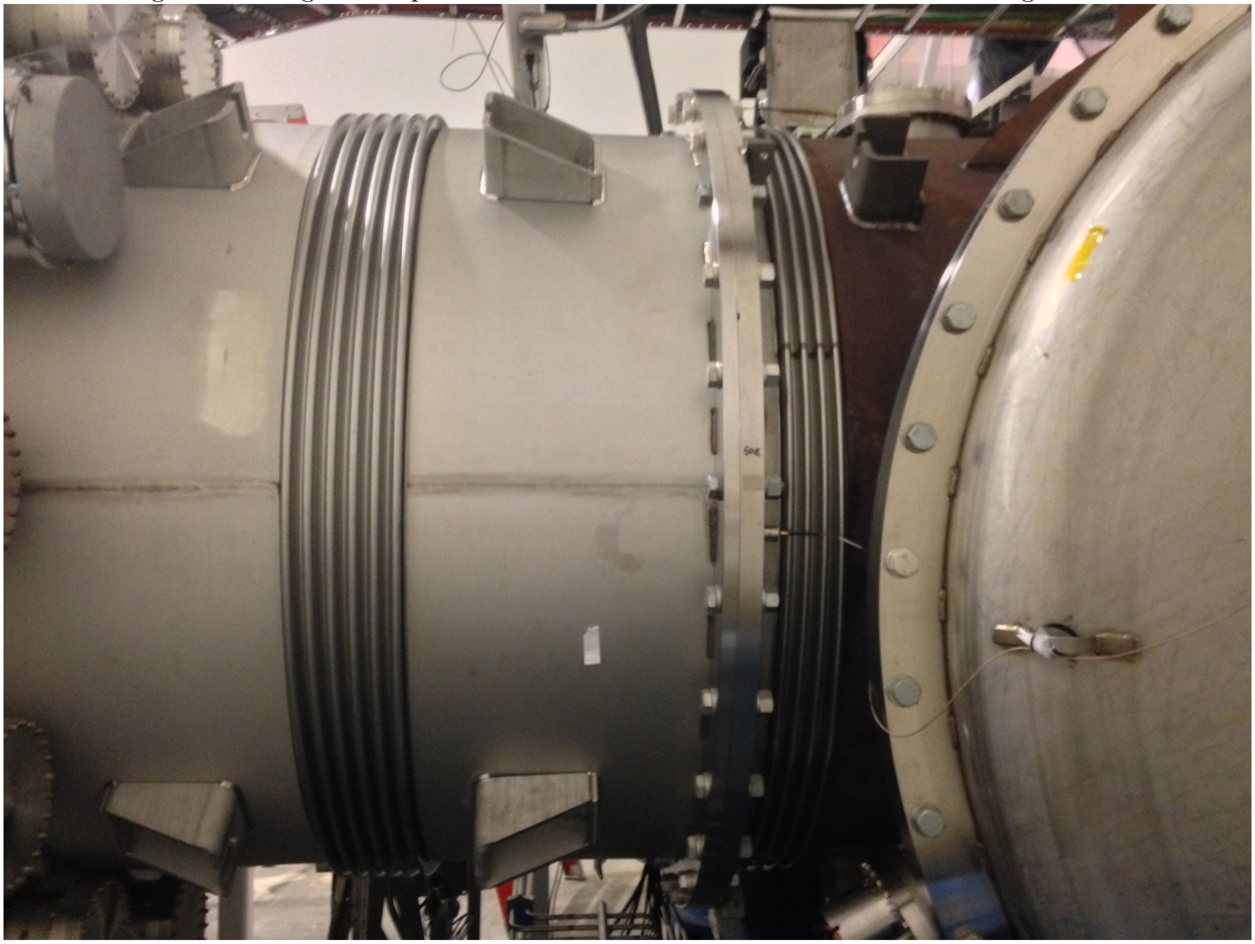


Figure 22: Image of the portion of the vacuum chamber wall and its enclosing bellows



portion of tube between the two bellows is especially "soft", or susceptible to movement. To see how prone this tube portion is to vibrating, we looked at its quality factor, Q, which is a measure of how well-damped this tube's vibrations will be when excited.
In order to determine this factor, we chose to look at the time constant of the tube's ringdown after being excited. In this case, our excitations came from gentle tapping on the tube, both in the +X and -Y directions, in order to see if there were different resonances for the different directions. [PSD for long. and trans. taps]

Before analyzing the recorded ringdown function, we used a simple butterworth bandpass filter to isolate the tube's main resonance at 77.2Hz. We found the Qs of several recorded ringdowns using a special MatLab function created by M. A. Hopcroft specially for finding the Q of a ringdown series [4]. Using these tools, we observed high Qs of roughly 1000, which were consistent between different ringdowns within an interval of $\pm$ 30. This very high Q suggests that this portion of the tube is very susceptible to being rung up by environmental vibrations.

Acoustic Injections

In response to these findings regarding the susceptibility of this section of the vacuum tube, we injected a line at 77Hz at about 400x and 200x background to try to observe any DARM response (Figs 28 and 29). We observed a broad, two-peaked response about 20x above background in DARM around the 77Hz resonance we observed previously (Fig 27). Assuming a linear system, this tube section's contribution to DARM

Figure 23: ASD of the accelerometer on the tube wall with and without injections

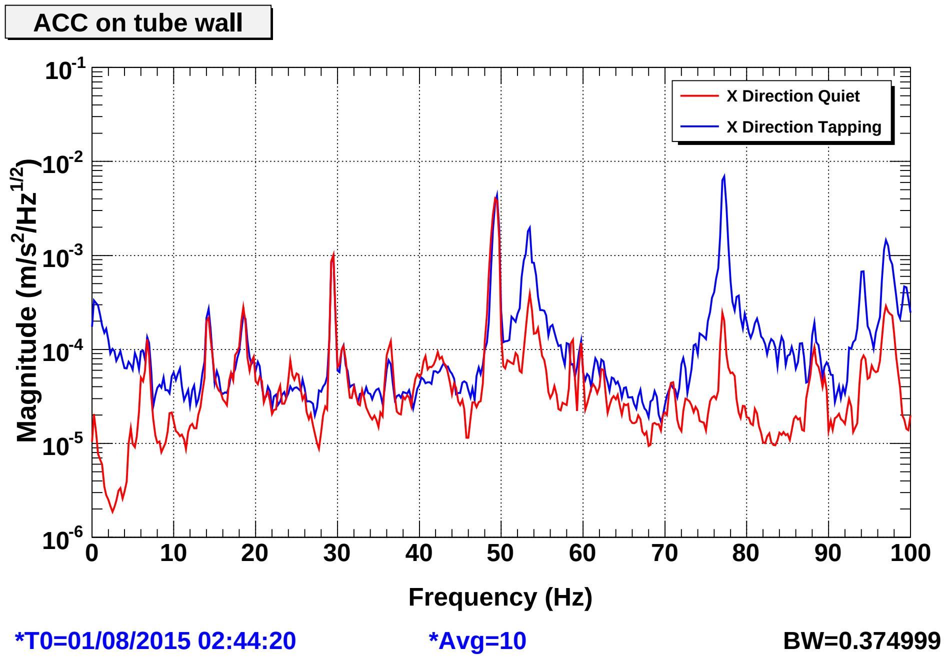


Figure 24: ASD of the accelerometer on the tube wall with and without injections

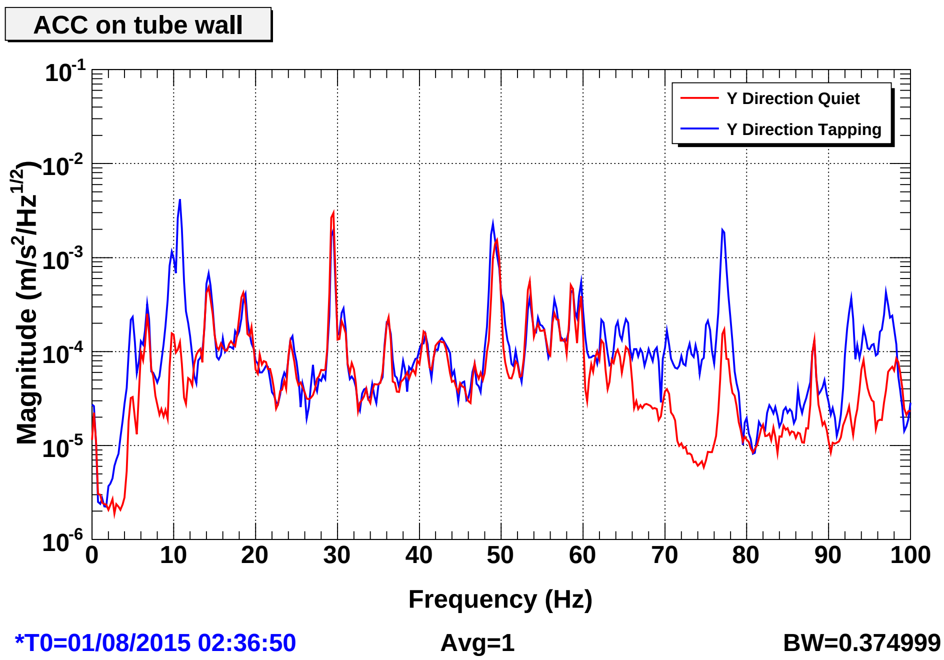


Figure 25: Time series of an example ringdown

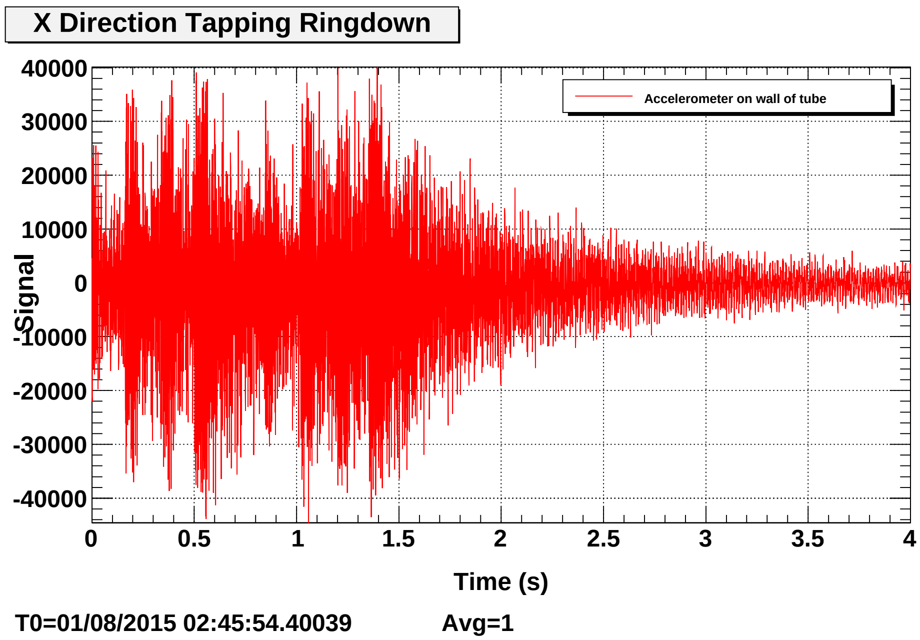


Figure 26: Ringdown data after bandpass filtering and model fit on top

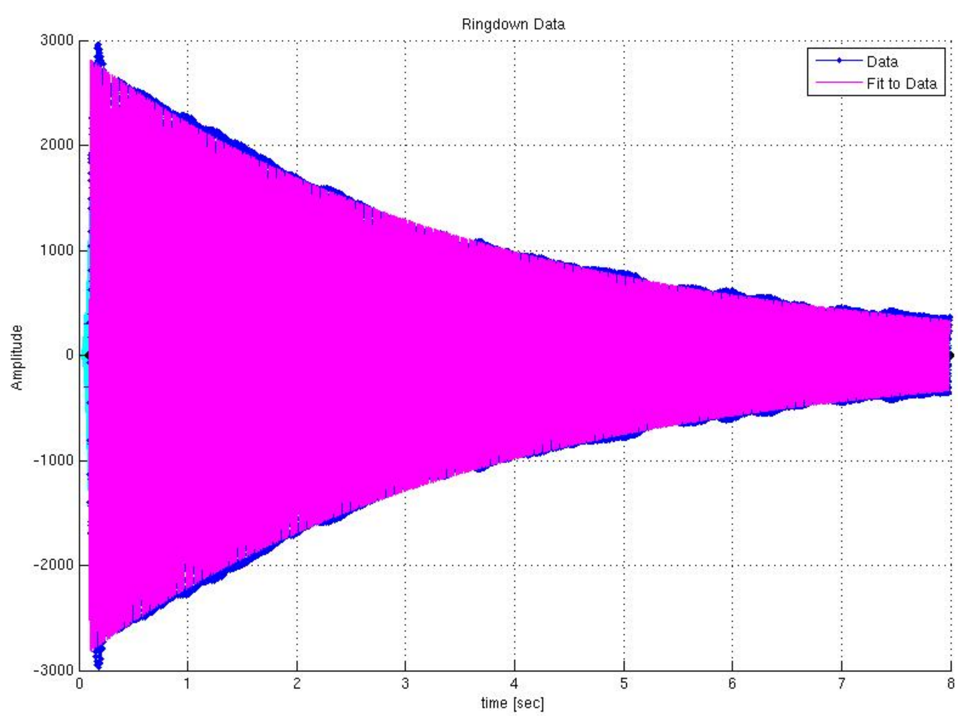
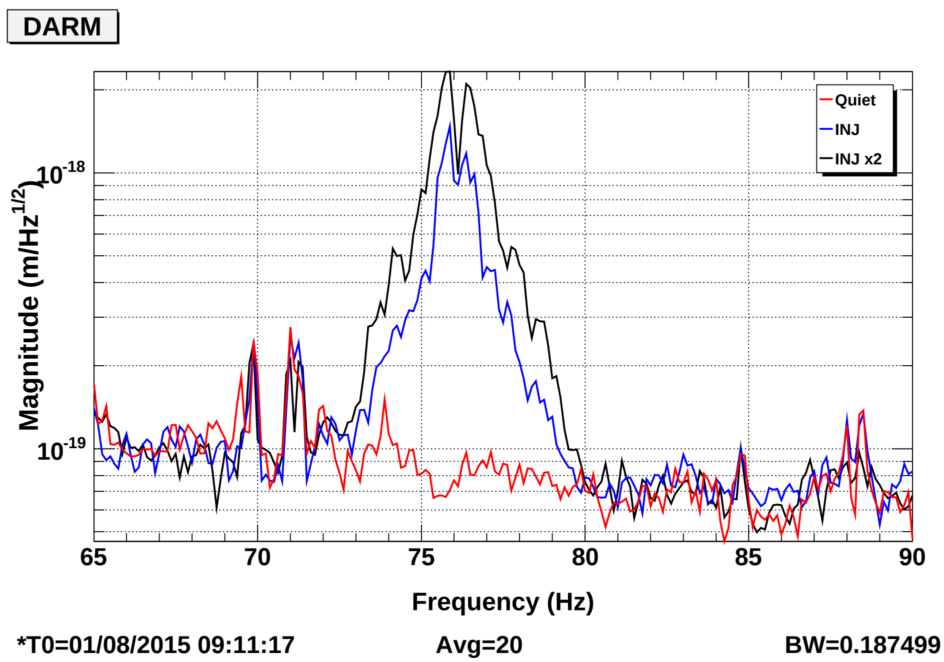


Figure 27: DARM during 77Hz tube injection



noise would be about 20x below current levels, however the two-peak form of the DARM response and the fact that it does not appear to scale linearly with increased injection magnitudes suggests this isn't the case.

Further Noise-Related 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 [9].

We did not notice any peaks in the 2400-4000Hz range where the aforementioned log showed high frequency wire resonances (Figure 32), although we only excited in this band to 20x background (Figure 33) 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 30). 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 28: Microphone between HAM5 and HAM6 during 77Hz tube injection

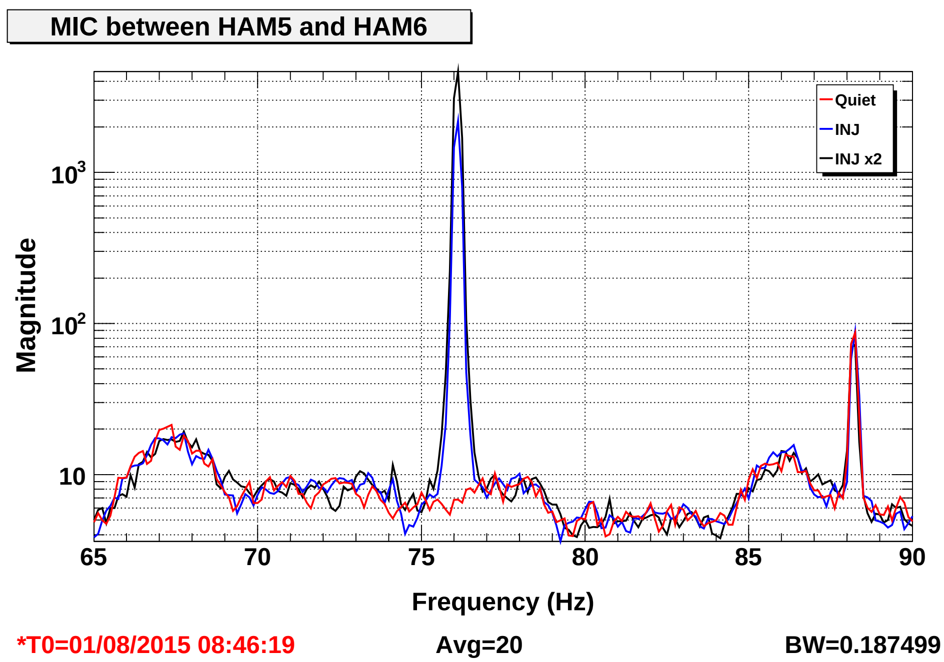


Figure 29: Accelerometer on the tube during 77Hz tube injection

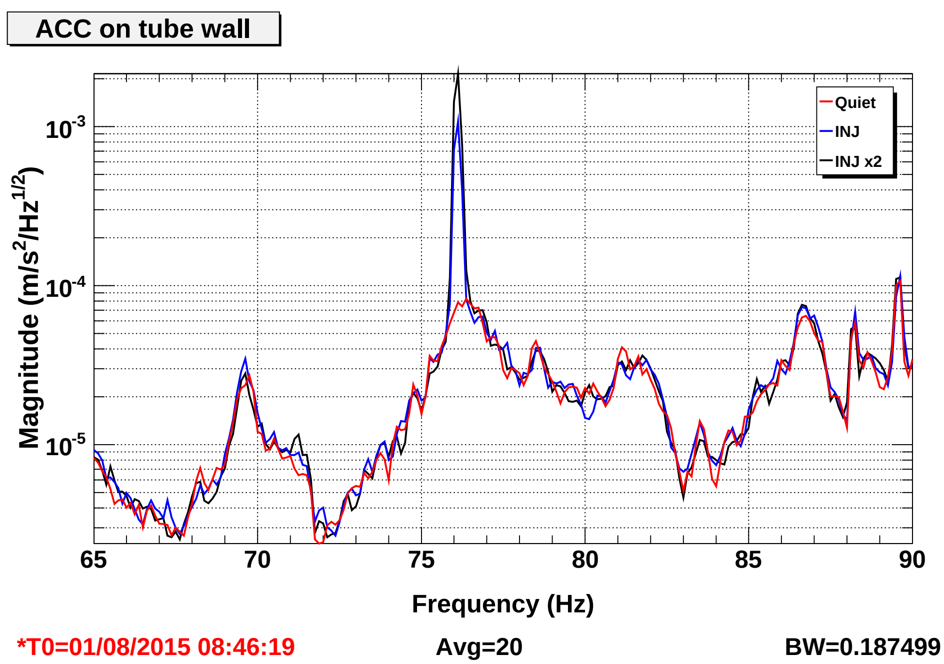


Figure 30: A closer look at the DARM signal observed during the various acoustic injections

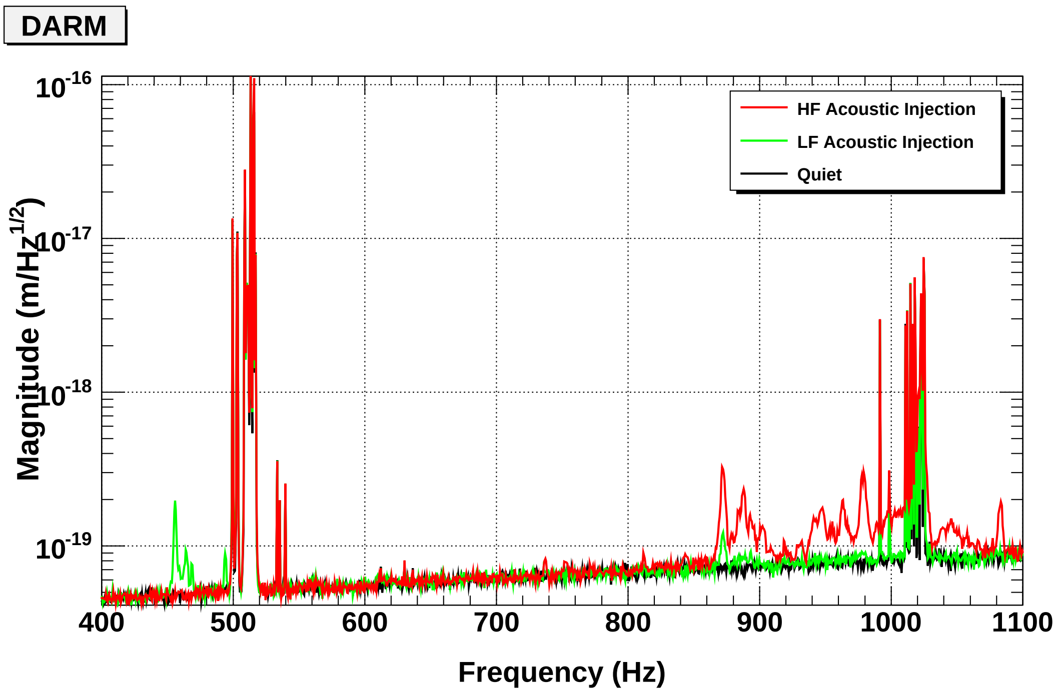


Figure 31: A closer look at the microphone signal observed during the various acoustic injections

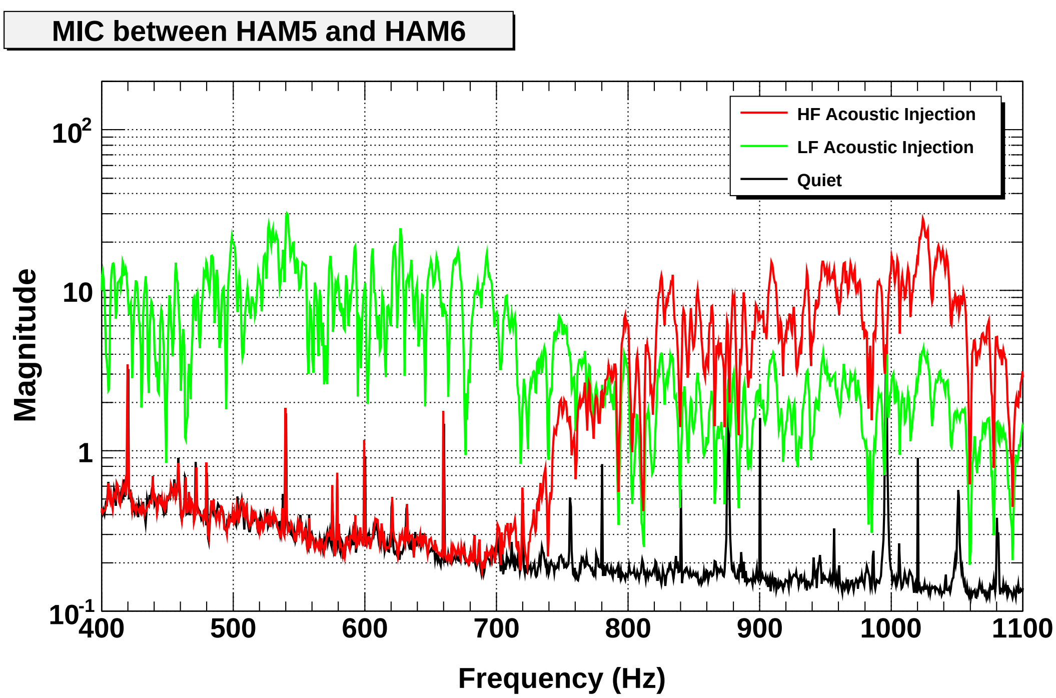


Figure 32: A more expanded look at the DARM signal observed during various acoustic injections

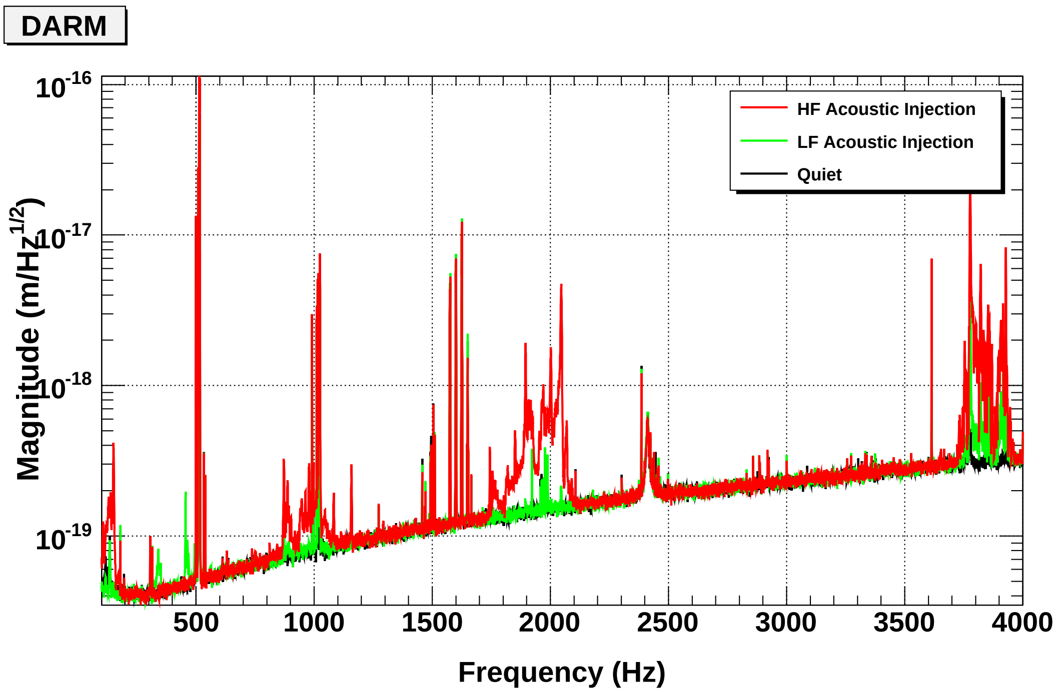
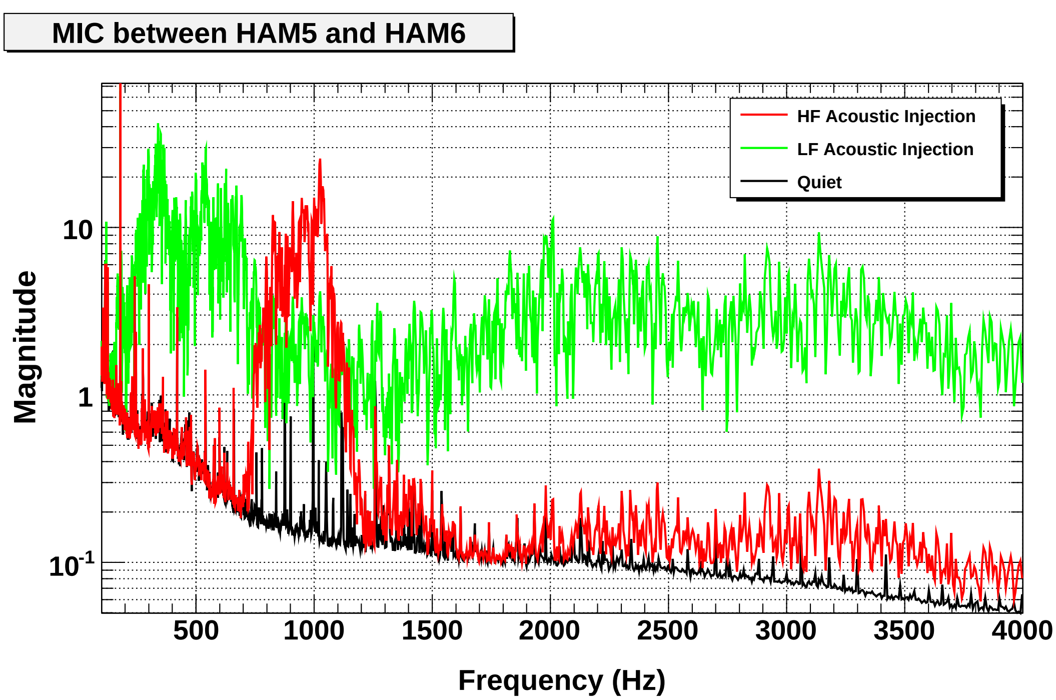


Figure 33: A more expanded look at the microphone signal observed during the various acoustic injections



New Questions

Now that we have a new, plausible theory describing our observed DARM noise, we must answer a set of new questions in the coming weeks. First and foremost, if this noise is to be in some way mitigated, we must find the mechanism by which the 1020Hz peak is seen in the OMC. It has been proven that the 1020Hz peak is the 17th harmonic of the 60Hz line, but we still need to know how this line could enter the OMC. [3]
We also need to learn more about the method by which our injected ISI noise is entering the OMC. Given the OMC's double pendulum mechanical isolation system, this kind of propagation from one element to another is unexpected at such high frequencies (due to the double pendulum's f^{-4} dropoff in its transfer function). As mentioned in a previous section, analysis of the reduction in low frequency noise from the HAM6 chamber internal improvements could provide some telling information on this topic.
Additionally, further reasearch should be done on the aforementioned 90Hz peak observed during HAM6 injections that is not adequately explained by the current working model for the proposed noise creating mechanism.

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Figure 34: Diagram of the LLO facility