SFP Progress Report 2

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Introduction

In the previous weeks of this program detailed in the previous progress report, we investigated scatter noise coupling mechanisms and sources near the output port of the Livingston LIGO Observatory interferometer. [1] Since that report, we have investigated these noise sources further. In addition, we created a noise budget using all of the noise sources we considered previously, naively assuming a linear system, and we investigated a specific part of the interferometer chamber that could present an additional source of noise.

Continued Investigations of Low Frequency Noise in DARM

As mentioned in the previous progress report [cite PR1], we applied an excitation to the ISI table in the HAM6 chamber over a relatively narrow frequency band, and we mentioned concerns that we may not have injected over a wide enough band, and the relevant injection bands may have been just above or below the band we injected originally. Since then, we have further investigated this possibility, injecting the HAM6 ISI table over a variety of different frequency bands.

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

First, we injected over the much broader interval between 700 and 1200Hz (Fig 2). 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 1). Notably, the vacuum pumps on HAM6 were running during the acquisition of all of this data, which created additional noise.
It was noticed during the 900-1200Hz injection (Fig 4) (which also created low frequency DARM noise (Fig 3)) that we observed corresponding noise in the output mode cleaner (OMC) length error noise readout (Fig 5).

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 3-5). 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 1: DARM readout during ISI 700-1200Hz injection

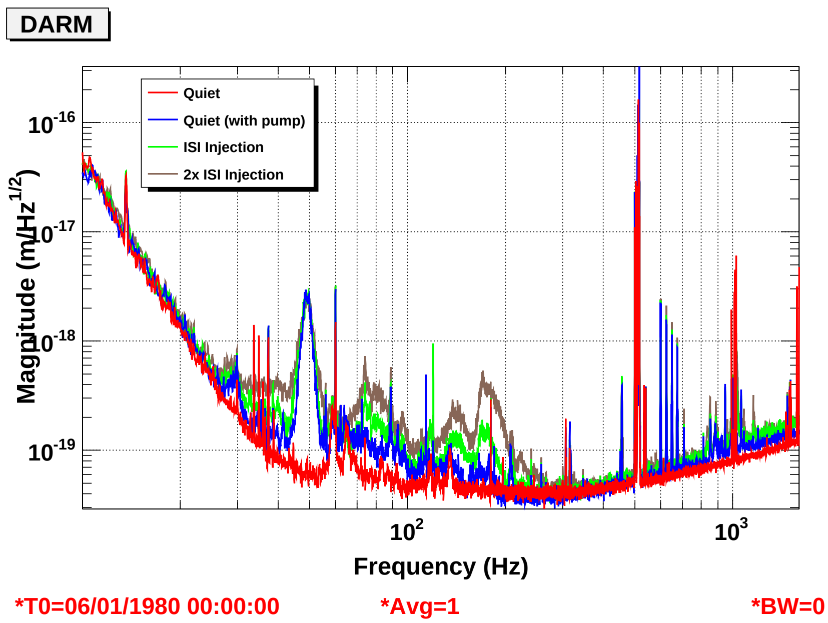


Figure 2: HAM6 ISI Table readout during ISI 700-1200Hz injection

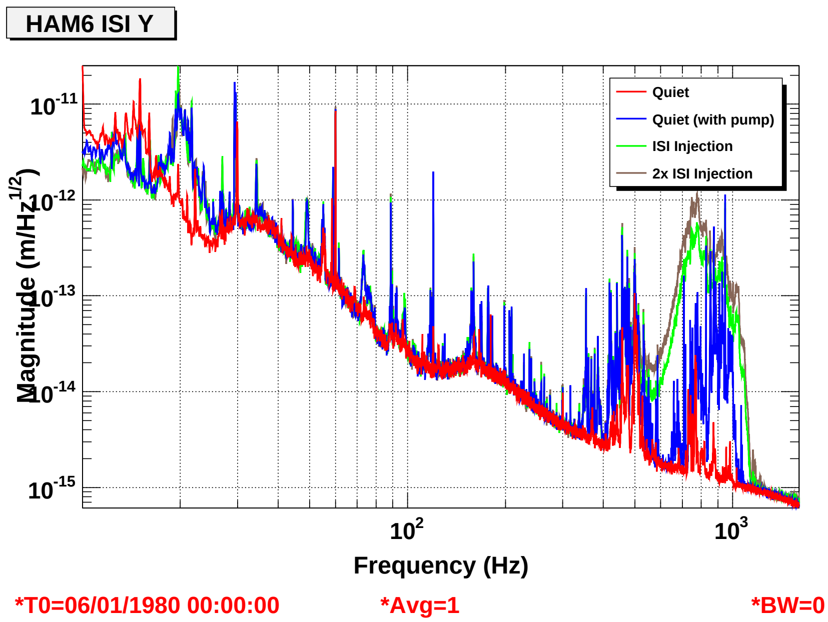


Figure 3: DARM readout during various ISI injections

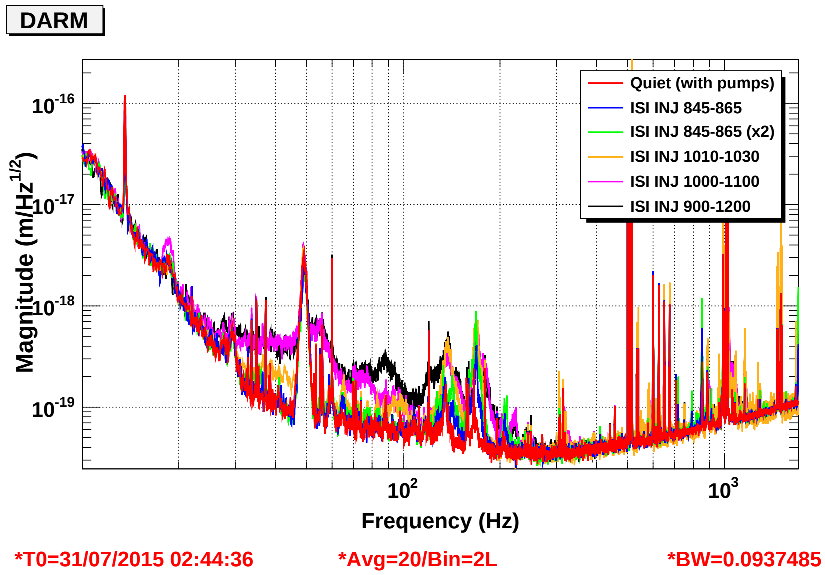


Figure 4: HAM6 ISI Table readout during various ISI injections

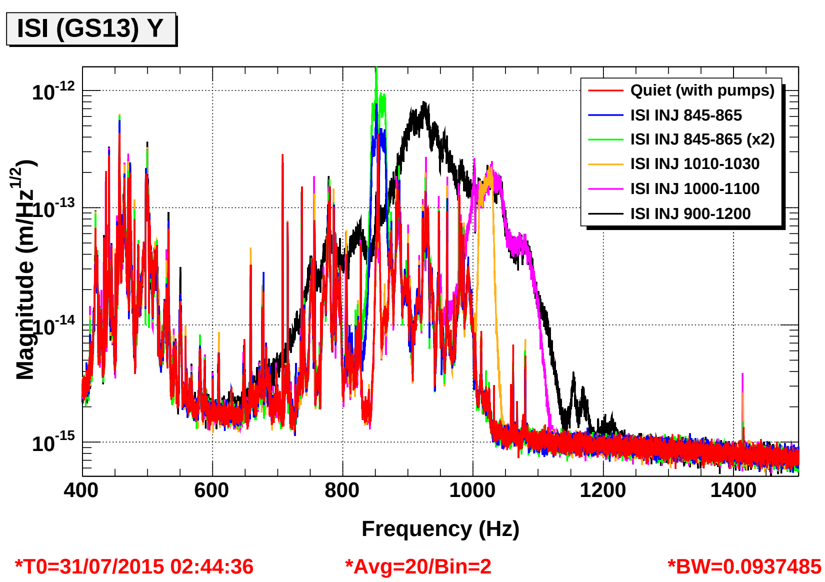
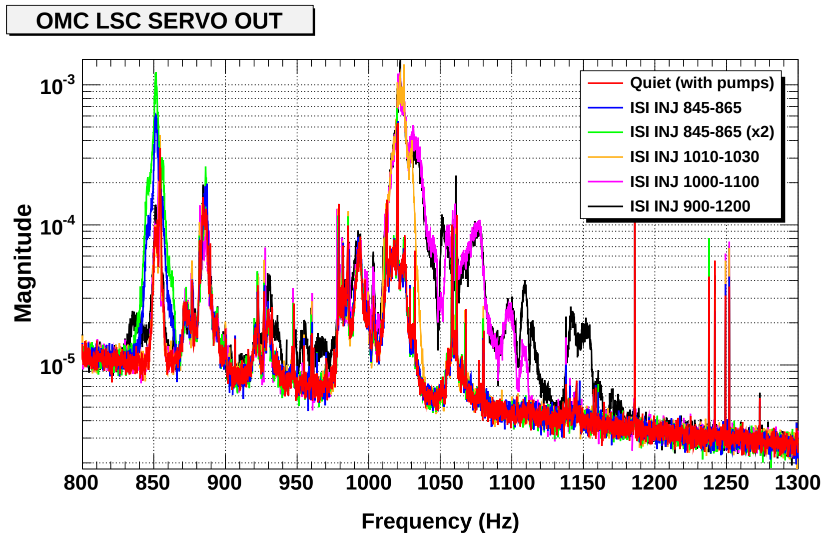


Figure 5: OMC length error readout during various ISI injections



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:

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

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

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 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 6-8).

Figure 6: DARM readout 1020Hz above 4800Hz

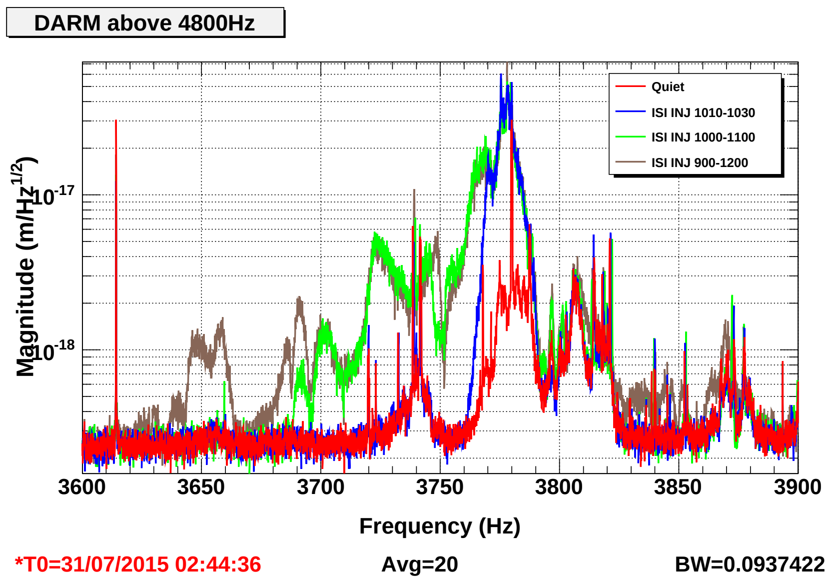


Figure 7: DARM readout 1020Hz below 4800Hz

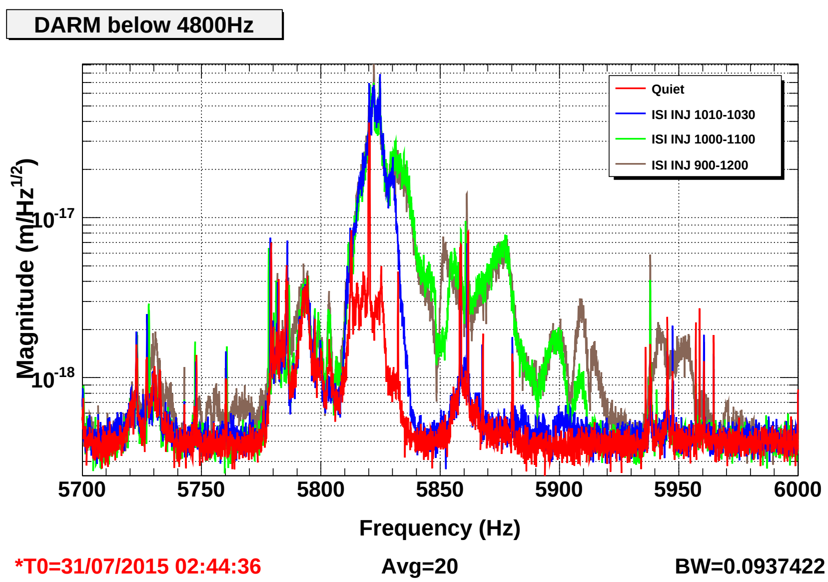
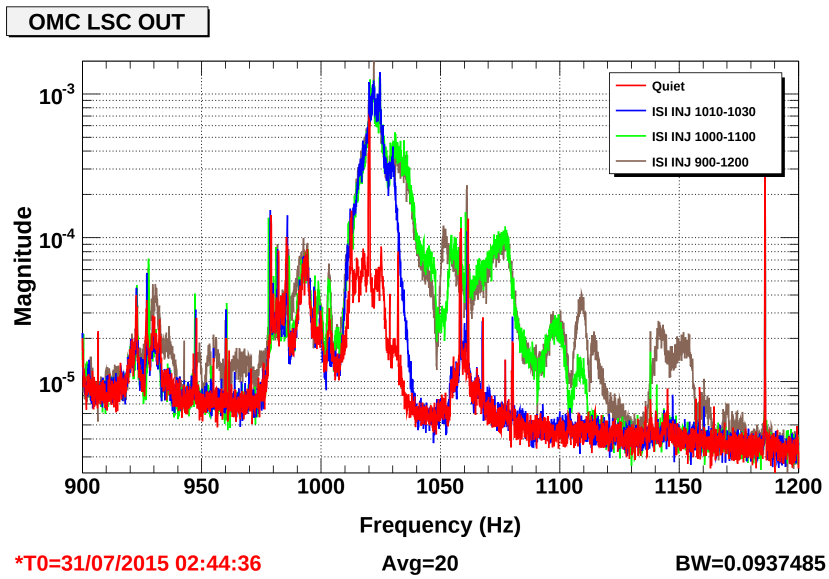


Figure 8: OMC length error readout during various ISI injections



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).

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.

Figure 9: Linear Noise Budget Plot

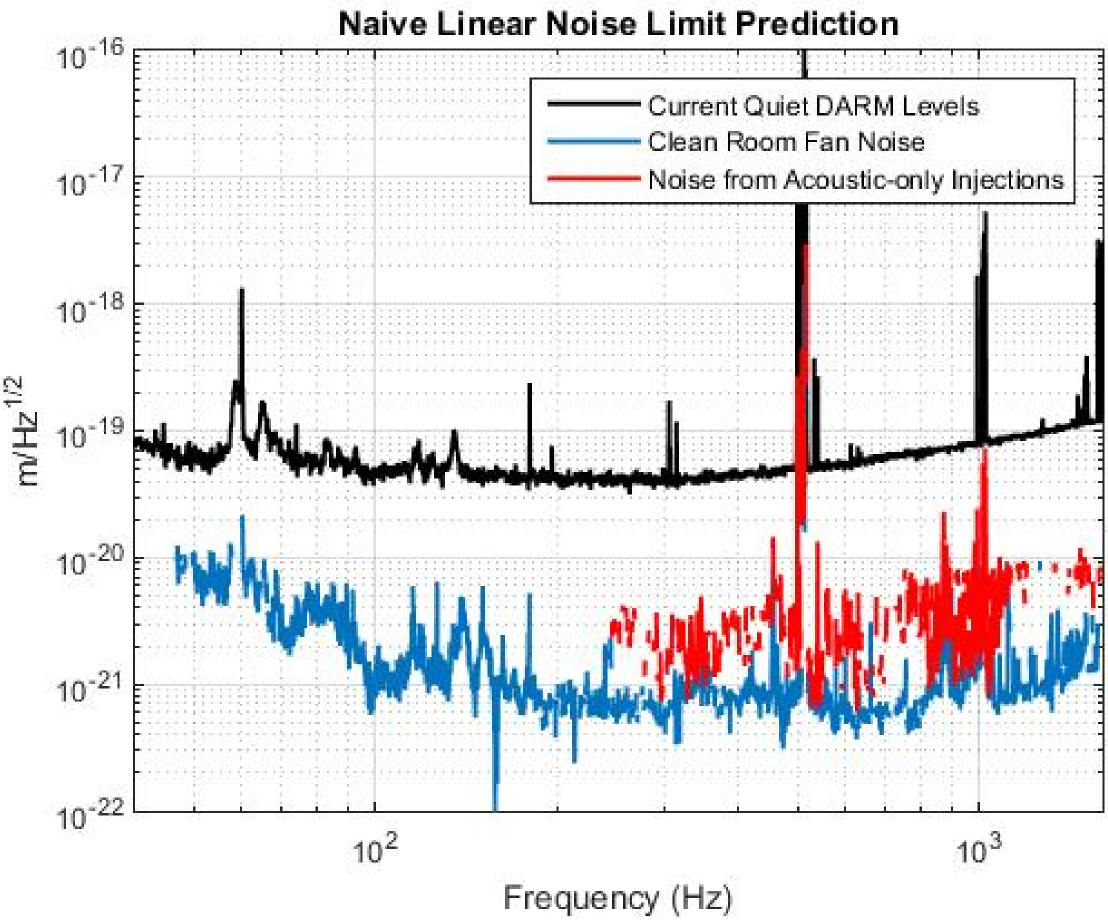
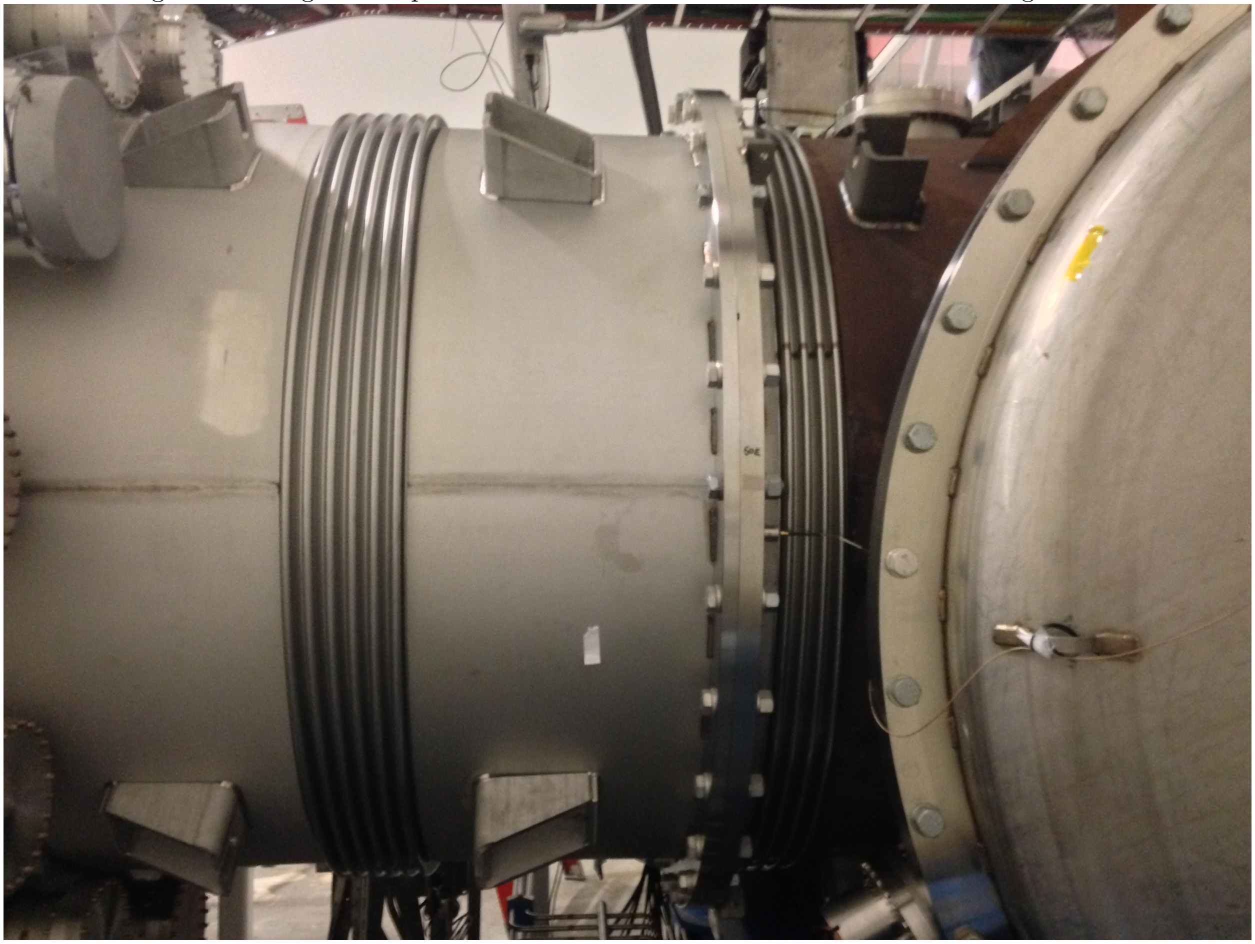


Figure 10: Image of the portion of the vacuum chamber wall and its enclosing bellows



Nonlinear Modeling

As we mentioned previously in this report, we hope to include the low frequency noise we observe in DARM in our noise budget plot. Due to this noise's fairly obvious non-linear behavior, however, we will need to take the specific down-conversion mechanism at work and create a more complex non-linear model to create a model with any significant level of accuracy.

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 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,

Figure 11: ASD of the accelerometer on the tube wall with and without injections

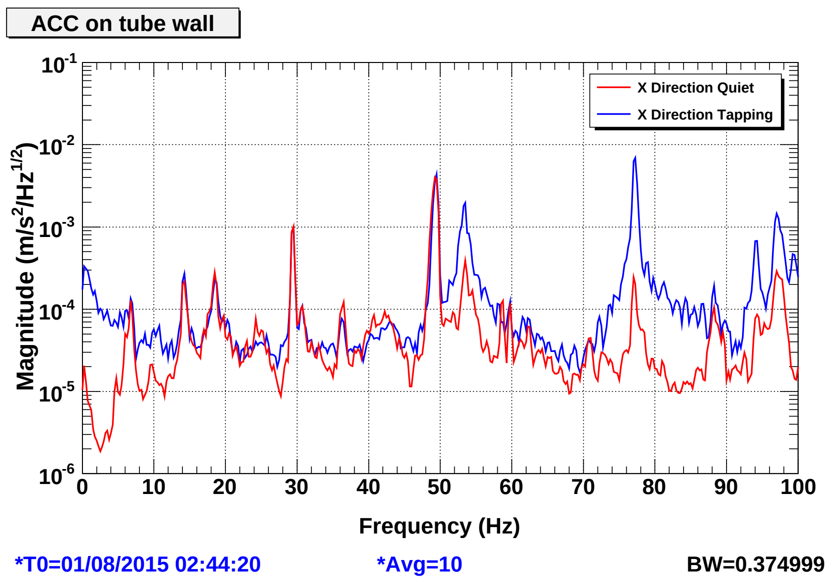


Figure 12: ASD of the accelerometer on the tube wall with and without injections

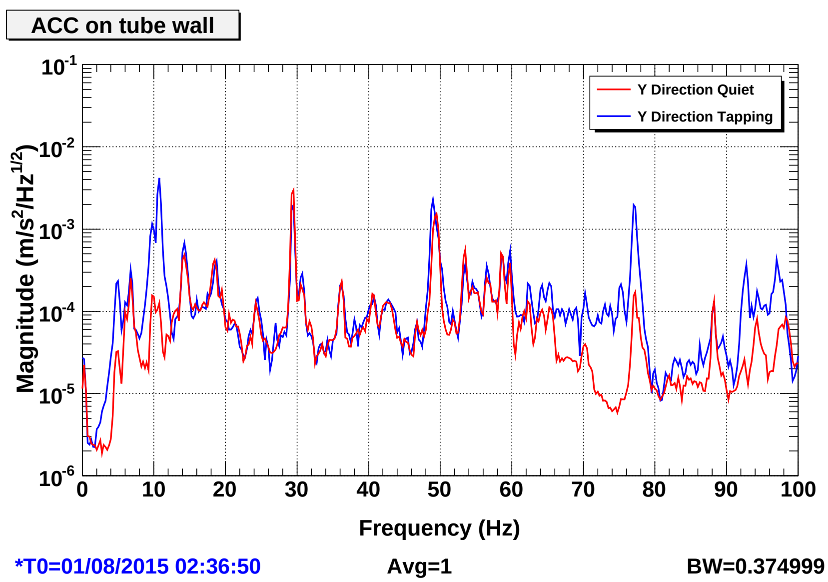
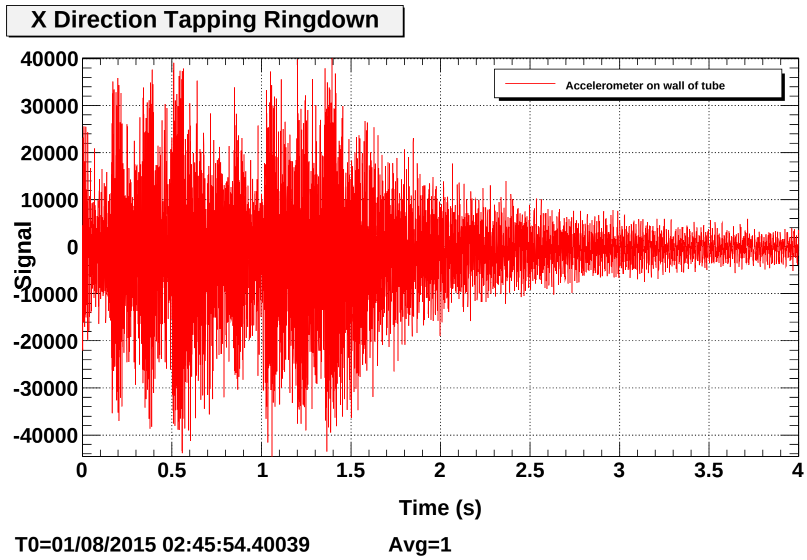


Figure 13: Time series of an example ringdown



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 16 and 17). We observed a broad, two-peaked response about 20x above background in DARM around the 77Hz resonance we observed previously (Fig 15). Assuming a linear system, this tube section's contribution to DARM 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.

Figure 14: Ringdown data after bandpass filtering and model fit on top

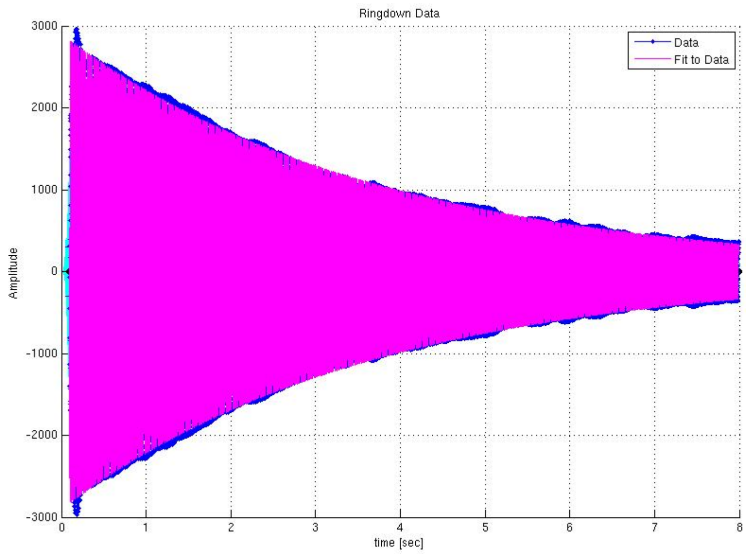


Figure 15: DARM during 77Hz tube injection

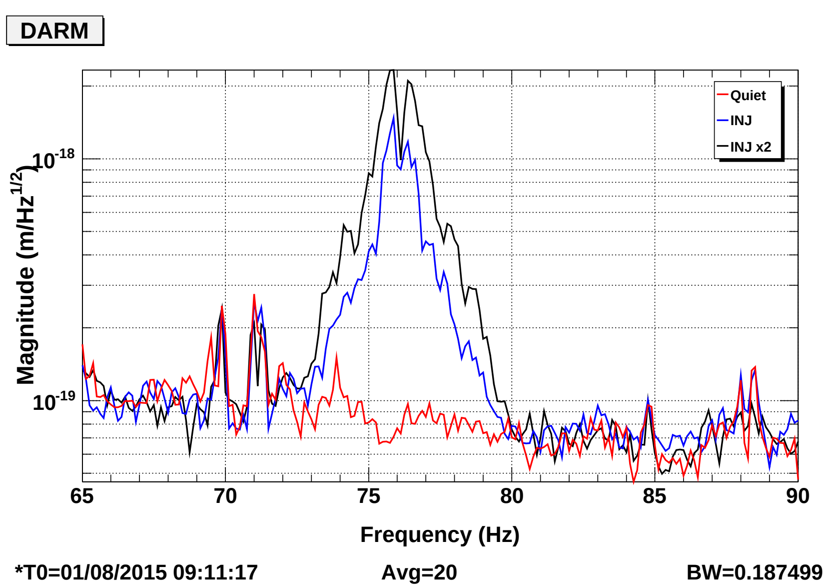


Figure 16: Microphone between HAM5 and HAM6 during 77Hz tube injection

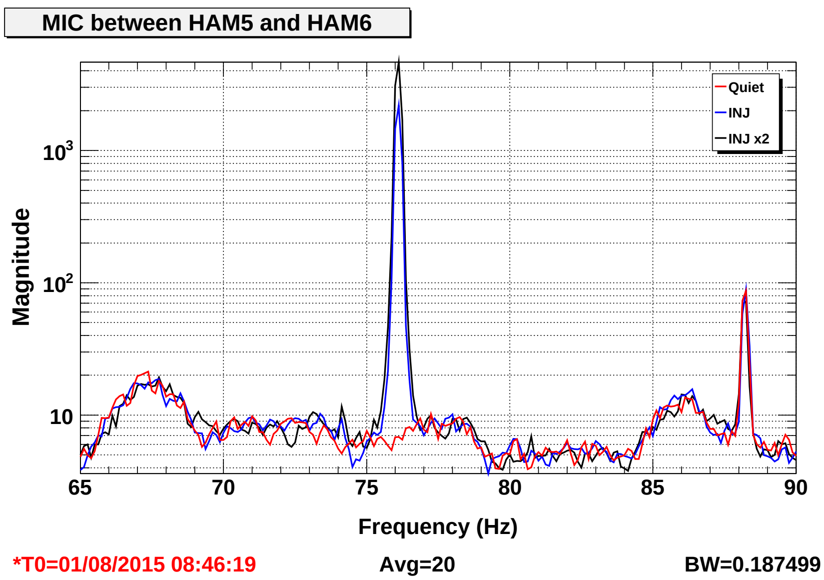
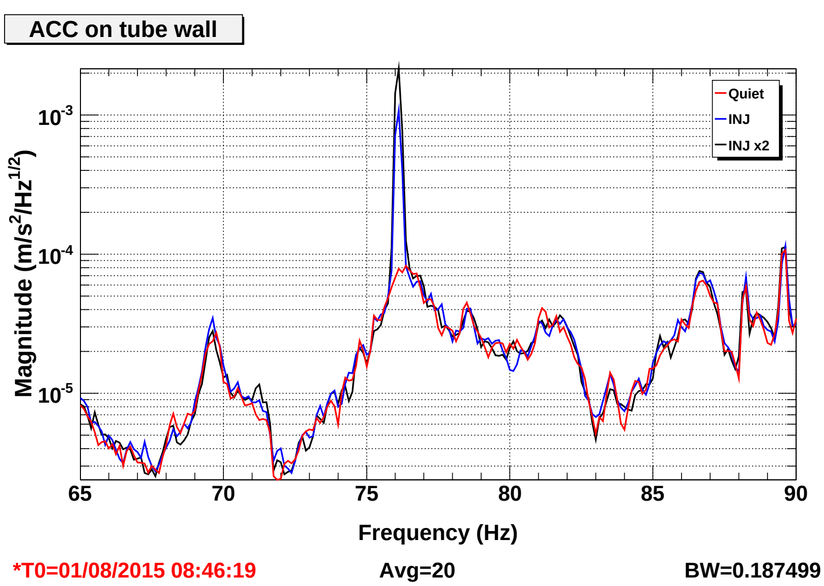


Figure 17: Accelerometer on the tube during 77Hz tube injection



References

[1] Trembath-Reichert, Stephen *SURF Progress Report 1 - Stephen Trembath-Reichert*. dcc.ligo.org N.p., 2015 Web. 5 Aug 2015

[2] Martynov, Denis. *downconversion from OMC length*. Livingston, LA: LIGO Livingston Observatory, 2015. Web. 7 July 2015.

[3] Smith, Joshua. *Tracking down 1020Hz line*. Livingston, LA: LIGO Livingston Observatory, 2015. Web. 7 July 2015.

[4] Hopcroft, M. 'Ringdown - File Exchange - MATLAB Central'. mathworks.com. N.p., 2010. Web. 5 Aug 2015