Installation of the Physical Environment Monitoring System For Advanced LIGO: SURF Final Report

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1. Abstract

LIGO uses an interferometer to try and detect gravitational waves. To detect these waves LIGO must be sensitive to as little as 10^-20m/sqrt(Hz). There are many environmental signals that can create noise. That noise can overwhelm signals on the gravitational wave channel. The installation of the sensors in the Physical Environment Monitoring system (PEM) will help the interferometer become more sensitive by disregarding signals from environmental sources and to also help identify excess noise that can then be decreased before advanced LIGO becomes fully operational. We installed all the sensors that were needed and helped to identify problem signals for the half interferometer test (HIFO-Y). We investigated the problem of cross talking between cables in Endevco boxes and using the sensors to look at propagation speeds. We continued to update PEM website with relevant information for each sensor, such as sample spectrum, calibration, and grid location.

1.1 Introduction

There are many different types of noise that can affect the gravitational wave channel. These noises can originate from the electronics that LIGO uses to control the interferometer. The noise can also be caused by vibrations from trucks driving by on the local highway. The noise isn't only caused by things located close to LIGO. A magnitude five earthquake anywhere in the world and the ocean tides can also interfere with the interferometer. PEM utilizes many different sensors to monitor signals from these different sources.

The PEM system monitors seismic motion using seismometers and accelerometers. There is one seismometer in the main building of LIGO, at the Mid-stations, in the middle of the desert, and in each of the end stations. These seismometers are strategically placed around important areas were the optical equipment is located. The accelerometers are located on every chamber and table that has optical equipment. They are also located on the beam tube at intermittent locations. It is important to monitor the optical equipment because the motion of the optics can create noise. There are many sources that are creating seismic activity at LIGO, including people moving, people working, cars, the wind, and seismic activity from the earth.

We also utilize magnetometers to monitor signals coming from the electronics used at LIGO and also external sources like power lines. These magnetometers are located in central locations in the optics and in the electronics area so they are able to accurately monitor the magnetic field. Last summer they found that the magnetic fields in LIGO were moving the test masses too much. PEM has begun to monitor these magnetic fields and find ways to reduce their effects on the test masses.

There are also microphones located around LIGO. These microphones monitor acoustical noise. The microphones are also located near important optical areas where sound can move the optics. [1]

1.2 Overview

For the first half of the summer we focused on the installation of all the sensors that will be used in advanced LIGO. We then continued to finish the PEM website. The last part of the summer we worked on the problem of resistivity of the accelerometers and cross talk. I will discuss our conclusions to these different aspects of the summer in the following sections.

2. Installation of Advance LIGO

The first part of the summer was focused on installing all the sensors that Advanced LIGO will be using. We started off by installing all of the accelerometers using the technique decided upon last summer. [2] This technique makes use of five minute epoxy and cling wrap to keep the accelerometers conductively isolated. The decisions on where to install the accelerometers were made depending on the importance of the optics in the chambers and tables. It was also determined based on which areas it was less likely to get knocked off or be in someone's way. We then cabled all of the accelerometers and confirmed that they were in the data acquisition system (DAQ).

To test that the accelerometers were working correctly we did tap tests on all of them. In the tap test we would bring up the channel corresponding to the accelerometer on DTT (a LIGO program). We would then bring up a power spectrum of that channel. We tapped an area close to the accelerometer and should be able to see a spike appear on the power spectrum. If there is a spike we knew that the accelerometer was working correctly. However, if there wasn't that could mean that the accelerometer was not completely cabled. We also needed to check the resistivity of the accelerometers. We used multimeters to check that the cling wrap was not breaking down and that the accelerometer was conductively isolated.

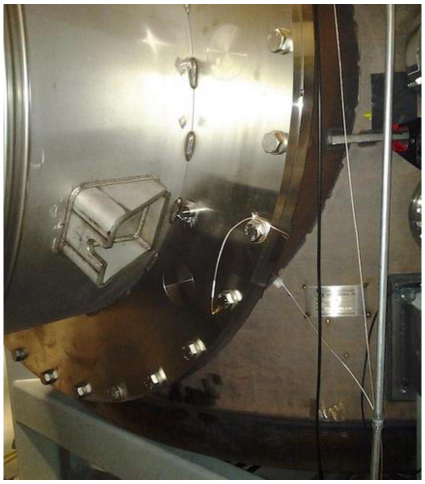

Figure 1: An Accelerometer fully mounted on a chamber

We also installed the magnetometers. We had to create a way for the magnetometers to attach to the racks without the magnetometer actually touching anything metal because metal distorts the magnetic fields. We solved this by using a PVC pipe. The magnetometers take measurements in three directions so we needed to make sure that the axis wouldn't change. To do this we cable tied the magnetometers to the PVC pipe and then attached the pipe to the racks. We found that this was bumped too easily and the magnetometer wouldn't return to its original location. We ended up cable tying the magnetometer to the PVC pipe nine times. This added enough stability that if bumped the magnetometer would rotate back to its original position.

The magnetometers are created to be installed vertically, but that wouldn't work for our situation. We needed the magnetometers to be horizontal. This meant we needed to re-label the axis on the magnetometer itself and on the power supply box to make sure that there was no confusion on what measurements it's actually making.

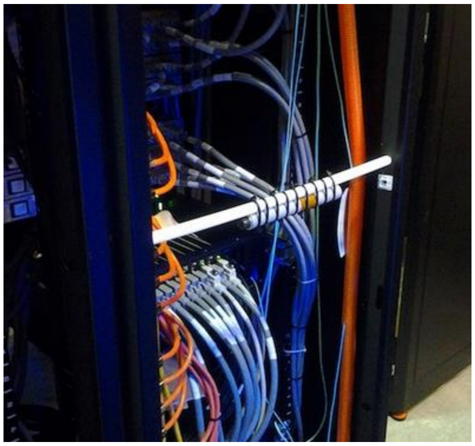

Figure 2: An Installed Magnetometer

We have installed all of the microphones that will be used in Advanced LIGO. The microphones needed to be suspended from the area they are located. Some microphones are hanging from a railing nearby; others are connected to the end of a metal rod which is then clamped to the area where it needed to be located. The microphones on the metal rods also have magnetometers attached to them.

We also did tap tests for the microphones. We selected the channel on DTT and created a noise to see if there was a spike on the power spectrum. If there was then we knew that the microphone was working correctly and was cabled.

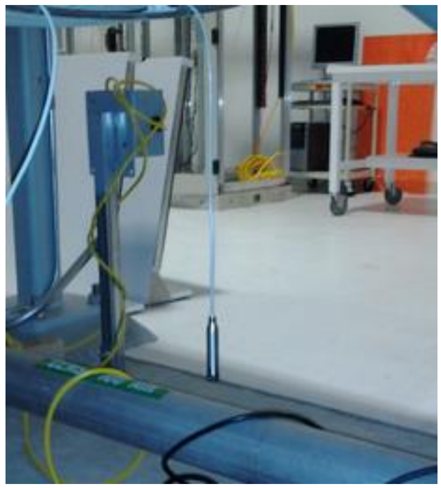

Figure 3: An Installed Microphone

2.1 Calibration

We began to calibrate the different sensors that are in LIGO. To calibrate the accelerometers we took an extra accelerometer and set it up on the seismometer. We then took a power spectrum of the two sensors. We put in the factory calibration of the two sensors and the manually changed the accelerometer’s calibration until the two power spectrums were very similar. With this calibrated accelerometer we then set it up next to another accelerometer and compared the power spectrums of the two. We put in the factory calibration of the un-calibrated accelerometer and the actual calibration of the second one. We then manually changed the calibration of the first accelerometer until the two power spectrums are the same for both the accelerometers. We continued to do this with all of the accelerometers and then put the new calibrations up onto the website.

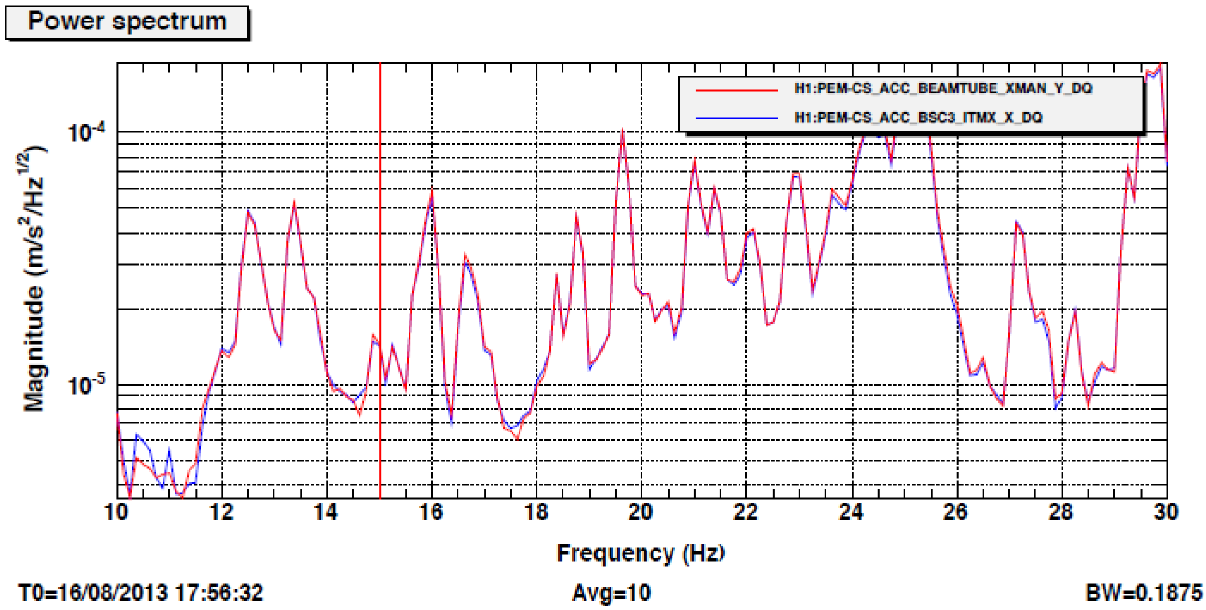

Figure 4: A correctly calibrated accelerometer

We also calibrated the microphones. For this we used a piston and took a time series of the piston attached to the microphone. We then looked at the graph and found the difference between two peaks. We divided the difference by 1.64 which is a factor from the piston. We took the inverse of that number and that gave us our new calibration which we then put up onto the PEM Website.

2.2 Accelerometer Resistivity

We began to notice that some of the accelerometers were no longer conductively isolated. They were now reading about 40Ω. We thought that the cling wrap which would keep the accelerometers conductively isolated was breaking down. We remounted the accelerometers and checked their resistivity right after. We continued to check the resistivity and a couple of accelerometers showed that there was resistance. We started to test different methods of mounting the accelerometers because we believed that the cling wrap was breaking down. However, we started to realize that the accelerometers that were showing a small resistance were the ones that we had cabled all of the way. We unplugged the accelerometers from their cables and checked the resistivity again and found that the resistivity overloaded which is what we wanted. We decided that the current was fine and we didn't need to change our mounting set ups.

3. PEM Website

Last summer a website was created for the PEM system. The website has a map of LIGO Hanford and also of LIGO Livingston. This map includes all of the sensors that will be used in advanced LIGO. The map is interactive and when a person clicks on a sensor it brings up a page with details on that specific sensor. Each sensor page includes the calibration factor, the sample rate, sample spectrum, the location, the date tested, a picture, and the date calibrated.

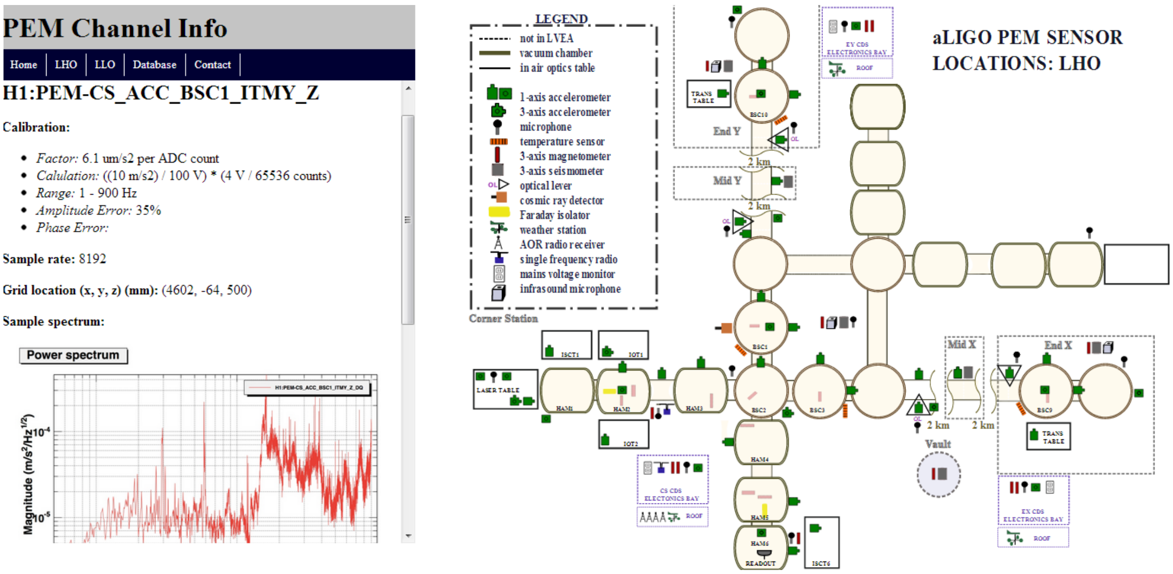

Figure 5: View of the website

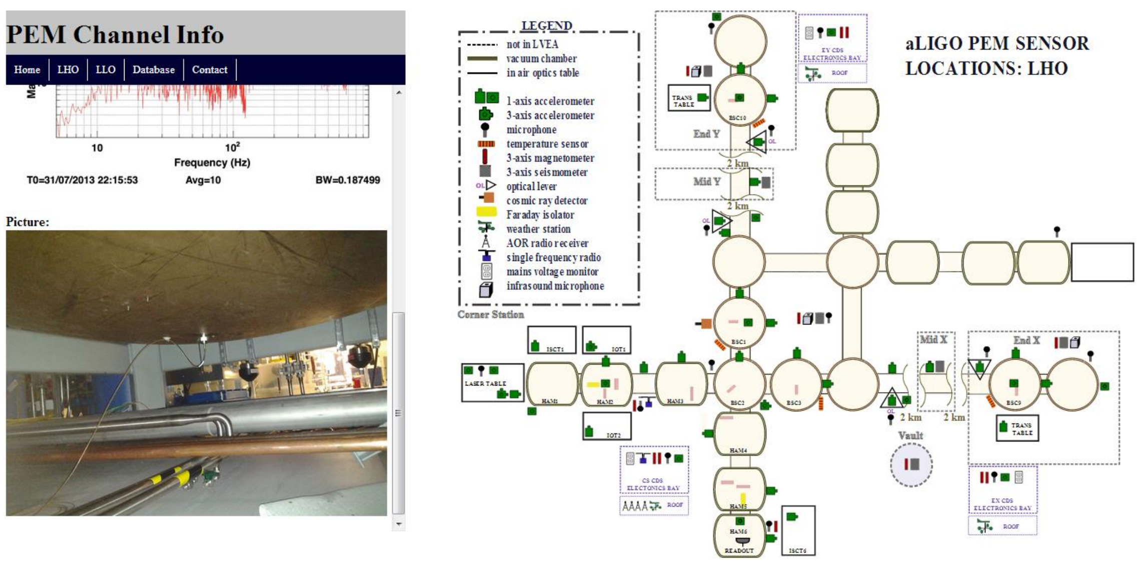

Figure 6: Another View of the Website

3.1 Determining locations of sensors

One major project relating to the website was determining a way to find the locations of the sensors. The locations are important because they help to calculate propagation speeds. With the locations we are able to find the speed and direction of a signal being detected by LIGO. This can also help us to determine the source of the signal which can help locate problem noises or give a general direction.

To find these locations we used two methods. The first was trilateration. We used the equation $r_1^2 = x^2 + y^2 + z^2$ [3] and created a program that was linked to an Excel spread sheet. For this approach to work we needed to know the X and Y coordinate for two monuments (usually a brass circle or an X on the ground). [4] We also needed to know the distance from the sensor to each of those monuments. That meant we needed a straight line path for this approach to work. We ran into some problems for this approach. The monuments located at LIGO were scarce and badly labeled which meant we had to create our own monuments. Every time we created a monument we created error. For some sensors we had to create multiple monuments each bringing with it more error. To alleviate this problem we started trying to only use official monuments and when possible using the beam line as a marker.

We also used the right angle approximation. This consisted of making a grid using right angles to compare a sensors distance to one monument. This was a superior method when in smaller distances. It only required one monument which decreased the error. It was also easier only having to be close to one monument rather than two. This method failed at larger distances, however. Anything greater than five meters became useless because of human error. We decided to use this approach only if the distance between the monument and the sensor was less than five meters.

4. Cross Talk Studies

During the half interferometer test we saw a signal coming from the Y end station. It was on two channels in that area. One was on an optical table and the other was on the optical lever. We weren't able to see the signal on the seismometer in that area. We weren't sure what could be creating this signal that wasn't showing up on the floor sensors. We investigated and found out that those sensors weren't plugged in. The only logical reason behind those signals was that another channel's signal was leaking into that channel, otherwise known as cross talk. Each accelerometer is cabled through two boxes. The first box is an Endevo box and that box powers the accelerometer and amplifies the signal. This signal then goes through an anti-aliasing chassis which then goes through to the DAQ system. We began to look at where the cross talk was taking place and at whether it was important.

4.1 Endevco Box at normal signals

One of the first places we looked for cross talk was in the Endevco boxes. The Endevcos are responsible for amplifying the signal and powering the accelerometers. For these experiments we found three channels next to each other. We would take a power spectrum for the three channels and would make a reference trace of the cable that would be unplugged. We then unplugged the cable and the middle and plotted the new power spectrums and also the coherence between the two channels and the unplugged one.

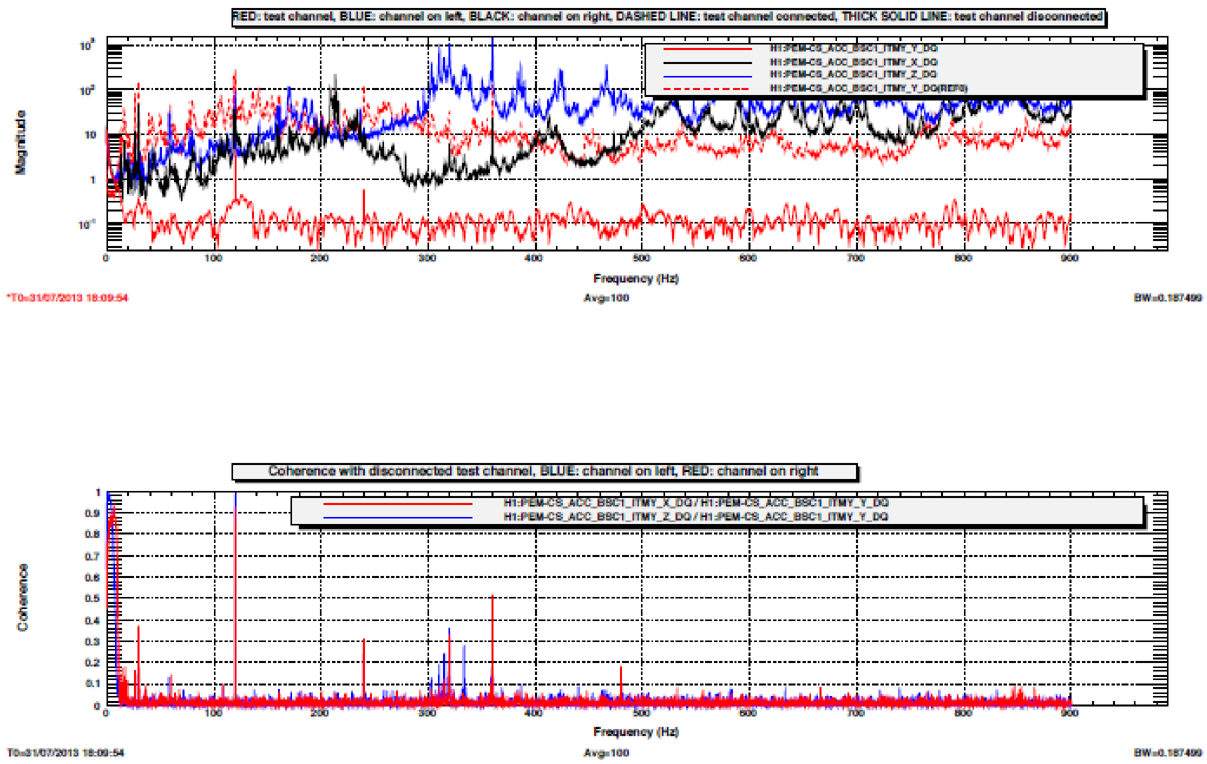

Figure 7: Endevco Signals at normal signals.

We did this for all of the PEM channels that were connected in the Endevco boxes. When we looked at the data we found that on all of the PEM channels there wasn't any significant coherence between the unplugged channels and the channels next to them. The only coherence we could see was at the 60Hz harmonics that come from the electronics. This was good because this is what the accelerometers are more likely to read on a daily bases.

4.2 Endevco Box with an injected signal

We then decided to see how the cross talk was affected if we injected a large signal. For this test we had a shaker set up with an accelerometer installed on it. We would then increase the shaker until just before saturation. We would inject this signal into the middle channel of three consecutive channels and take the power spectrum. We looked to see if there was a peak in the neighboring channels and also at what magnitude these peaks were happening at.

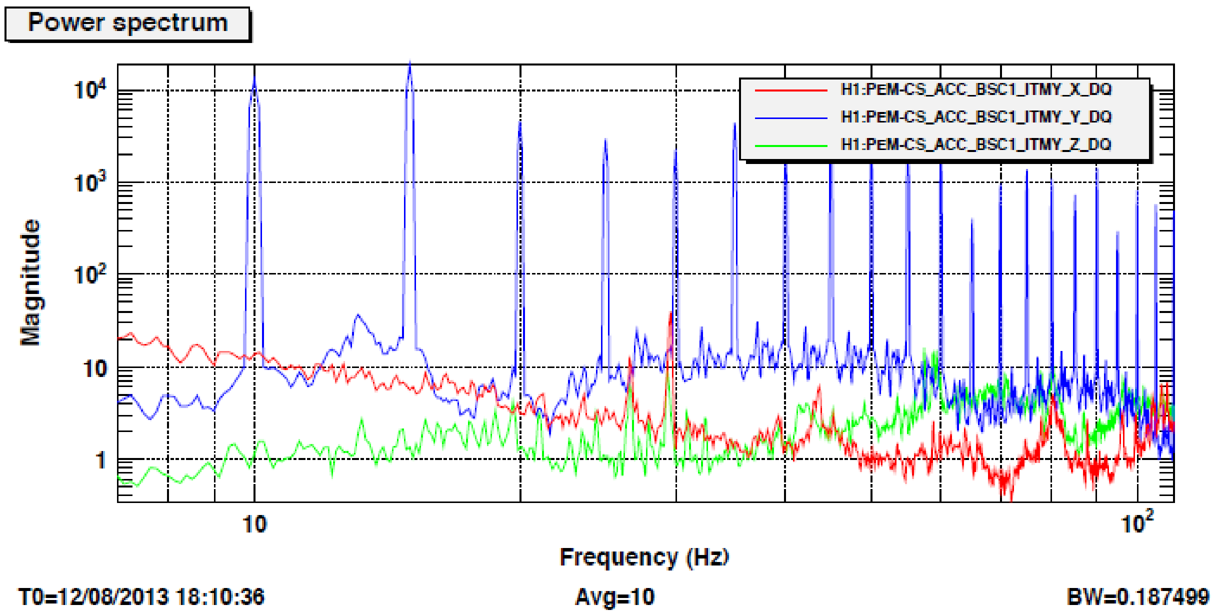

Figure 8: Power Spectrum of three channels with the middle one unplugged at saturation

After we did this test we would then run it again at ten times saturation to see if we were able to see cross talk at that point. This is important because the more saturation it takes to see the cross talk the better the channel in that box is.

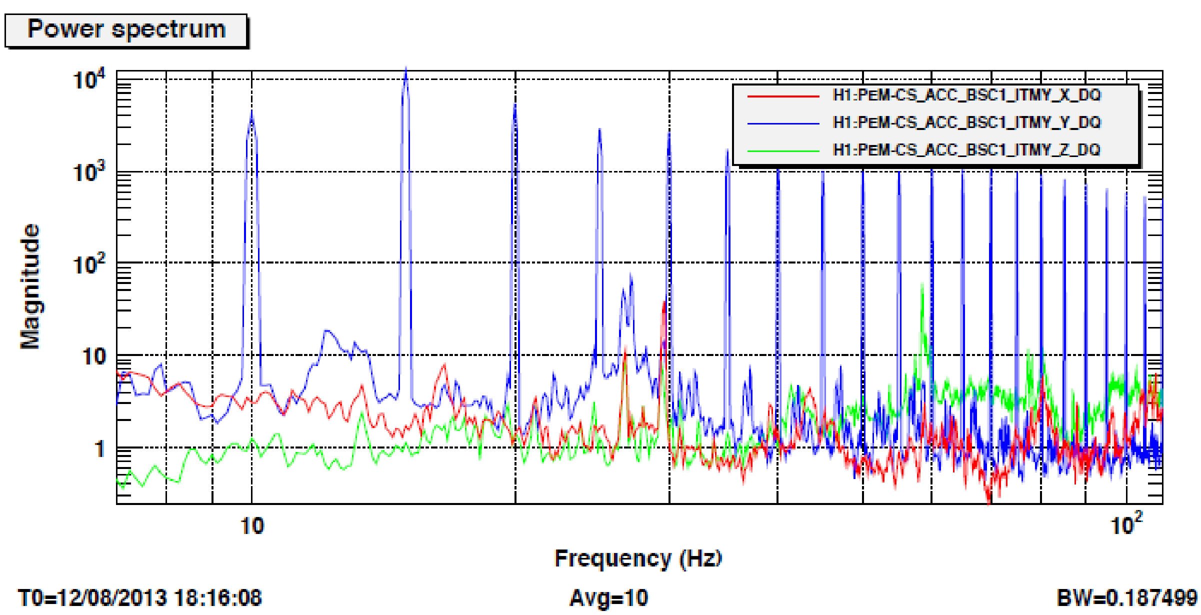

Figure 9: Power Spectrum of same three channels with middle one unplugged at 10x saturation

We did this experiment for all of the channels that had PEM channels connected into them. When looking at the data we were looking at the 10 HZ peaks. Most of the channels gave power spectrums like the ones above. The normal power spectrum of a channel without any cross talk should be four orders of magnitude greater than the neighboring signals. Anything over three orders of magnitude would be deemed fine.

Channel	Orders of magnitude of attenuation of cross talk	Channel	Orders of magnitude of attenuation of cross talk
Endevco 1 Channel 1	4	Endevco 1 Channel 9	3
Endevco 1 Channel 2	3	Endevco 1 Channel 10	3
Endevco 1 Channel 3	2.5	Endevco 1 Channel 11	2.5
Endevco 1 Channel 4	2.5	Endevco 1 Channel 12	3
Endevco 1 Channel 5	4	Endevco 1 Channel 13	3.5
Endevco 1 Channel 6	4	Endevco 1 Channel 14	4
Endevco 1 Channel 7	2	Endevco 1 Channel 15	4
Endevco 1 Channel 8	2	Endevco 1 Channel 16	4

Figure 10: Cross talk attenuation for Endevco 1

Channel	Orders of magnitude of attenuation of cross talk	Channel	Orders of magnitude of attenuation of cross talk
Endevco 3 Channel 1	2.5	Endevco 3 Channel 9	2
Endevco 3 Channel 2	4	Endevco 3 Channel 10	2
Endevco 3 Channel 3	4	Endevco 3 Channel 11	2
Endevco 3 Channel 4	4	Endevco 3 Channel 12	2
Endevco 3 Channel 5	4	Endevco 3 Channel 13	2
Endevco 3 Channel 6	3	Endevco 3 Channel 14	2
Endevco 3 Channel 7	1.5	Endevco 3 Channel 15	2
Endevco 3 Channel 8	2	Endevco 3 Channel 16	2

Figure 11: Cross talk attenuation for Endevco 3

4.3 Anti-Aliasing Chassis at normal signals and with injected signals

We also did this experiment with the anti-aliasing chassis. For the normal signal we would find three consecutive channels and unplug the middle channel and look for coherence between that channel and the channels surrounding it. We did not find any significant coherence in those tests.

We then injected signals into the anti-aliasing chassis. For this we injected a 5Hz ramp signal directly into the chassis at right before saturation and took a power spectrum of those channels.

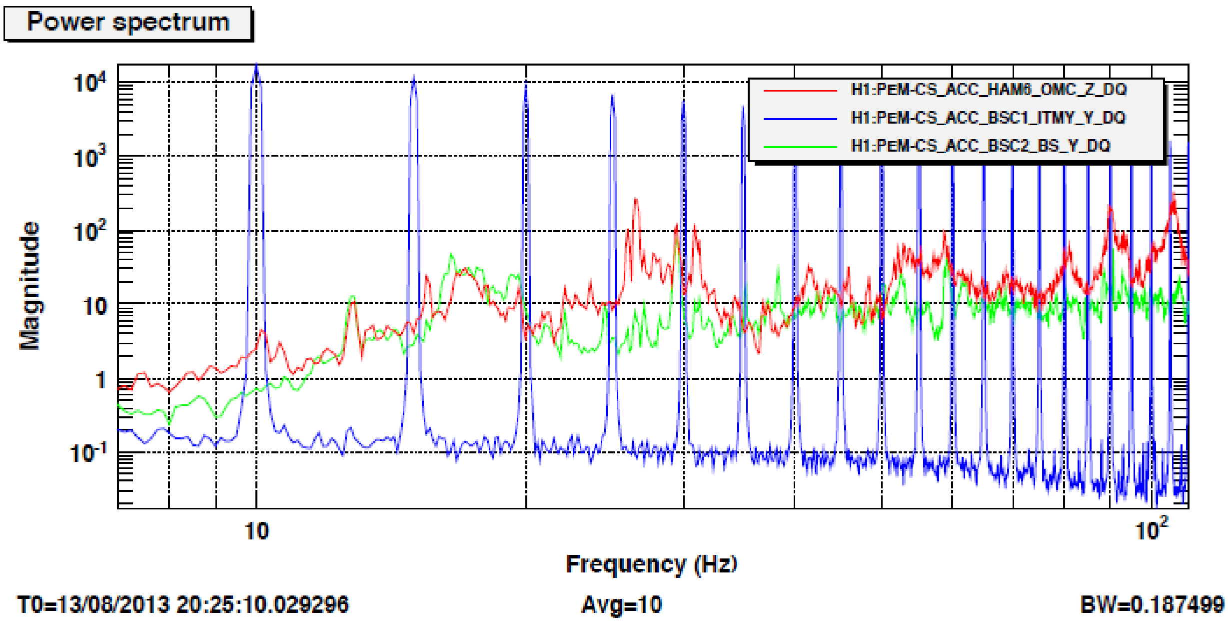

Figure 12: Power Spectrum of three channels at saturation

We then did the experiment again at 10x saturation.

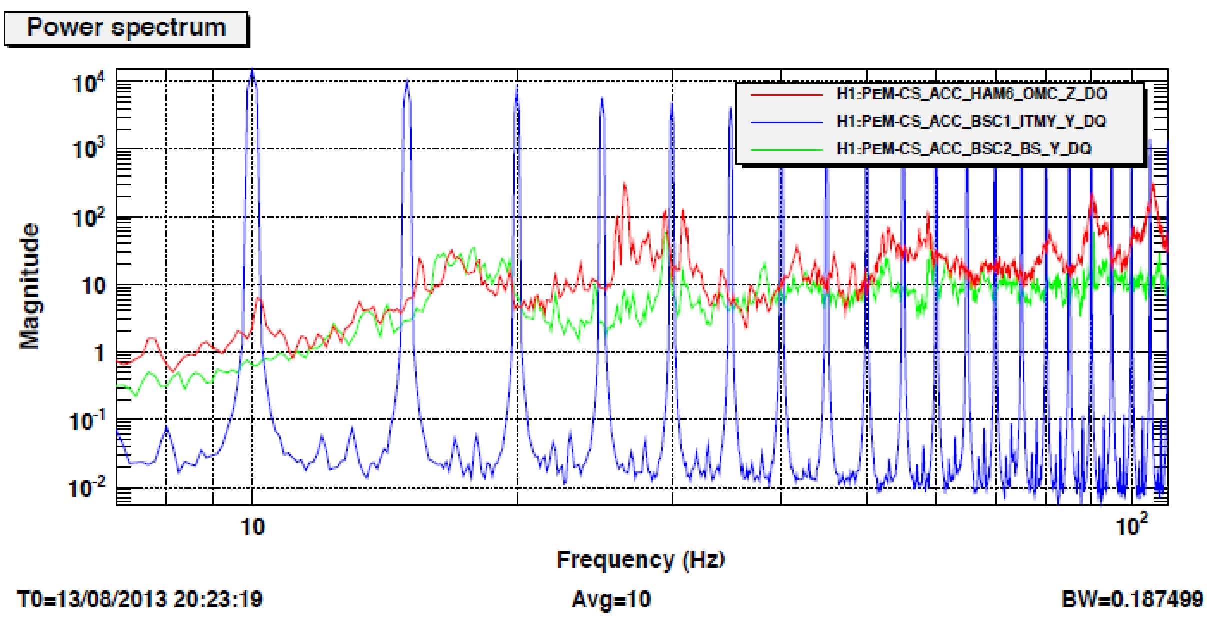

Figure 13: Power Spectrum of three channels at 10x saturation

For all of the tests we again looked at the peaks at 10Hz. We didn't find any channels that were showing coherence with the injected signal. All of the neighboring channels were in the ball park of 3-4 orders of magnitude smaller than the injected signal.

Channel	Orders of magnitude of attenuation of cross talk	Channel	Orders of magnitude of attenuation of cross talk
Anti-Aliasing Chassis 1 Channel 1	4	Anti-Aliasing Chassis 1 Channel 17	3
Anti-Aliasing Chassis 1 Channel 2	4	Anti-Aliasing Chassis 1 Channel 18	3
Anti-Aliasing Chassis 1 Channel 3	4	Anti-Aliasing Chassis 1 Channel 19	3.5
Anti-Aliasing Chassis 1 Channel 4	3.5	Anti-Aliasing Chassis 1 Channel 20	3.5
Anti-Aliasing Chassis 1 Channel 5	4	Anti-Aliasing Chassis 1 Channel 21	3.5
Anti-Aliasing Chassis 1 Channel 6	4	Anti-Aliasing Chassis 1 Channel 22	4
Anti-Aliasing Chassis 1 Channel 7	4	Anti-Aliasing Chassis 1 Channel 23	4
Anti-Aliasing Chassis 1 Channel 8	3.5	Anti-Aliasing Chassis 1 Channel 24	4
Anti-Aliasing Chassis 1 Channel 9	3.5	Anti-Aliasing Chassis 1 Channel 25	4
Anti-Aliasing Chassis 1 Channel 10	4	Anti-Aliasing Chassis 1 Channel 26	4.5
Anti-Aliasing Chassis 1 Channel 11	2.5	Anti-Aliasing Chassis 1 Channel 27	4.5
Anti-Aliasing Chassis 1 Channel 12	4	Anti-Aliasing Chassis 1 Channel 28	4
Anti-Aliasing Chassis 1 Channel 13	4	Anti-Aliasing Chassis 1 Channel 29	4
Anti-Aliasing Chassis 1 Channel 14	3.5	Anti-Aliasing Chassis 1 Channel 30	4
Anti-Aliasing Chassis 1 Channel 15	4	Anti-Aliasing Chassis 1 Channel 31	3.5
Anti-Aliasing Chassis 1 Channel 16	3	Anti-Aliasing Chassis 1 Channel 32	3.5

3

Figure 14: Cross Talk attenuation for Anti-Aliasing Chassis 1

Channel	Orders of magnitude of attenuation of cross talk	Channel	Orders of magnitude of attenuation of cross talk
Anti-Aliasing Chassis 2 Channel 1	3.5	Anti-Aliasing Chassis 2 Channel 17	3
Anti-Aliasing Chassis 2 Channel 2	3.5	Anti-Aliasing Chassis 2 Channel 18	3.5
Anti-Aliasing Chassis 2 Channel 3	3.5	Anti-Aliasing Chassis 2 Channel 19	3.5
Anti-Aliasing Chassis 2 Channel 4	4	Anti-Aliasing Chassis 2 Channel 20	3.5

Anti-Aliasing Chassis 2 Channel 5	4	Anti-Aliasing Chassis 2 Channel 21	3.5
Anti-Aliasing Chassis 2 Channel 6	3.5	Anti-Aliasing Chassis 2 Channel 22	3
Anti-Aliasing Chassis 2 Channel 7	3.5	Anti-Aliasing Chassis 2 Channel 23	4
Anti-Aliasing Chassis 2 Channel 8	3	Anti-Aliasing Chassis 2 Channel 24	3.5
Anti-Aliasing Chassis 2 Channel 9	3	Anti-Aliasing Chassis 2 Channel 25	3
Anti-Aliasing Chassis 2 Channel 10	3.5	Anti-Aliasing Chassis 2 Channel 26	3
Anti-Aliasing Chassis 2 Channel 11	4	Anti-Aliasing Chassis 2 Channel 27	3.5
Anti-Aliasing Chassis 2 Channel 12	3.5	Anti-Aliasing Chassis 2 Channel 28	4
Anti-Aliasing Chassis 2 Channel 13	3	Anti-Aliasing Chassis 2 Channel 29	3.5
Anti-Aliasing Chassis 2 Channel 14	3	Anti-Aliasing Chassis 2 Channel 30	3
Anti-Aliasing Chassis 2 Channel 15	3.5	Anti-Aliasing Chassis 2 Channel 31	3
Anti-Aliasing Chassis 2 Channel 16	4	Anti-Aliasing Chassis 2 Channel 32	3

Figure 15: Cross talk attenuation for Anti-Aliasing Chassis 2

	Orders of magnitude of attenuation of cross talk		Orders of magnitude of attenuation of cross talk
Anti-Aliasing Chassis 3 Channel 1	3	Anti-Aliasing Chassis 3 Channel 17	3.5
Anti-Aliasing Chassis 3 Channel 2	3.5	Anti-Aliasing Chassis 3 Channel 18	3
Anti-Aliasing Chassis 3 Channel 3	3	Anti-Aliasing Chassis 3 Channel 19	3
Anti-Aliasing Chassis 3 Channel 4	3	Anti-Aliasing Chassis 3 Channel 20	3.5
Anti-Aliasing Chassis 3 Channel 5	4	Anti-Aliasing Chassis 3 Channel 21	3.5
Anti-Aliasing Chassis 3 Channel 6	3.5	Anti-Aliasing Chassis 3 Channel 22	3
Anti-Aliasing Chassis 3 Channel 7	3	Anti-Aliasing Chassis 3 Channel 23	2.5
Anti-Aliasing Chassis 3 Channel 8	3	Anti-Aliasing Chassis 3 Channel 24	3
Anti-Aliasing Chassis 3 Channel 9	3	Anti-Aliasing Chassis 3 Channel 25	3

Anti-Aliasing Chassis 3 Channel 10	3.5	Anti-Aliasing Chassis 3 Channel 26	4
Anti-Aliasing Chassis 3 Channel 11	3.5	Anti-Aliasing Chassis 3 Channel 27	3.5
Anti-Aliasing Chassis 3 Channel 12	4	Anti-Aliasing Chassis 3 Channel 28	3
Anti-Aliasing Chassis 3 Channel 13	4	Anti-Aliasing Chassis 3 Channel 29	3
Anti-Aliasing Chassis 3 Channel 14	3	Anti-Aliasing Chassis 3 Channel 30	3.5
Anti-Aliasing Chassis 3 Channel 15	3	Anti-Aliasing Chassis 3 Channel 31	3
Anti-Aliasing Chassis 3 Channel 16	4	Anti-Aliasing Chassis 3 Channel 32	3.5

Figure 16: Cross talk attenuation for Anti-Aliasing chassis 3

4.4 Endevco Box 2

When we did all of these experiments most of the boxes were within the working range. However, Endevco box 2 was showing more cross talk then all of the others. We then did the experiment on all of the channels in all of the PEM channels and not just the ones that had sensors hooked up to them to see if there were better channels in the second Endevco box which we could move our current channels into new ones.

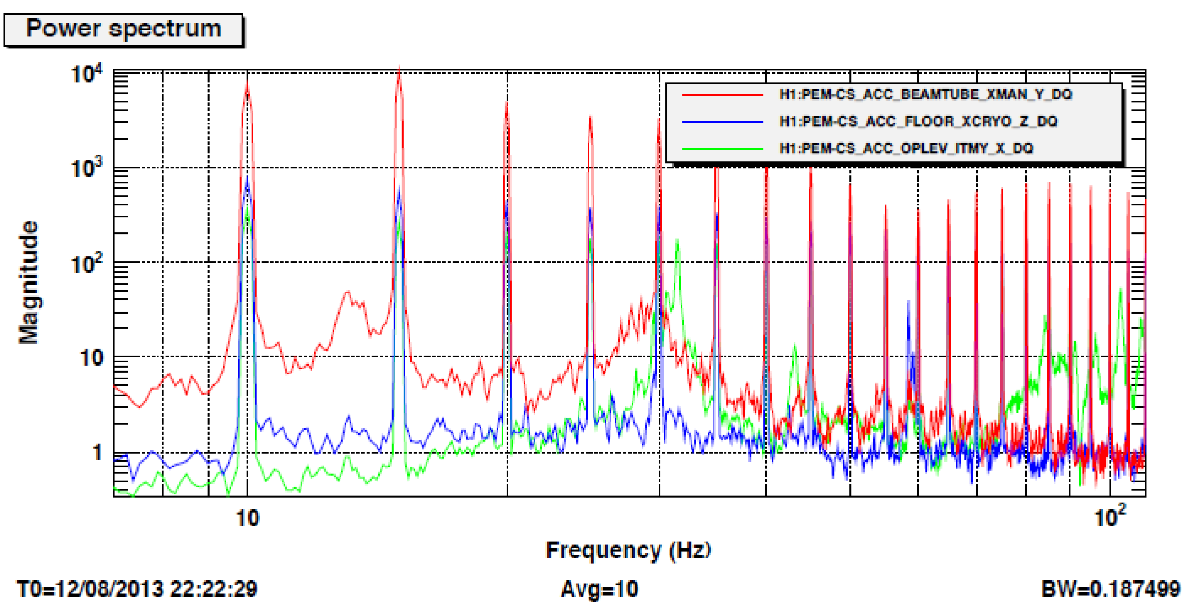

Figure 17: Power Spectrum of Endevco Box 2

Channel	Orders of magnitude of attenuation of cross talk
Endevco 2 Channel 6	1.5
Endevco 2 Channel 7	1.5
Endevco 2 Channel 8	1.5
Endevco 2 Channel 9	1
Endevco 2 Channel 10	1.5
Endevco 2 Channel 11	1.5
Endevco 2 Channel 12	0.5
Endevco 2 Channel 13	1
Endevco 2 Channel 14	1.5
Endevco 2 Channel 15	1
Endevco 2 Channel 16	1

Figure 18: Table of Endevco 2 attenuation

4.5 Conclusion

We found out that Endevco box 2 didn't have any channels that were in the acceptable range of 3-4 orders of magnitude. We decided the solution to this is to buy a new Endevco box because something in the wiring of this box just isn't working. At the very end of the summer we changed Endevco box 2 and we were able to decrease the cross talk.

Channel	Orders of magnitude of attenuation of cross talk	Channel	Orders of magnitude of attenuation of cross talk
Endevco 2 Channel 1	2	Endevco 2 Channel 9	2
Endevco 2 Channel 2	2	Endevco 2 Channel 10	2
Endevco 2 Channel 3	2	Endevco 2 Channel 11	2
Endevco 2 Channel 4	2	Endevco 2 Channel 12	2
Endevco 2 Channel 5	2	Endevco 2 Channel 13	2
Endevco 2 Channel 6	2	Endevco 2 Channel 14	2
Endevco 2 Channel 7	2	Endevco 2 Channel 15	2
Endevco 2 Channel 8	2	Endevco 2 Channel 16	2

Figure 19: Cross talk attenuation of new Endevco 2

We put our findings in the aLOG for others who could be interested in our findings. The other boxes had more channels that were in the acceptable range. However, there were some areas that were reading at two orders of magnitude smaller. This is not ideal, but we will accept it at this current time.

5. Future Work

The PEM website will continue to be updated as more sensors are being installed in places like the end stations. All of the sample spectrum will need to be taken again when LIGO goes into science mode. LIGO will be much quieter when the construction is done and we are actually looking for gravitational waves. So the sample spectrum will have changed and need to be retaken. When all of the new sensors are installed we will need to calibrate those sensors also.

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