Setting up the Physical Environment Monitoring System for Advanced LIGO: SURF Final Report

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1 Introduction

Environmental influences contribute noise to the gravitational wave data stream at LIGO. In order to reach advanced LIGO's design sensitivity, these environmental influences need to be identified and characterized. The physical environment monitoring (PEM) system was set up in initial LIGO, and consisted of a network of various sensors that detected seismic, magnetic, acoustic, and other disturbances in the detector environment [1].

During the science runs at LIGO, lessons were learned about the performance of the initial PEM system and previously unexpected coupling mechanisms were found, so changes to the system are planned for advanced LIGO [5].

1.1 Noise Sources, Coupling Mechanisms, and Sensors

Many of the environmental noise sources are off-site, many miles away, yet have considerably affect the data. Identifying these sources helps with finding the resulting signal in the data based on the frequency or timing of the noise coming from the source. In addition, it is important to identify the mechanisms by which environmental disturbances introduce noise into the data stream, since these coupling sites are where sensors should be mounted, or setups altered to prevent coupling.

Acoustic noise can be detected by hanging microphones near coupling sites. One major type of coupling site is optical tables, where optic supports are excited by environmental sound, and the Gaussian laser beam gets clipped, with the amount of lost laser power modulated by the acoustic noise. Relative motion between table optics and the interferometer caused by acoustic noise can also lead to Doppler shifting of the laser light. Sources of acoustic noise include electronics fans, chillers, the HVAC system, nearby vehicles (including aircraft), and wind [3].

Seismic noise can be detected with accelerometers and seismometers. These sensors are placed near or around chambers containing important optics, on optical lever supports, and on optical tables. Seismic disturbances can affect the test masses when vibrations travel up the stacks that hold up the chambers, and can affect our perception of the test mass alignment by shaking the optical lever setup [3]. One contribution to seismic noise is turbulence in water pipes, in particular the ones used in chilling systems [4] [6]. The chiller yard external to the Y-endstation has pipes carrying chilled water underground to the endstation building, so turburlence in these pipes can directly cause shaking in the ground beneath the building. Various motors around the site, wind, trucks, aircraft, and earthquakes can also create seismic noise [3].

Magnetometers are used to detect stray magnetic fields around the detector. These fields can affect the various electronics and cables around the site, as well as the magnets used to control the mirrors. Sources of magnetic fields include building heaters, large motors, lights, power supplies, fluctuations in the mains voltage, and nearby power lines [3]. More recently, fans on electronics chassis have been found to create voltage fluctuations that are picked up by magnetometers [6].

1.2 The One-Arm Test

One major investigation currently being carried out at LHO is the one-arm test. A new feature that will be introduced in advanced LIGO is the Arm Length Stabilization system. This system allows each arm cavity length to be independently controlled. In addition, a new seismic isolation system and a new suspension system have been added. Testing these systems and verifying that they can achieve the performance required for aLIGO are part of the goals of the one-arm test. The first step in the one-arm test will involve locking the H2 Y-arm. Once this can be consistently done, the performance of the new seismic isolation and suspension systems will be investigated [2]. Part of the PEM work this summer involves measuring envronmental coupling to the one-arm test by making injections and measuring the effect in the arm length channel.

1.3 The aLIGO PEM System

Our work during this summer is divided into three parts. The first is an investigation on methods for mounting accelerometers, with the goal of addressing flaws in the iLIGO mounting scheme. The second is installing and using PEM sensors in conjunction with the one-arm test, and the third is creating a website that provides information about PEM sensors and channels to the public. In the following sections, we describe our conclusions from the mounting experiment, the initial setup of several PEM sensors and their use in supporting the one-arm test, and the final design for the PEM website.

2 Sensor Mounting Experiment

The purpose of this experiment is to improve on the triple-axis accelerometer mounting scheme that was used in iLIGO. The main flaw in the iLIGO design was a 900 Hz resonance coming from the mounting setup, that contaminated the accelerometer signal (see Figure 2). One of the first tasks in this experiment was to investigate this 900 Hz resonance, and identify the part of the mounting setup that caused this resonance.

For all the tests, we used as our reference an accelerometer that was attached to the table surface with a thin layer epoxy. The hole at the bottom of the accelerometer normally used for bolting it to cubes was sealed with a set screw to avoid having epoxy seep between the threads. We applied Devcon 5-minute epoxy to the bottom of the accelerometer. Excess epoxy was scraped off using the flat side of the mixing stick, to have the layer be as thin as we could make it. The accelerometer was then placed on the table, in an area where it was not over any of the holes for bolts, and the epoxy was allowed to cure for 5 minutes before the cable was attached to it. The thickness of such a layer of epoxy is $\sim$ 0.3mm.

2.1 iLIGO Setups

We used the iLIGO setup to mount an accelerometer on the table, in the same area as the reference accelerometer. Through this setup we were able to see the 900 Hz resonance that is intrinsic to the iLIGO mounting, since it is not present in the reference signal.

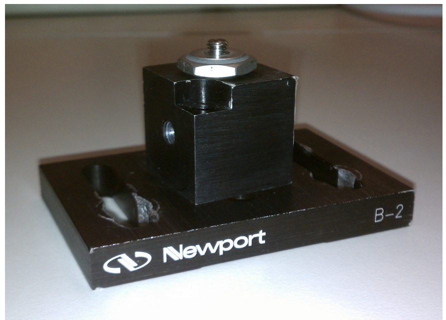


Figure 1: Triple-axis accelerometer mount used in iLIGO.

By removing the plate from the cube, and mounting the cube directly to the table using epoxy, the 900 Hz resonance was removed. The cube did not sit on the plate on a completely flat surface, so we conclude that the resonance was a result of the cube "wobbling" against the mounting plate, about the central bolt holding them together.

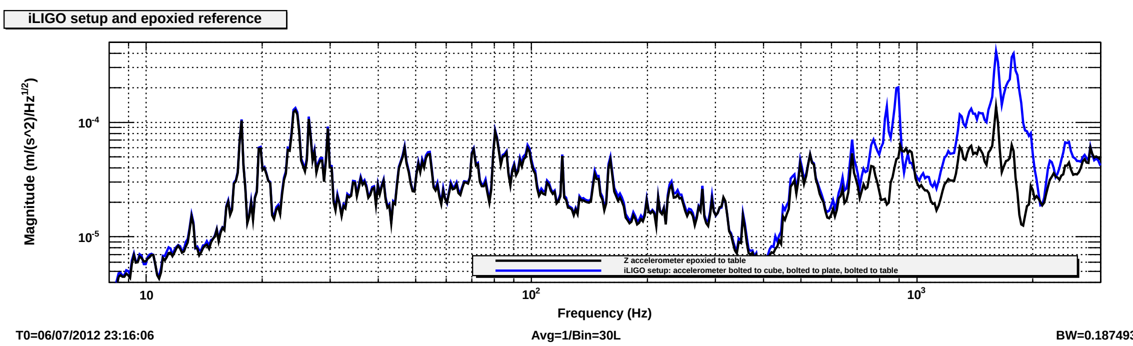


Figure 2: iLIGO mounting vs. epoxy reference.

The next mounting scheme we tested was the double-sided tape used in temporary setups during iLIGO. The tape used was Scotch Permanent Double Sided Tape, 0.5in wide. Two parallel, non-overlapping strips were placed across the bottom of the accelerometer, which is 1in in diameter, and the accelerometer was pressed to the table surface, again away from any holes, but near the reference accelerometer. The tape was also found to be non-conductive, so it electrically isolates the accelerometer from the object it is mounted to. We found that when taped to the table, the accelerometer behaves very similarly to one that is epoxied to the table, up to 2000 Hz.

2.2 aLIGO Setups

For the aLIGO mounting scheme, we were looking to remove the 900Hz resonance from the iLIGO setup, as well as find a way to electrically isolate the accelerometers from ground. The latter is crucial as several accelerometers sharing a common ground can have cross-talk levels of up to 10%.

In searching for a new permanent mounting scheme to use in aLIGO, we tried various combinations of tape, epoxy, cubes, plates, and clamps. The following setups were compared:

- Accelerometer bolted to steel cube bolted to brown plastic plate (one of the iLIGO setups)
- Accelerometer resting on the table (no mount)
- Accelerometer bolted to cube taped to table
- Accelerometer bolted to cube epoxied to table
- Accelerometer taped to cube epoxied to table
- Accelerometer epoxied to cube dog clamped to table
  - + polyethylene wrap between cube and table
  - + foam stuffed in dog clamp slot
  - + foam between dog clamp and cube
  - + different position on the table
  - + cube replacement
  - + tightening of the clamp
  - + maximum tightening of the clamp
  - + foil between clamp and cube
  - + foil between cube and table
  - + foil above and below cube
- Accelerometer with a thin layer of epoxy + polyethylene wrap + a thick layer (0.7-1.0mm) of epoxy to the table
- Accelerometer epoxied to cube bolted to plate
  - + foil between cube and plate
  - + foil between plate and table
  - + foil above and below plate

We concluded that the method that provided both electrical isolation of the accelerometer from the optics table as well as performance closest to that of the epoxied reference was using epoxy and polyethylene wrap in combination with the steel cube used in the iLIGO setup.

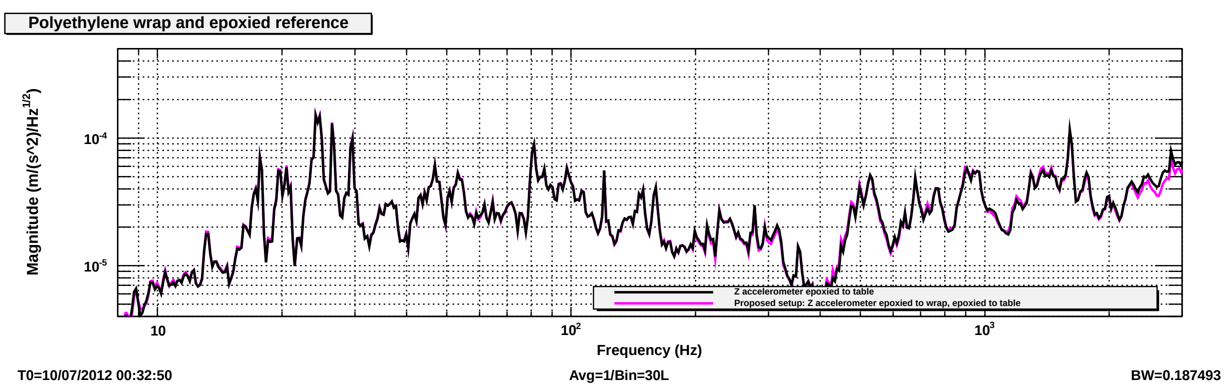


Figure 3: Performance of Z-axis accelerometer mounting.

In the Z-axis setup with the best performance, we added a layer of Glad polyethylene wrap between the accelerometer and the table. A thin layer of epoxy was first applied to the accelerometer, and a piece of wrap was pulled taut against the bottom of the accelerometer. Then another thin layer of epoxy was applied to the wrap, and then the accelerometer was pressed to the table. The purpose of adding the layer of polyethylene wrap is to isolate the accelerometer from the object it's mounted to, since a thin layer of epoxy may actually allow parts of the metal exterior of the accelerometer to come into contact with the table. We found that adding this layer does not make the signal deviate too much from that of the reference (see Figure 3).

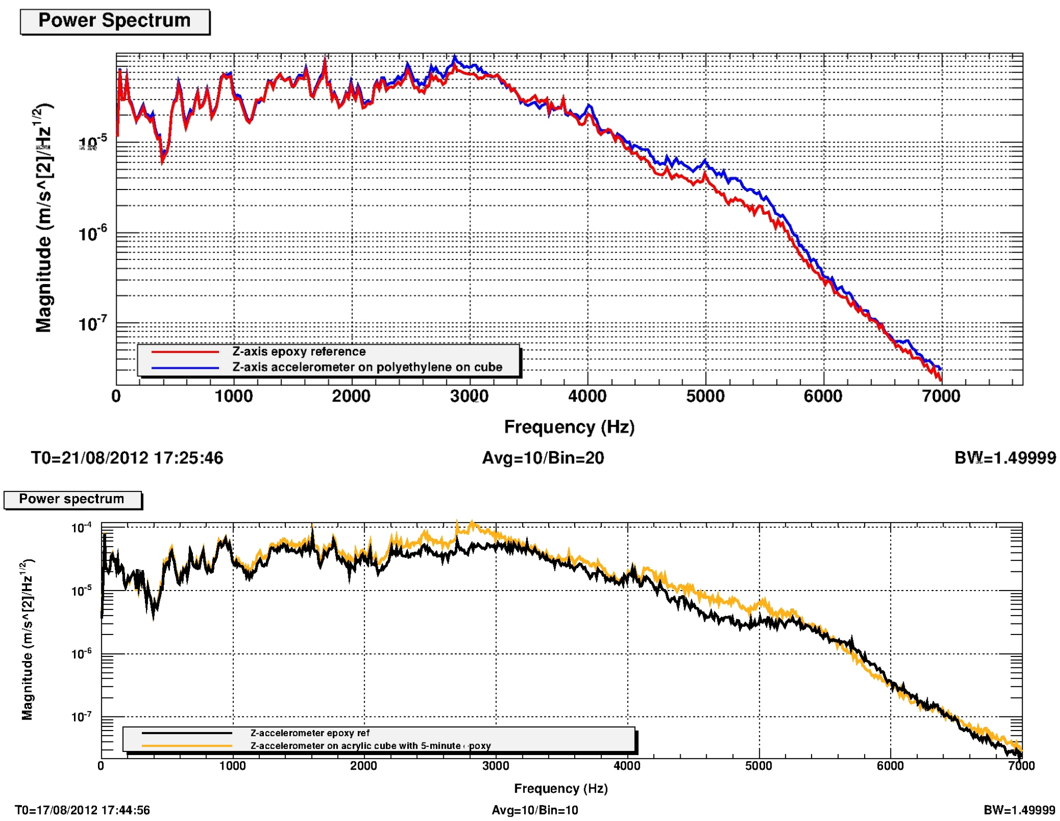


Figure 4: Performance of triple-axis accelerometer mountings.

For a triple-axis mounting, we tried attaching an accelerometer with a layer of polyethylene wrap on the bottom (as described above) to a Wilcoxon triaxial aluminum mounting cube using epoxy, and attaching that cube to the table using epoxy. This also does not make the accelerometer signal deviate significantly from that of the reference (see Figure 4). For actual installation of triple-axis accelerometers, we recommend first attaching three accelerometers to a metal cube using the epoxy-polyethylene-epoxy method described above, outside the LVEA. Once the epoxy has cured and the triple-axis setup is stable, one only needs to use one batch of epoxy near the table to mount the cube. We tested a similar setup but with a (non-conductive) acrylic cube instead, but found that the aluminum cubes give better performance (see Figure 4).

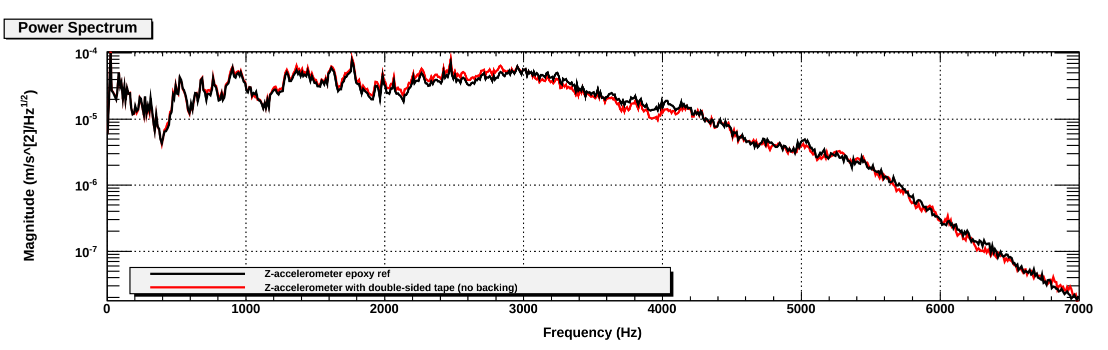


Figure 5: Performance of clean room tape mounting.

For temporary installations, we tested 1in wide double-sided clean room tape. As mentioned above, double-sided Scotch tape was used in iLIGO, but for aLIGO we wish to use particle-free adhesives such as clean room tape. We used Ultratape 1520CL100P3D and found that this mounting allowed the accelerometer to respond to vibrations in a similar way to the epoxied reference (see Figure 5). There were two kinds of clean room tape we tried, one that had a peel-away backing, and one that did not. Since the backing was troublesome to peel off, the tape without the backing is preferred.

3 One-Arm Test Support

3.1 Sensor Installation

The sensors relevant to the one-arm test were installed in the first three weeks of the summer. This involved measuring distances between electronics setups and the sensors, cutting cables to the desired lengths, and assembling the connectors at each end. The next steps were running cables in the proper cable trays, getting approved to use epoxy near the chambers, some of which were open for cleaning, and setting up channel names in the DAQ system. Openings around the mounted accelerometers (eg. bolts on chamber flanges) were taped off to prevent contamination from epoxy fumes.

For the one-arm test, some of the most important sensors were those in the electronics bays, both in the Y-endstation and in the corner station, where the electronics setups are as they will be during aLIGO. We also focused on the accelerometer on the laser table in the endstation, and accelerometers on the optical lever piers. The accelerometers on the chambers containing test masses are less important as the one-arm test is not expected to be sensitive enough for chamber vibrations to be relevant.

3.2 Optical Lever Noise

Using the PEM sensors we installed along the Y-arm, we were able to identify and remove several noise sources that were contributing the optical lever spectra for ETMY and ITMY, as well as the arm length error signal (see Figure 6). Using the multiple accelerometers and one seismometer placed in the endstation, we were able to quickly identify the general location of each noise source. The three sources we found were:

29.5 Hz: Annulus pump that was left on after pumping was finished. The pump has since been turned off and removed from the Y-endstation.

90-91 Hz: Power supply for optical lever laser on the receiver pier, which contains a fan. We moved this to the floor by the receiver pier and seismically isolated it from the floor using inflated clean room gloves.

56.5 Hz: Power supplies on floor near receiver pier. We placed these on a seismically isolated platform using springs.

3.3 Magnetic Excitations

We wished to investigate how easily environmental magnetic fields can couple into the interferometer, so we set up two large coils on opposite sides of BSC8 to generate magnetic fields at ITMY. Using the arm length signal and the optical lever signals for ITMY, we were able to see the motion of ITMY in response to the magnetic injections. Through several injections, we found that the motion of ITMY at 60 Hz was 10^{-14} m, five orders of magnitude higher than the goal for aLIGO.

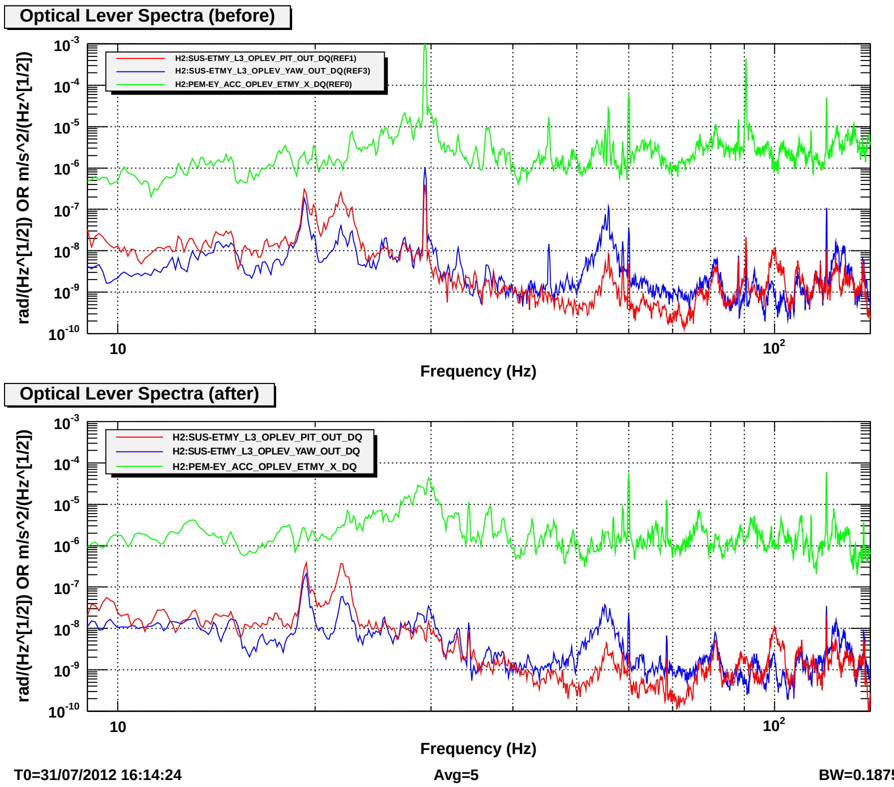
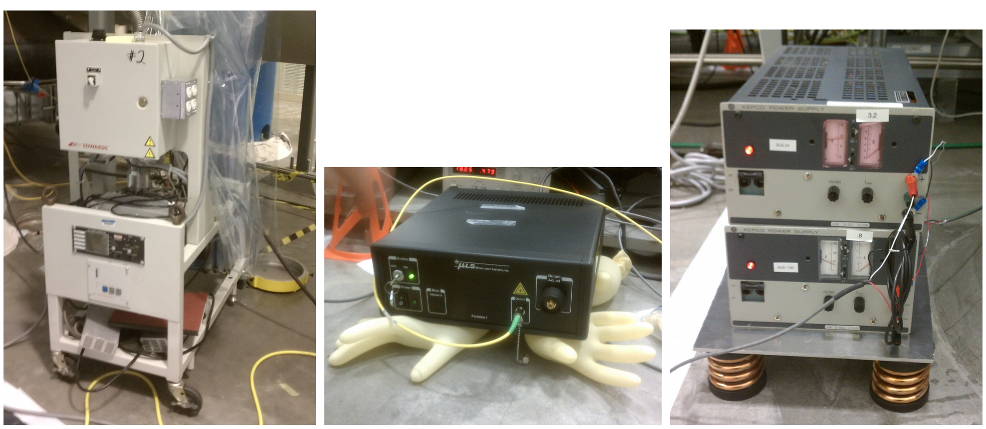


Figure 6: Optical lever spectra before and after noise sources were removed.



(a) Annulus pump on BSC6. **(b)** Optical lever power supply. **(c)** Power supplies on floor.

Figure 7: Noise sources contributing to optical lever spectra.

Our first idea was that the magnetic fields were coupling through HEPI or ISI. However, upon repeating the injections with HEPI and ISI turned off, we found that the ITMY response did not decrease, so coupling through these two systems is ruled out. We then repeated the injections with SUS turned off (except for a bias that shifts the pendulum's position and holds it), which also resulted in the same ITMY response. From this we suspected the magnetic field was coupling through the voice coil actuators that were still carrying currents for maintaining the bias. We wished to short these out so that our magnetic injections could not couple into these coils, but doing so requires realignment of the optical lever if we wish to use those channels

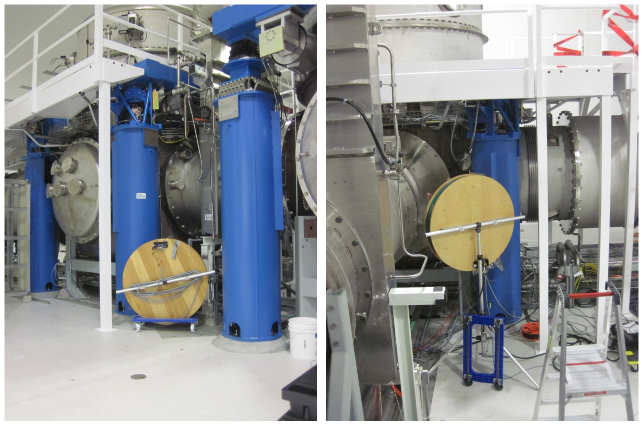


Figure 8: Setup of coils used for magnetic excitations on ITMY.

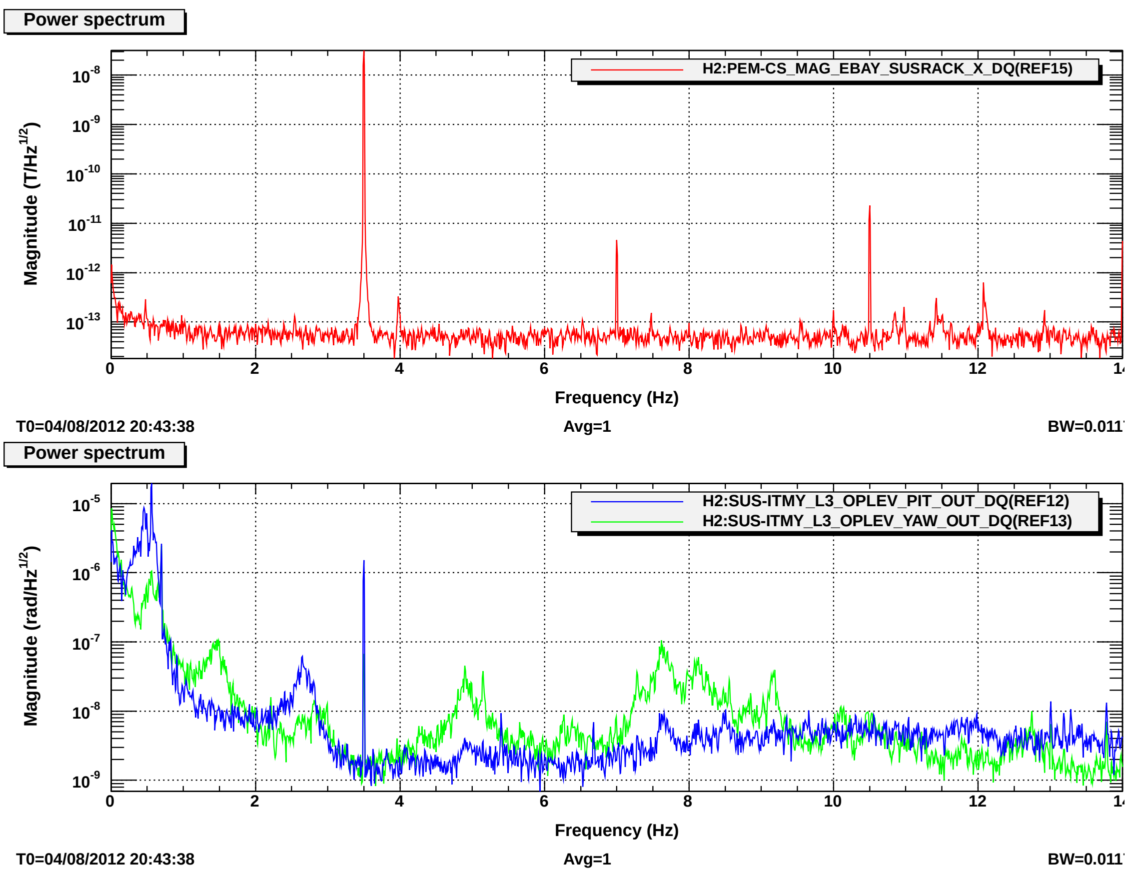


Figure 9: ITMY response to a magnetic excitation.

to monitor ITMY motion.

4 Website

Information on the aLIGO PEM system has been made publicly available at `http://pem.ligo.org`, where maps of the PEM system sensor setups for LHO and LLO are displayed. The website features multiple search options that allow a user to paste channel names into a search box, choose from a dropdown list, or select a sensor from an interactive map of all aLIGO PEM sensors.

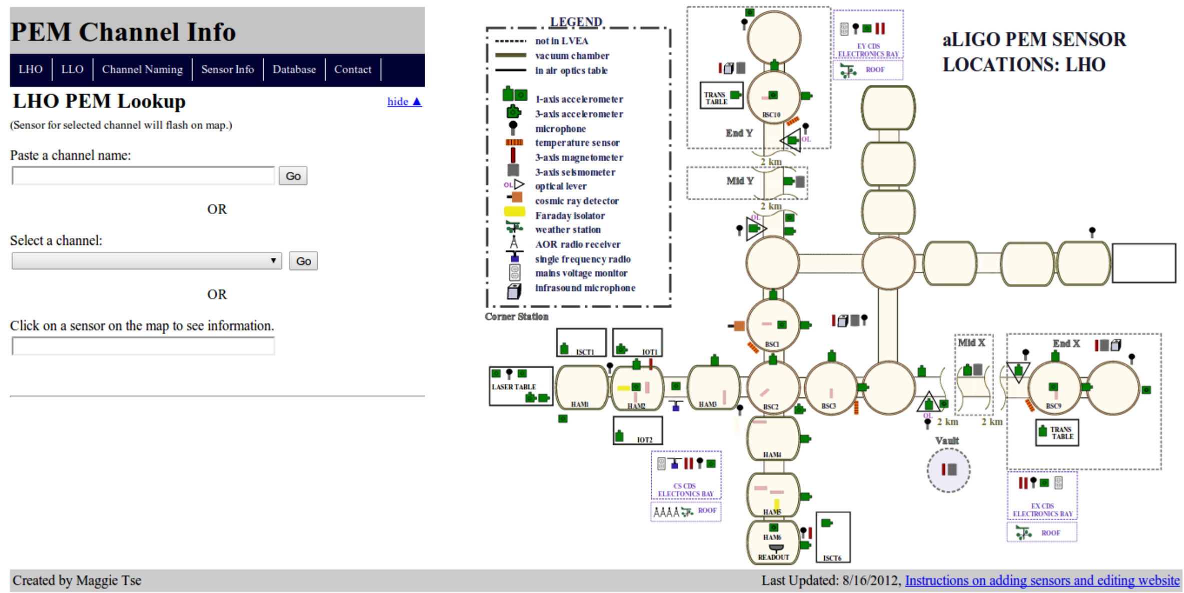


Figure 10: Screenshot of the aLIGO PEM website.

For each channel, our database provides the calibration factor for the channel, how that calibration factor was calculated and its amplitude and phase errors, and the frequency range over which the sensor operates. It also provides the sample rate for the channel, a sample calibrated spectrum, and a picture of the sensor in its actual location. Each sensor will also have a grid location using global LIGO coordinates (centered on the beamsplitter, aligned with the X- and Y- arms), given in millimeters. This information can be used for propagation studies and triangulation of noise sources.

The website will be hosted from LHO computers, and will be open to public access. In particular, high school students who are using PEM data in their science classes can access the website to find information about the channels they are studying. The database can be edited by anyone with a ligo.org login through a user-friendly web interface. There is also a written guide for editing and maintaining the website for future upkeep at `http://pem.ligo.org/channelinfo/documentation`.

5 Future Work

After the conclusion of the summer, the rest of the sensors for aLIGO will be mounted at both LHO and LLO, with accelerometers mounted using the recommended mounting scheme. Investigation into the excess magnetic coupling into the test masses will continue, with our target shifting to ETMY for comparison. The website database already contains all the channels needed for LHO, but work will need to be done to expand the database to cover LLO.

6 Acknowledgements

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