LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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–First Progress Report– Low Noise Seismic Sensing and Actuation for Adaptive Filtering

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1 Motivation

Gravitational waves, according to Einstein's General Theory of Relativity, will contract and expand space in two orthogonal directions. Like with electromagnetic waves, there are two fundamental polarizations to such waves: X and +. The analogy only goes so far, however, because gravitational waves are waves *of* spacetime and produced by quadrapole radiation, while electromagnetic waves are *in* spacetime and produced by dipole radiation. Since gravitational waves are the result of changing quadrapole moments, they will be created by systems such as binary black holes, where instead of a constant strain in space, the strain oscillates with time as the curvature of space shifts to match the changing system.

Such waves are expected to be seen with a uniquely sensitive array of Michelson-type interferoemeters. There need to be several of them in order to determine coincidences and localize the sources in the sky. LIGO, the Laser Interferometer Gravitational Wave Observatory, hopes to be sensitive enough to fit this bill.

To achieve the necessary sensitivity to observe gravitational waves requires extreme measures in noise reduction. Noise comes from many sources, including frequency changes in the laser light, thermally from the test masses, quantum mechanical shot noise from the laser, and seismic noise. Some noise sources are sharp lines in the frequency domain, such as violin modes of the pendula strings and the 60 Hz power line (and its harmonics) from nearby electronics.

Seismic noise is due to a variety of sources, from ocean waves to various man-made sources. To combat this noise at LIGO, all of the optics are suspended by pendula which act as mechanical low pass filters, so vibration at a frequency higher than the resonance frequency of the wire won't be transmitted. As a second stage, the suspension point for the pendula lies on a passive damping device which consists of four alternating layers of masses and springs. This mass-spring system provides good isolation from 10 Hz and up, while the pendula filter down to around 1 Hz, their resonant frequency [1].

This summer I will focus on using active seismic isolation techniqes to reduce low frequency seismic noise. Such low frequency noise causes several problems. The most obvious is that it limits low frequency data collection by obscuring the gravitational wave signal in that frequency range. Also, such noise makes it more difficult to achieve "lock" in the interferometer: the differential lengths of the arms must be such that a resonant condition is achieved in the Fabry Perot optical cavities in the arms, and this will be harder to achieve if there is vibration in the arms. Finally, low frequency noise can be upconverted by beating against other sharp noise lines (such as violin modes in the pendula strings); this broadens the lines, further limiting the frequency range available for gravitational wave observation.

My project this summer revolves around the STACIS 2000 isolators, a commercial active isolation system in place at the 40m Prototype Interferometer Lab at Caltech[2]. The system was installed several years ago but shut off, because, while it isolated well at higher frequencies, it did a poor job at lower frequencies[3]. The geophones in the STACIS did not detect ground motion well because of their noise, leading to noisy actuation. This noise was then fed through the pendula, since the STACIS provide their suspension point, and from the pendula the noise then went on to the mirrors, making it more difficult to achieve lock of the interferometer. However, there is incentive to turn them back on: a working isolation system will increase low frequency sensitivity as well as allow implementation and testing of adaptive filtering techniques that are being developed at the 40m Lab.

An adaptive feed forward least mean squared filter is expected to help reduce seismic noise[4]. One approach being investigated at the 40m Lab is predicting the type of noise as it starts, identifying it, and providing instructions for an active isolation system to actuate and reduce the noise. Such an algorithm could be put in place at the aLIGO (Advanced LIGO) sites if it can be shown to be effective in reducing sesimic noise in the 40m Lab.

Currently, however, the only way to provide active isolation at the 40m Lab is to push directly on the mirrors. This approach is not ideal, because it means that the pendula which typically provide a mechanical low pass filtering effect are being bypassed, and thus any testing is not directly analogous to the aLIGO sites, where any actuation will be filtered by the pendula. The system in place for aLIGO that will provide active seismic isolation is known as HEPI, the Hydraulic External Pre-isolator. This serves a similar function to the STACIS units, and has a similar acting principle: geophones on HEPI register motion, a seismometer on the floor corrects for ground motion, and the resulting signal is filtered and sent to actuate the hydraulics (rather than the piezoelectrics in STACIS)[5].

The solution could be the STACIS isolators, which provide the suspension point for the pendula which support the optics. High sensitivity witness sensors will send data through the adaptive algorithm which will actuate the STACIS units accordingly. This motion will be filtered by the pendula, so the results are more directly applicable to the aLIGO sites. This scheme will provide better isolation than the standard STACIS isolators alone, since the noisy geophones that come with the STACIS will be replaced with higher quality sensors.

2 Progress and Difficulties

I have been working on gaining an understanding of the STACIS circuitry and structure. I disassembeled a spare STACIS unit, and obtained a clear picture of the fundamentals. Geophones at the top send signals to a total of five piezoelectric (PZT) stacks which actuate in all three axes (one each in x and y, and three in z). This signal is filtered and amplified by the STACIS circuitry since a high voltage signal is necessary to drive the PZT stacks. This is the active isolation aspect of the STACIS, but there is also a damping layer which provides some amount of passive isolation. The STACIS unit I am working with is shown in Figure 1.

Since the geophones' signal is very noisy, there would be no point in using them to test the adaptive filtering method- more noise would be added than subtracted. Instead, higher quality sensors such as Wilcoxon 731A ultra-quiet, ultra low frequency seismic accelerometers should replace the geophones[6]. That way, even if the adaptive filtering technique is not used, there would still be the benefit of the STACIS's own active isolation without the noise introduced by its own sensors.

To replace the STACIS's geophones, I must have a point in the circuit to input a signal to drive the PZT stacks. Fortunately, the spare STACIS unit that I am working on has an extension board with ports which read out the geophone signal and allow input of an

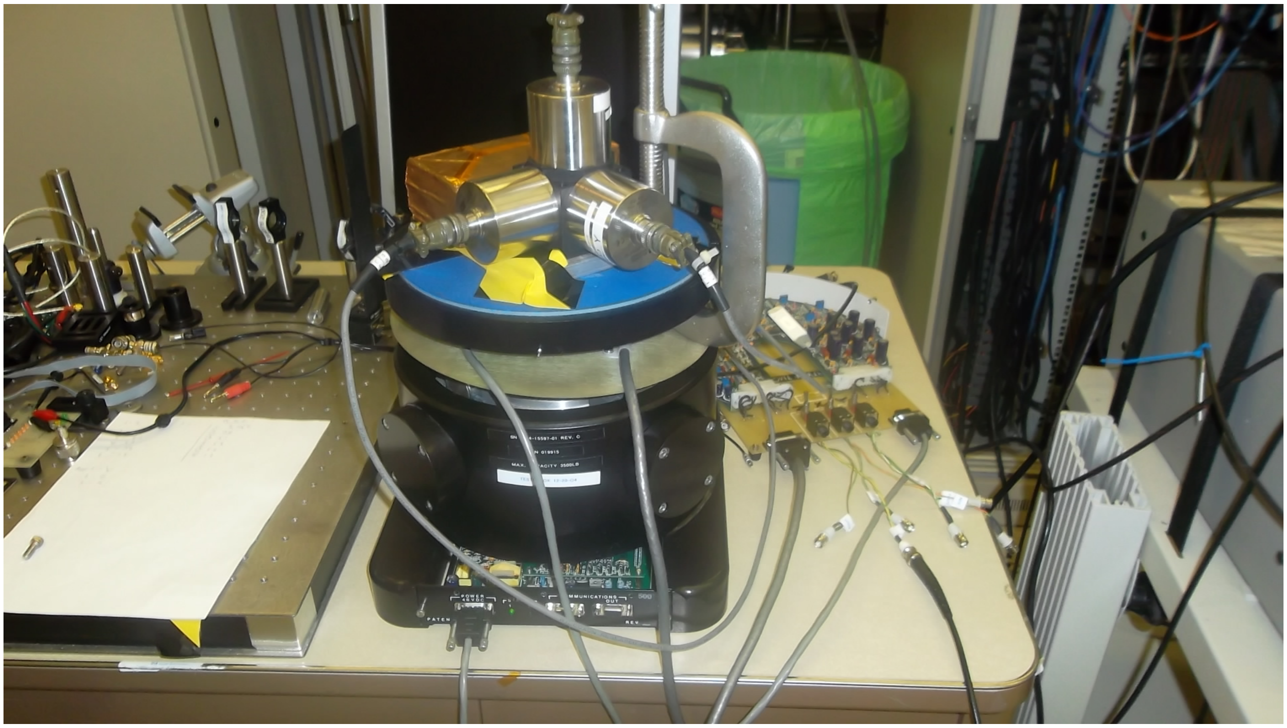

Figure 1: The STACIS unit I am working with. The cylinders on top are the accelerometers; the internal geophones are not visible. The x and y PZTs are the horizontal cylinders protruding midway up the STACIS, and to the right is the extension board that allows access to some of the electronics.

independent signal. There are also switches for open and closed loop, which either bypass the geophone signals or allow them to provide feedback, respectively, as shown in Figure 2. To modify the other STACIS units in the lab, however, I will have to identify the proper signal injection points without an extension board.

The first issue I had to overcome before I could turn on the STACIS unit was to replace a burnt resistor on the high voltage amplifier board that limited current to the PZTs. According to previous work at the 40m Lab, these resistors burn when a PZT stack short circuits, which must have happened at some point in the past with this spare unit. The resistor was visibly singed, and when measured with a multimeter had a resistance orders of magnitude higher than the others, which were all close to their expected value. To ensure proper driving of the PZTs, I replaced this resistor, and when I turned on the STACIS there were no visible issues. The PZT stack that caused the problem originally was likely replaced.

In the spare STACIS unit I am working with, when I switch from open to closed loop operation it sometimes oscillates uncontrollably. This effect was reduced when I placed some weight on top of the STACIS, and since under real operation there are several hundred pounds on them this is probably not indicative of a real problem.

I have been investigating driving the PZTs with an external signal and measuring transfer functions using both the internal geophone and external accelerometers. I am definitely driving the PZTs, as confirmed by the external accelerometers, and am currently in the pro-

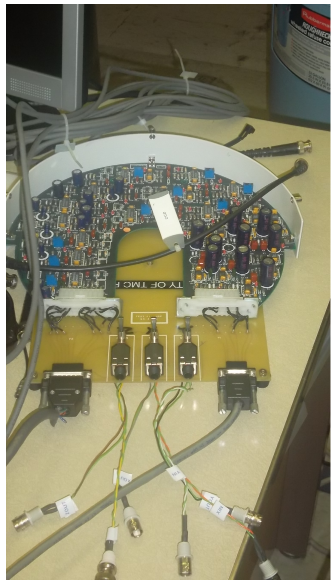

Figure 2: The extension board which allows me to control the feedback to the PZT stacks. In the foreground are the ports to input a signal and read the internal geophone signal for each axis as well as the switches to open and close the feedback loop.

cess of taking transfer functions of the system. Figure 3 shows the open loop gain I measured for the STACIS; the plots are very similar to those measured by the STACIS manufacturer.

The major difficulties I have encountered so far have had to do with the lack of documentation of the STACIS circuitry. Though I now have a clearer understanding of the basic function, the lack of technical drawings and electronics schematics makes any modifications to the circuit board more difficult. In replacing the geophones, I may simply be able to use the existing circuitry, but if that is not possible it may be necessary to build the necessary filters and amplifiers myself.

3 Next Steps

The geophones must be replaced to get any benefit from using the STACIS units, because their signal is too noisy. My next step, since I have found it is possible to drive the PZTs with an external signal, is to try to provide feedback using the external accelerometers.

At this stage, there are several options involving the accelerometers. First, I could simply replace the geophones with accelerometers, which should provide better low frequency isolation than the current system. The STACIS circuitry would act on the accelerometer signal in the same way as it would have acted on the geophone signal, providing the same level of feedback (though better at low frequency because the initial sensor data will be less noisy).

The second option would be incorporating a feed forward algorithm, where accelerometers would act as a witness sensor, send their signal through the algorithm, and then sent

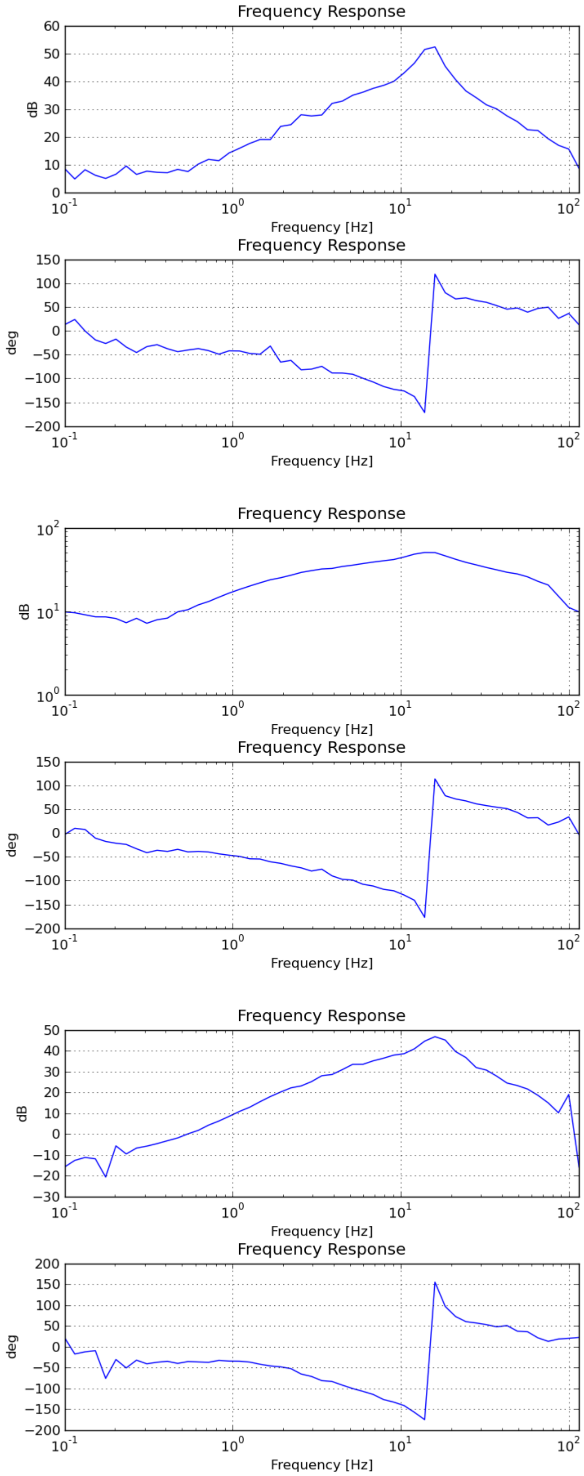

Figure 3: Bode plots of the open loop gain of the STACIS in the x, y and z axes from top to bottom (there is a magnitude and a phase plot for each axis). These were obtained by driving the PZT stacks with a swept sine signal and measuring the output of the STACIS' internal geophones.

back to the STACIS to be amplified and drive the PZTs. In this case, the filtering can be bypassed since that will be done digitally by the algorithm, but the signal must still be sent through the high voltage amplifier in order to drive the PZT stacks.

A third possible means of seismic isolation is to use an interferometric differential sensor. To do this, I would set up Helium Neon lasers between the STACIS and the platform they support. The interference fringes of these lasers would tell us about the relative motion of the STACIS and the platform, and we could use this information to either keep the distance constant or actuate the STACIS to act as a spring with a low resonance frequency, giving anther isolation factor of $1/f^2$ at high frequencies.

I hope to conduct at least basic testing of each of these options by the end of the summer.

References

[1] Rana Adhikari, *Sensitivity and Noise Analysis of 4 km Laser Interferometric Gravitational Wave Antennae*. Thesis, Department of Physics, Massachusetts Institute of Technology (2004).

[2] http://www.techmfg.com/products/advanced/stacis2100.htm

[3] http://nodus.ligo.caltech.edu:8080/40m/1598

[4] Jennifer C. Driggers, et al., *Active noise cancellation in a suspended interferometer*. Review of Scientific Instruments 83, Issue 2 (2012). http://arxiv.org/abs/1112.2224

[5] Joe Giaime , Louisiana State University and LIGO Livingston, *Hydraulic External Preisolation at LIGO Livingston*. http://www.ligo.caltech.edu/LIGO_web/0409news/0409liv.html

[6] http://www.wilcoxon.com/vi_index.cfm?PD_ID=33