LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Technical Note **LIGO-T1500218–v1** 2015/07/07

Building a tilt-free seismometer, Progress Report 1

Megan Kelley

California Institute of Technology
LIGO Project, MS 18-34
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project, Room NW22-295
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
Route 10, Mile Marker 2
Richland, WA 99352
Phone (509) 372-8106
Fax (509) 372-8137
E-mail: info@ligo.caltech.edu

LIGO Livingston Observatory
19100 LIGO Lane
Livingston, LA 70754
Phone (225) 686-3100
Fax (225) 686-7189
E-mail: info@ligo.caltech.edu

http://www.ligo.caltech.edu/

1 Motivation

The Laser Interferometer Gravitational-Wave Observatory (LIGO) experiment uses an enhanced Michelson interferometer to determine the relative distance between two test masses that may be perturbed by a passing gravitational wave. At a frequency of 100 Hz, the displacement sensitivity of LIGO's 4 kilometer long arms is $10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$, which is about five orders of magnitude smaller than the classical radius of the proton.[1] The level of precision required to make this measurement effectively requires that all sources of noise be carefully considered and reduced as far as possible. The three primary sources of noise in the experiment are quantum noise (shot noise) dominant at high frequencies, thermal noise dominant at mid-range frequencies, and seismic noise dominant at low frequencies. The seismic noise begins to dominate at about 10 Hz; lower than 10 Hz the noise increases many orders of magnitude, creating what is known as the "seismic wall" on the low end of LIGO's sensitivity band, as seen in Figure 1.

The sources of this low frequency noise vary from microseisms (ex. ocean waves minutely pushing on the continent), people walking near the detector, and wind on the detector. There

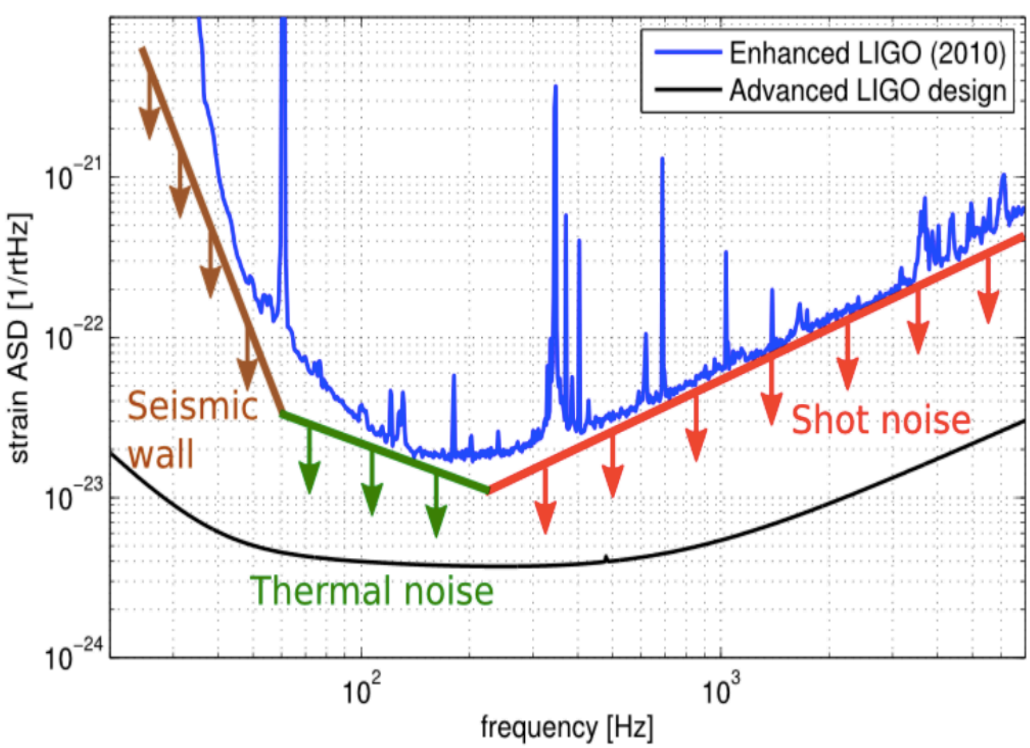

Figure 1: The noise curves for Initial and Advanced LIGO, showing the three main contributors to noise in the three regions.[2]

is great interest in lowering the seismic noise present in the experiment because continuous sources of gravitational waves, such as closely orbiting neutron stars and black holes, emit waves at low (<10 Hz) frequencies. If LIGO can reduce its seismic noise, a greater range of phenomena will be available for study.

The basic structure of a seismometer is that of a mass that can oscillate about an equilibrium, returned by some restoring force. A simple example of this is a mass on a spring. When the ground moves, the mass is forced into oscillation, and some aspects of the ground's motion can be determined from observing the mass's motion. Two aspects of ground motion that are detected with inertial (mass on a spring) seismometers are ground translation and ground tilt. Especially at low frequencies, the tilt component of ground motion contaminates the reading of the seismometer. In present-generation seismometers, the tilt is subtracted out of the signal via a tilt-sensitive instrument. However, the noise in the this additional instrument often reduces the precision of the data greatly. Therefore, the end goal of this project is to create a 'tilt-free' seismometer that is mechanically insensitive to tilt, in order to remove the necessity for the second, tilt-only measurement.

As described by Matichard et al.,[3] no inertial sensor can fully distinguish between horizontal translation of the ground and tilt of the ground. However, by clever mechanical design, a sensor that is insensitive to tilt within a certain frequency range can be constructed. The basic design of this sensor is a traditional seismometer in a box that is suspended from a thin wire. The top of the wire is connected to a frame that is rigidly attached to the ground. Assuming a perfect suspension point, the suspended box and seismometer will not move if the ground tilts, and will move if the ground translates. In practice, this method is only effective for ground motion frequencies that are above the resonant frequency of the pendulum formed by the suspended box. So by creating pendula that have very low resonant frequencies, a large range of translational ground motion frequencies can be measured without contaminating tilt motion.

2 Summer Project

The project for this summer is to make a prototype of the theoretical tilt-free seismometer described above. Designs were developed in previous years by Dooley et al.[4]. The design consists of an inverted pendulum on a frame, called the rhomboid, that is suspended from above by thin wires. The relative distance of the pendulum and the rhomboid will be continuously measured via a small Michelson interferometer. When the ground translates, the rhomboid is able to swing on its wires, causing the inverted pendulum to move, and register a change of distance in the interferometer. However, when the ground tilts, the orientation of the rhomboid will not change due to its suspension by wires, and no change in distance will be measured by the interferometer. However, due to the fact that no inertial sensor can completely separate tilt and translation, this method is only effective at frequencies above the resonant frequency of the suspended rhomboid.

The interferometer will be a typical Michelson interferometer, in which light travels down two orthogonal arms and is reflected back to the junction of the arms. The resulting interference of the light when it recombines allows the calculation of the relative distance between two objects (in this case the rhomboid and the inverted pendulum). The lengths of the arms of the interferometer must be accurate to less than 1mm, to reduce frequency noise. Fiber coupled light from another optics table goes to the interferometer, where there will be a 10kHz piezoelectric transducer (PZT) actuator. This PZT is used to modulate the length of one of the arms of the interferometer, which produces a known signal to look for at the asymmetric port. This error signal will be fed back to the PZT after being digitized through a control filter and a digital-to-analog converter.

This prototype seismometer will also include an insulative housing and a temperature-control system. The operating temperature of the seismometer will be kept at roughly 10°C above room temperature. Thermal noise is negligible in this prototype, so the ability to heat the seismometer gives the ability to more precisely hold the seismometer's internal temperature at a single value. The housing will consist of aluminum alloy sheets that cover the frame of the seismometer, one flat silicone rubber heater per face of the seismometer, and foam insulation covering the whole of the frame. An analog temperature-control loop will be constructed and used to keep the temperature at a desired value.

3 Project Progress

3.1 Thermal Housing

The frame for the seismometer was constructed from 45mm square aluminum McMaster-Carr extrusion pieces. It is a simple rectangular prism, 36" high and 27.5" wide and deep. There is a crossbar across the top of the frame, for use in suspending the rhomboid. Once the frame was constructed, the attachment of the aluminum sheets and foam insulation were discussed at great length. The sheets, along with the foam on top of them, will be attached to the frame via drop-in spring-held fasteners to the frame, and 1" screws. The top portion of the frame, including the cross bar and any supports above it, will be enclosed in a lid made of the same aluminum and foam that surrounds the base. Thus far, the aluminum sheets have been cut, the through hole placements have been measured, and all of the holes have been drilled.

A thermal time constant for the system was calculated via basic differential equations. Starting from the simple equation $dQ = mc \cdot dT$ and defining the dQ as the net flow of energy through the system, the following differential equation was calculated:

$$T'(t) = A - BT(t) \tag{1}$$

where the constants A and B are defined as follows:

$$A = \frac{1}{mc}(P_{in} - KA_{side}d_{insul}T_{lab}),\ B = \frac{KA_{side}d_{insul}}{mc} \tag{2}$$

where P_{in} is the power delivered into the system by the heaters, K is the K-factor of the insulation, d_{insul} is the thickness of the insulation, T_{lab} is the constant temperature of the lab room, A_{side} is the area of one face of the frame, m is the mass of the frame and outer layers, and c is the specific heat of aluminum. Solving equation (1) yields the following:

$$T(t) = \frac{A}{B} + C_1 e^{-Bt} \tag{3}$$

which implies that the time constant for the system is the inverse of B. Using estimates for the parameters of the system, the time constant was calculated to be 2.25 hours. This is longer than the desired 500 second time constant, so parameter space of the system must be explored in order to yield a lower time constant.

3.2 Michelson Interferometer

The rhomboid has been suspended from the outer frame using high-carbon steel wires, secured at the lower end with pin vises and at the upper end with pin vises and plate clamps. A first attempt to suspend the rhomboid resulted in a broken pin vise, but after using epoxy to secure it, the rhomboid was successfully suspended and remained suspended for a long period of time. More pin vises were ordered, so that in a later generation of the project epoxy will not need to be used.

The rhomboid had a very low resonant frequency of about 40 mHz. The tens of millihertz range approaches the lower limit of resonant frequencies in mechanical devices, which bodes well for this design. The resonant frequency will change as we add the inverted pendulum and the Michelson optics to the rhomboid, but the initial suspension test was completed with good results.

4 Project Challenges

The biggest challenge of the project has been the design of the thermal enclosure. The basic design, including the layered structure of frame, aluminum sheeting, heaters, and insulation, was well-defined, so the challenges have lain in the specifics of fitting all the layers together. The initial design was to have one sheet of aluminum per face of the frame, but after cutting the aluminum sheeting too short, the design was modified to include a separate lid component. An added benefit of the lid is accessibility: it offers the ability to access the inside of the seismometer without having to completely remove one of the side panels.

Another challenge has been the behavior of the suspended rhomboid. When first suspended, it did not hang straight down from the suspension point, rather, it twisted slightly around its two support wires. It also hung slightly higher to one side than the other. The twisting could be due to a wire being attached when it was not fully unwound, and the uneven hang could be due to uneven upper pin vises. Re-suspending the rhomboid after confirming that the wires are not twisted on themselves may fix the twisting problem, while careful weight distribution will fix the uneven hang.

References

[1] Abramovici, A.; Althouse, W. E.; Drever, R. W. P.; Gürsel, Y.; Kawamura, S.; Raab, F. J.; Shoemaker, D.; Sievers, L.; Spero, R. E.; Thorne, K. S.; Vogt, R. E.; Weiss, R.; Whitcomb, S. E.; Zucker, M. E., *LIGO: The Laser Interferometer Gravitational-Wave Observatory*. Science, 256, 325-333, 1992.

[2] Dooley, K. *Seismic Isolation*. Presentation for LIGO SURF, DCC G1500851-v1, 2015.

[3] Matichard, F.; Mittleman, R.; Evans, M., *On the mechanical filtering of the transmission of tilt motion from ground to horizontal inertial sensors*. Pre-print for submission to the Bulletin of the Seismological Society of America (2015).

[4] Dooley, K.; Moon, S.; Arai, K.; Adhikari, R., *Towards a tilt-free seismometer design*. Poster at March LVC Meeting (2015), DCC G1500315-v1.