Prototyping a Tilt-Free Seismometer for the Laser Interferometer Gravitational-Wave Observatory

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What is LIGO?

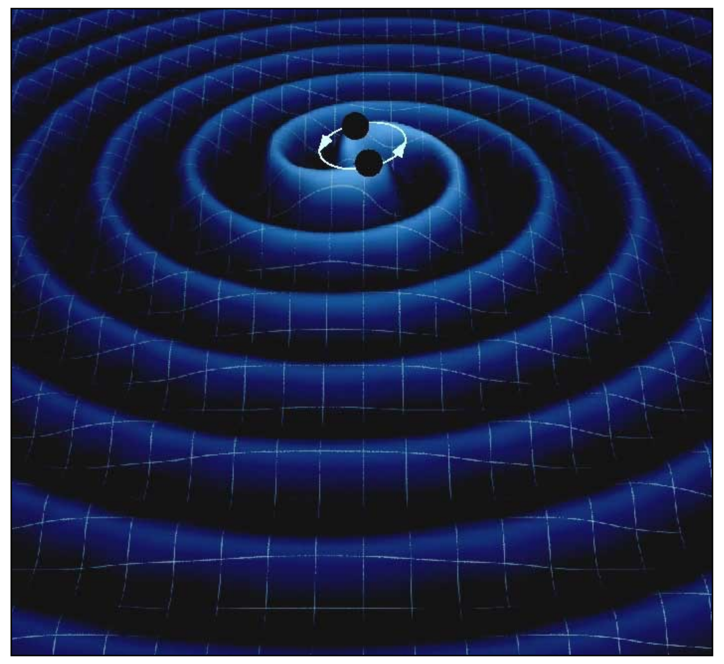

Fig. 1 - Two orbiting black holes producing gravitational waves.

Gravitational waves are ripples in spacetime that are caused by masses in motion. With current detector technology, only very large, fast-moving masses produce gravitational waves that have an amplitude large enough to be detected. Such events are black hole and neutron star mergers, supernovae, and pulsars. Inspiraling bodies produce low frequency gravitational waves over many years, while coalescing bodies produce high frequency gravitational waves for just several seconds.

Because gravitational waves induce relative motion between test masses, they can be detected with a Michelson interferometer (Figure 2). An incoming gravitational wave will disturb the Michelson's end mirrors, and this differential change in length can be detected at the output port.

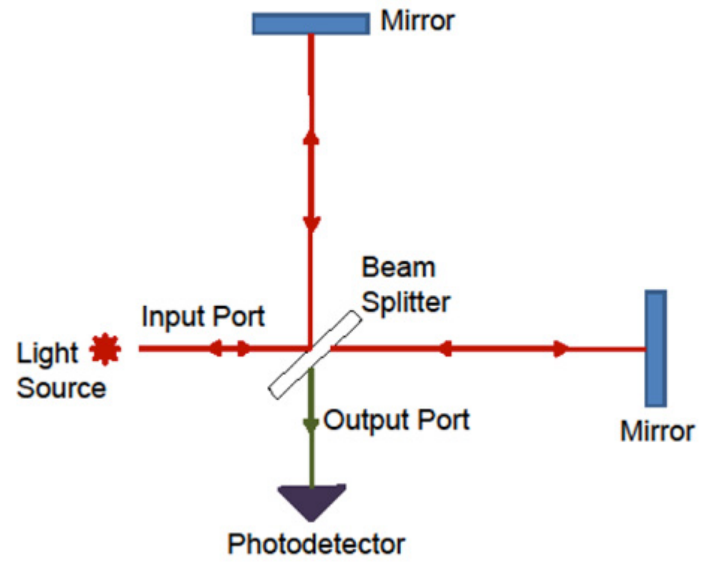

Fig. 2 - A Michelson interferometer, which can be treated as a simplified version of LIGO.

LIGO = Laser Interferometer Gravitational-Wave Observatory

Fig. 3 - The LIGO detector in Livingston, Louisiana. A second identical detector is located in Hanford, Washington.

Initial LIGO operated from 2002-2010, and a shutdown occurred between 2010-2015 to upgrade the system to Advanced LIGO. Advanced LIGO uses:

- 4 km interferometer arms
- Fabry-Perot cavities on each arm to increase effective cavity length
- ~750kW 1064nm laser
- ~34cm diameter, ~40kg fused silica test masses
- Quadruple pendulum suspensions for test masses

First observing run of Advanced LIGO is September 2015 through January 2016. The first direct detection of gravitational waves is widely expected within the next two years.

LIGO's Seismic Noise

A major source of noise for LIGO is ground motion that disrupts the test masses. This noise can be produced by people walking near the detector, trucks driving by, ocean waves, wind, and many other things. This noise is dominant at frequencies below approximately 40Hz. Gravitational waves produced by inspirals occur at this frequency, so to detect them, seismic noise must be reduced: the "seismic wall" in LIGO's sensitivity curve (Figure 4) must be lowered.

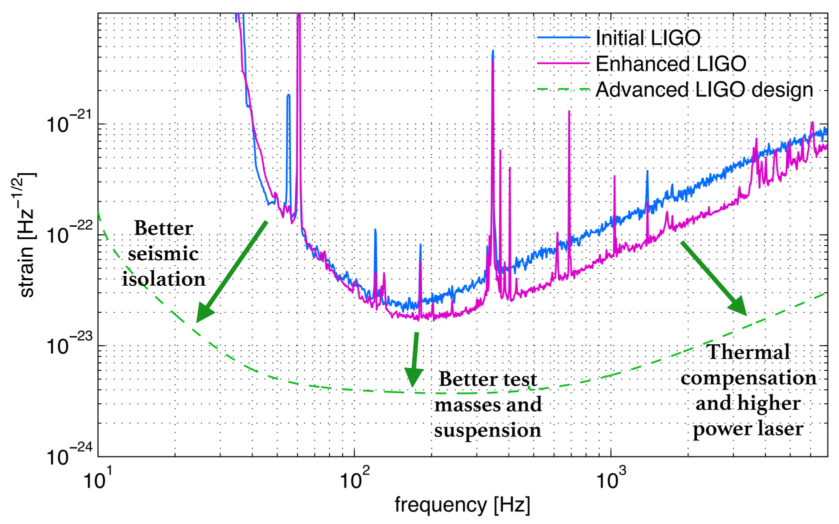

Fig. 4 - LIGO's sensitivity curve showing the three regimes of limiting noise: seismic, thermal, and quantum.

Two types of seismic isolation:

- **Passive**
  - Inherent to the device's mechanical structure (ex. shocks on a car).
- **Active**
  - Motion is measured (with seismometers) and actively corrected for via actuators (ex. a Segway).

Tilt-Free Seismometer: Theory

Problem: Ground tilt, occurring at low frequencies and often caused by wind, can contaminate the translation readings of seismometers (Figure 5). Current seismic isolation systems measure ground tilt separately with a tiltmeter then subtract the tilt component from the seismometer reading. However, the noise in this additional instrument often reduces the precision of the data greatly.

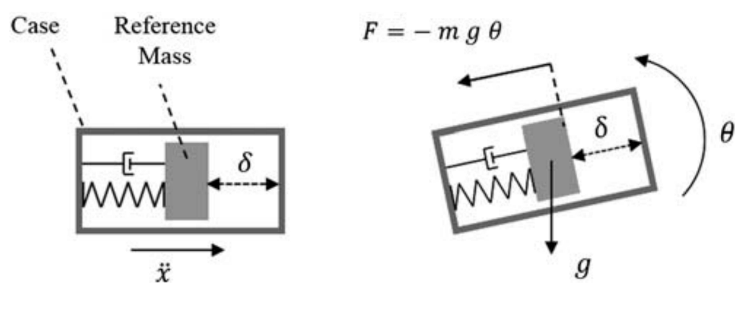

Fig. 5 - Tilt-translation coupling, a consequence of the principle of equivalence, shown in an oscillating mass seismometer. Ground translation (left) causes the same spring compression as ground tilt (right).[1]

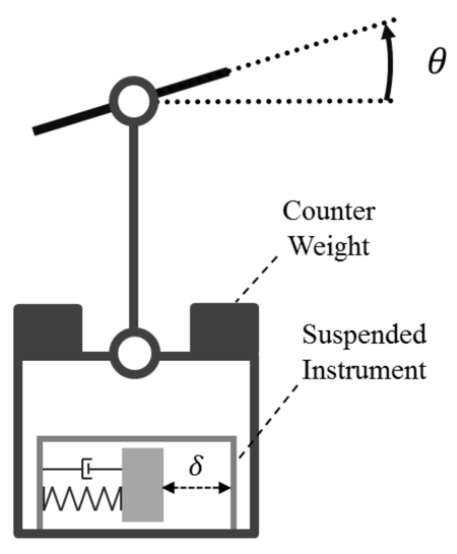

Fig. 6 - A seismometer suspended as a pendulum.[2]

Solution: Rather than have the seismometer in direct contact with the ground, suspend it as a pendulum (Figure 6) with the suspension point on 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, but *will* move if the ground translates.

However, the suspension point will not be ideal, so the pendulum's ability to filter tilt becomes frequency dependent (Figure 7). The general shape of the oscillator's behavior in frequency space is that of a high-pass filter. Because the decrease in oscillator response takes effect only above the resonant frequency, it is important to push the tilt resonant frequency as low as mechanically possible.

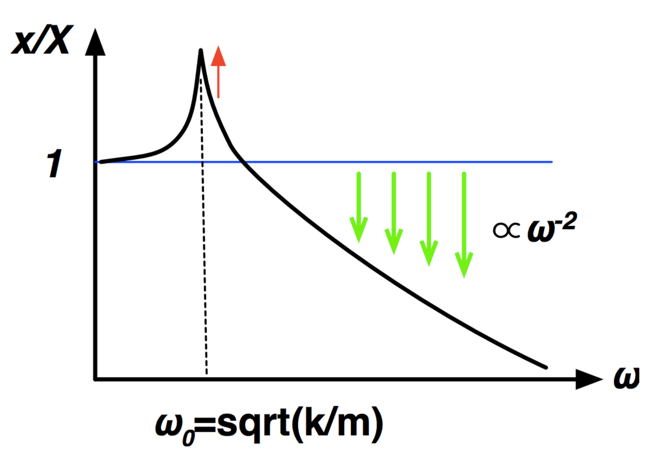

Fig. 7 - The frequency-space behavior of a pendulum: a high-pass filter.[3]

Tilt-Free Seismometer: Design

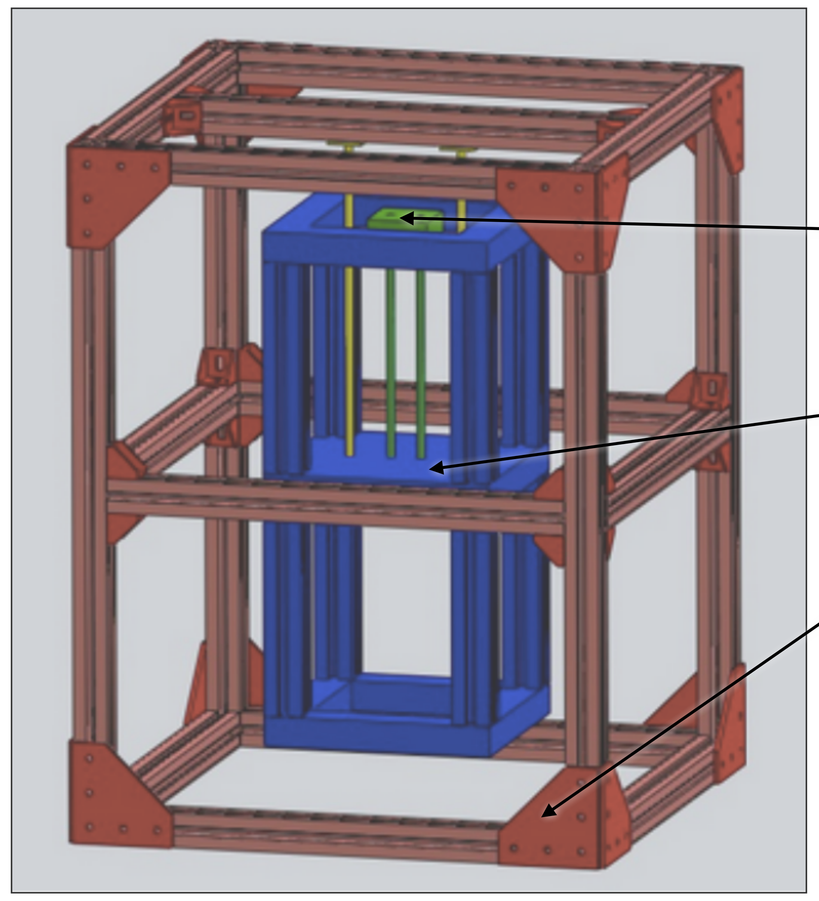

Fig. 8 - The tilt-free seismometer as designed by K. Dooley, S. Moon, and R. Adhikari.[4]

Inverted Pendulum: The oscillator that allows the seismometer to measure ground motion. Analogous to the mass on the spring in Figure 6.

Rhomboid: The 'box' for the oscillator that is suspended as a pendulum (suspension wires are shown in yellow).

Frame: The outer support of the seismometer that supports the pendulum and is rigidly attached to the ground.

Two major components to the the initial prototype of the tilt-free seismometer:

- **Michelson interferometer**
  - Used to measure the relative motion of the rhomboid and the inverted pendulum and provide the information about ground motion.
- **Thermal enclosure and temperature control system**
  - Used to stabilize the temperature of the seismometer and the frame in order to prevent large temperature fluctuations from disturbing the Michelson interferometer.

Construction

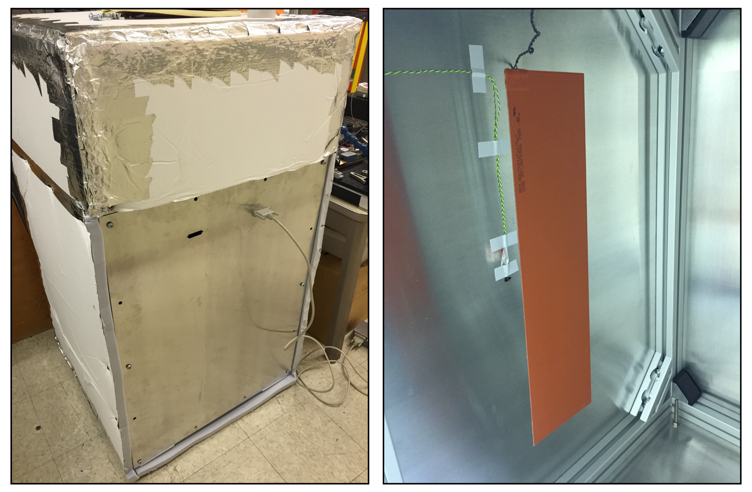

Fig. 9 - The outside of the thermal enclosure (left) and a heater and thermistor inside the enclosure (right).

Thermal Enclosure

- 1/8" aluminum sheeting and 1" melamine insulation fastened to the seismometer frame via drop-in fasteners
- Two 720W flexible silicone-rubber heat sheets and four 10kΩ thermistors used to supply heat and measure enclosure temperature
- For heating, two time constants of 247.1 min. and 7.49 min. For cooling, two time constants of 119.5 min. and 6.39 min.[5]
  - Double exponential behavior suggests a heat leak

Rhomboid Suspension

- Piano wire used in conjunction with pin vises to suspend the rhomboid within the frame
- Initial resonant frequency of rhomboid was ~40mHz, which is near the mechanical limit
- Adding optics increased the resonant frequency to ~100mHz, but the hang of the rhomboid can be fine-tuned to decrease this frequency
- Pin vise clamps were custom designed to prevent any wires from snapping under the rhomboid's weight

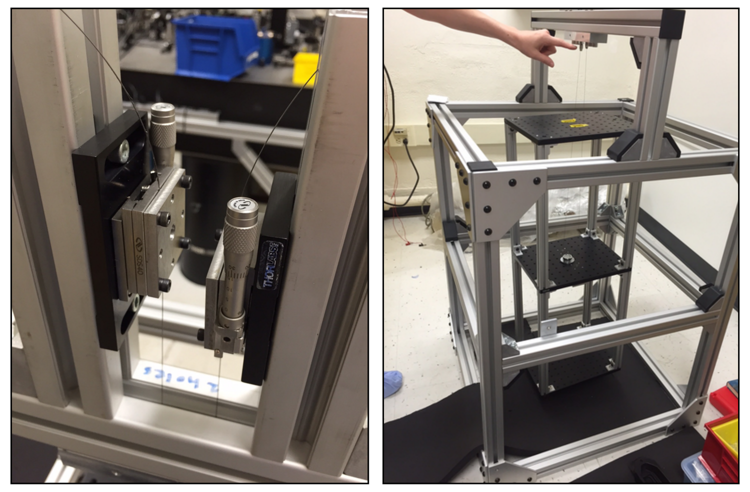

Fig. 10 - The wires suspending the rhomboid (left) and the rhomboid suspended inside the frame (right).

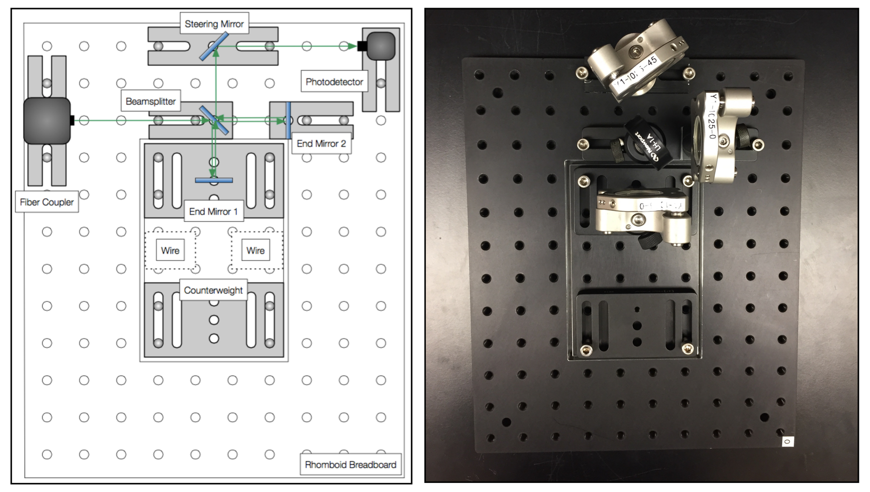

Fig. 11 - The Michelson layout design (left) and the constructed Michelson (right).

Michelson Interferometer

- The Michelson was designed with room to add balancing weights on the opposite side of the breadboard
- To allow the rhomboid to swing freely, ~200mW, 1064nm laser light is fiber-coupled onto the breadboard
- The inverted pendulum mass (rectangular inset of the breadboard) will be machined to allow the suspension wires to pass through it

Conclusions

Future Work

- Constructing a more robust thermal enclosure that will support larger temperature gradients
- Completing the fiber coupling system and calibrating the Michelson
- Installing the Michelson inside the thermal enclosure
- Calibrating the seismometer with known ground motions

End Goals for Seismometer Implementation

- Increase the up-time of the detectors, and thus the chance of detecting gravitational waves.
- Improve the signal-to-noise ratio of a detection, allowing for a better estimation of the parameters of the gravitational wave source.

Acknowledgements & References

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