LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Note **LIGO-T1800273–v2** 2018/06/29

Seismic Cloaking for LIGO

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Abstract

New developments in metamaterials may offer a potential avenue for reducing seismic noise at low frequencies (> 50 Hz). In this study, we investigate the feasibility of using trees as a seismic metamaterial that could shield the LIGO detectors from seismic activity. This seismic cloak would reflect low frequency surface waves away from the detector, thereby increasing the sensitivity of the detectors. This study models the energy transfer from surface waves as they pass through the bandgap filters designed from trees in different arrangements. The attenuation and reflection will hopefully serve to cloak the LIGO detectors from seismic activity. This work could have future impact on high sensitivity detectors, leading to more detections of merger events.

1 Introduction and Literature Review

The LIGO collaboration's goal is to develop gravitational wave astrophysics through the detection of cosmic gravitational waves. The collaboration has built two detectors, located in Hanford, WA, and Livingston, LA. The detectors are laser interferometers with 4km long arms (Figure 1). A laser enters the system and is split into two parts, each of which go down one of the two arms. The beams are then reflected in a mirror, and are read by a photodiode. If a gravitational wave event occurs, spacetime is slightly altered and the length of the beam arm is changed. That change in length puts the two halves of the laser beam out of phase with each other, and that data can be analyzed to find gravitational wave signals [3].

LIGO was designed to measure a wide range of astrophysical sources, but one of the most anticipated first detections was of binary neutron star mergers. Of the six detections that have occurred so far, only one, GW170817, has been of a NS-NS merger, while the rest have all been binary black hole mergers, upending expectations about BBH abundance in the universe.

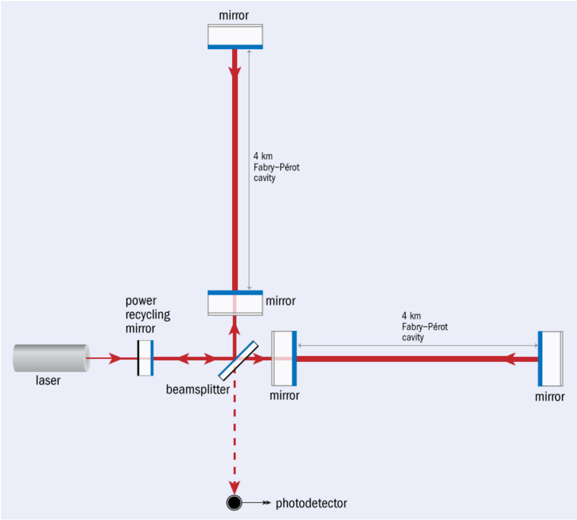

Figure 1: A diagram of the Advanced LIGO detectors [7].

1.1 Limits precision

Ground-based gravitational wave detectors look for signals in the tens to hundreds of Hz via laser interferometers, making filtering out astrophysical signals over terrestrial noise difficult. LIGO operates by looking for strain noise,

$$\Delta L = L - L_1 \rightarrow strain = \frac{\Delta L}{L}, \tag{1}$$

where L is the length of the detector arm and L_1 is the altered length due to some sort of activity. If the strain is high enough, there is a signal, and the LIGO team must then determine its origin. There are many sources of noise in the same band as gravitational wave signals, so reduction of noise is extremely important for data analysis. Figure 2 describes LIGO's current and past sensitivity. L1 stands for the Livingston, LA detector, and H1 stands for the Hanford, WA detector. Signals below the curves cannot be seen for that configuration. The green trace is from the sensitivity reached using the first generation of the LIGO detectors, Enhanced LIGO. After significant improvements to the technology, Advanced LIGO debuted in 2015. The grey trace is the eventual planned sensitivity after all upgrades are completed. Figure 3 shows the different types of noise that can affect LIGO. The red trace is the measured noise, while the other traces are from predicted and measured noise. There are many different types of noise that limit the precision of the detectors ranging from quantum noise to thermal noise to seismic noise. This study focuses on contributions from seismic and Newtonian noise.

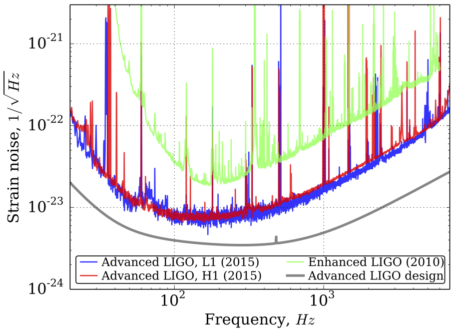

Figure 2: Amplitude spectral density of the detector noise. GW signals that have amplitudes lower than the noise floor cannot be detected with that generation of LIGO [9].

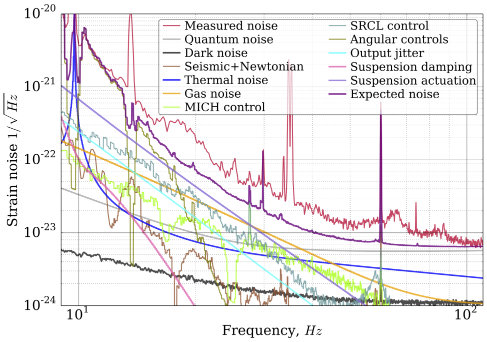

Figure 3: Different types of noise affecting LIGO. The red trace is overall measured noise, while the brown trace is the seismic and Newtonian noise that this paper focuses on [9].

1.2 Newtonian noise

Newtonian noise is caused by mass-density fluctuations due to micro-seismic noise, such as from transportation, ocean waves, and construction [4]. The fluctuations in mass-density then create small gravitational fields, which can then cause instrument components to shift slightly, thereby shortening or lengthening the beam path.

1.3 Seismic noise and LIGO

Seismic noise is a persistent issue for highly precise interferometers, such as gravitational waves. As an example, the gravitational wave strain amplitude of GW170817 (the neutron star merger) was on the order of 10^{-22} [2], while average seismic activity at LIGO-Livingston and LIGO-Hanford is $\sim 10^{-9}$ at 10 Hz [9]. The sensitivity needed to detect such events necessitates extraordinary noise reduction. Seismic waves affect the differential length measurement by slightly shaking the mirrors, and by creating Newtonian noise. As Rayleigh waves move through the ground, they create areas of greater and lesser density in the soil. The mass-density fluctuations will create Newtonian noise, thereby changing the LIGO measurement.

The LIGO detectors already have significant protection from seismic noise by hanging the test masses from a quadruple pendulum system. The quadruple pendulum system has a resonance as low as 0.4 Hz and isolate up to $1/f^8$ in the detection bandwidth. The pendulums themselves are mounted onto active platforms to provide further isolation. The existing isolation systems work mainly in the 1 Hz to 10 Hz band [9].

1.4 Seismic cloaking

One idea to provide further isolation against Newtonian noise is seismic cloaking. Seismic cloaking grew out of the concept of invisibility cloaks, which manipulate electromagnetic waves around an object–making it appear invisible. Shortly after thermodynamic, acoustic and seismic cloaking were investigated. All cloaking is done with metamaterials, which are carefully designed building blocks densely packed into a structure. The structure is usually periodic, but not always [8]. While the majority of metamaterials are artificially made, some natural materials can be manipulated into metamaterials via spacing or other techniques [6].

The first experiment to explore seismic metamaterials was conducted by Brûle et al in 2014. They created a seismic metamaterial by creating a grid of 5 m deep self-stable holes, diameter 0.32 m and spaced 1.73 m apart and tested it with a 50 Hz source. They found that the elastic energy was 2.3 times larger at the source than it was in the metamaterial, suggesting that the seismic metamaterial has a significant effect on energy dissipation [5]. A subsequent experiment by Columbi et al tested trees as a seismic metamaterial and found that forests could attentuate seismic activity in predicted frequencies given the properties of the forest [6].

1.5 Seismic cloaking use in LIGO

This study aims to see if the results of Brûle and Columbi can be applied to LIGO. This project will combine theoretical and experimental work by modeling the effects of trees as a way of reducing the noise properties. Further isolating LIGO against seismic noise ~ 50 Hz will further reduce anthropogenic noise. The goal of this study is to determine if planting trees around the LIGO-Livingston detector will be an effective method of seismic cloaking, and hopefully explore what types of trees or cacti could be used at LIGO-Hanford. Implementing seismic cloaking could both reduce the amplitude of seismic waves, and deflect them away from the detector, thereby enabling better accuracy in signal detection.

1.6 LIGO sensitivity and detection rate

Current estimates place the number of compact binary coalescences per Milky Way Equivalent Galaxy per Myr at around 1000 for a NS-NS merger, 100 for a NS-BH merger, and 30 for a BH-BH merger for realistic estimates. Advanced LIGO is not yet sensitive enough to detect all merger events, so present approximations determine that LIGO can be expected to detect around 40 NS-NS mergers, 10 NS-BH, and 20 BH-BH mergers a year [1]. This is assuming LIGO is constantly observing, so the numbers must be adjusted for the length of observing runs. If seismic cloaking is put into placed at LIGO Livingston or LIGO Hanford, the sensitivity of LIGO would increase, thereby increasing the detection rates.

2 Methods (Progress so far)

Much of this project depends on verifying the results of the Columbi paper (2015). Columbi found with experimental and numerical methods that forests could be modeled as locally vertically resonant metamaterials.

2.1 Rayleigh Waves

How Rayleigh waves interact with trees.

Rayleigh waves are usually in the frequency range of less than 1 Hz to a few tens of Hz [11].

The Rayleigh function [10]

$$\left(2p^2 - \frac{1}{\beta^2}\right)^2 - 4p^2\left(p^2 - \frac{1}{\alpha^2}\right)^{1/2}\left(p^2 - \frac{1}{\beta^2}\right)^{1/2} = 0 \tag{2}$$

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Seismic wave equation [10]

$$\rho\ddot{\mathbf{u}} = \nabla\lambda\left(\nabla\cdot\mathbf{u}\right) + \nabla\mu\cdot\left[\nabla\mathbf{u} + \left(\nabla\mathbf{u}\right)^T\right] + \left(\lambda + 2\mu\right)\nabla\nabla\cdot\mathbf{u} - \mu\nabla\times\nabla\times\mathbf{u} \tag{3}$$

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2.2 Theoretical Work

The focus of the theoretical work will be to understand how seismic waves transfer energy into trees. Since trees have their own resonant frequencies, we will first model them as simple harmonic oscillators and then progress to more complex models. As an introduction, we will understand seismic waves in one dimension. We will model the simple harmonic oscillator in python, then link together multiple oscillators to model individual trees as a forest. Modeling seismic waves as one-dimensional while varying the spacing, Q factor, resonance, etc. of the trees will allow us to determine how these parameters affect cloaking. This will help us understand how reflection and transmission works with metamaterials. COMSOL will then be used for multi-dimensional analysis of seismic waves, which will allow for more precise work.

2.3 Experimental Work

The experimental part of the project will be measuring how trees can affect seismic noise. This can be done in a few ways. Seismometers can be used to measure waves propagating along the ground or in trees, or vibrometers could be attached to multiple points in the tree to determine resonant frequencies. While travel to LIGO-Livingston or LIGO-Hanford is unlikely for this project, the Los Angeles County Arboretum has a large diversity of plant species and could be used to measure the different types of trees. This location would require a portable data logger for vibrometers. The goal of the experimental work is to confirm the theoretical work and begin a plan for how to use trees as seismic metamaterials.

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