LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Seismic Cloaking for LIGO

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Abstract

This paper serves to summarize the work completed so far on LIGO seismic cloaking. Seismic activity is a significant source of noise for the LIGO detectors, and cloaking would increase the sensitivity of the detectors. This paper contains a summary of seismic and Newtonian noise, along with current LIGO detection rates. It describes methods used to determine if seismic cloaking is a feasible option, and the results so far. It concludes with work yet to be completed, and options for extending the project.

1 Introduction

Laser Interferometer Gravitational-Wave Observatory (LIGO) is an observatory with locations in Hanford, WA, and Livingston, LA, with the goal of developing gravitational wave (GW) astrophysics through the detection of cosmic GW. LIGO works with a laser interferometer system. A laser enters the system and is split into two parts, which each go down one of the two 4km long arms (separated by 90 degrees). If a gravitational wave event occurs, spacetime is slightly altered, and one of the two beams is out of phase with the other. When the two beams recombine, they form an interference pattern [2]. LIGO was originally expected to detect mainly neutron star-neutron star (NS-NS) mergers, as binary black hole (BBH) mergers were thought to be more difficult to detect. However, of the six detections that LIGO has so far achieved, only one, GW170817, was of a NS-NS merger, while the others have all been BBH mergers.

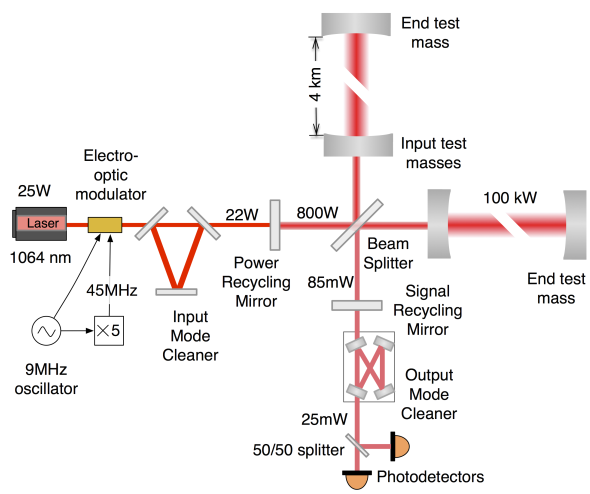

Figure 1: A diagram of the Advanced LIGO detectors [6].

1.1 Limits precision

GW signals are in the tens to hundreds of Hz, making filtering out legitimate signals over noise difficult. The many sources of noise are often in the same range as GW signals, so cancellation of noise is extremely important. The main sources of noise for LIGO can be seen in Figure 3. You can see how all the difference sources of noise affect the overall sensitivity of LIGO by looking at Figure 2. Signals below the amplitude of the different noise floors cannot be detected by LIGO.

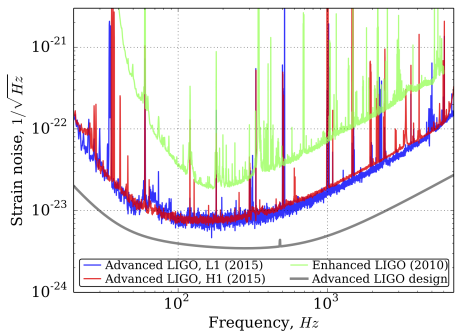

Figure 2: Amplitude spectral density of the detector noise. GW signals that have amplitudes lower than the noise floor cannot be detected with Advanced LIGO [6].

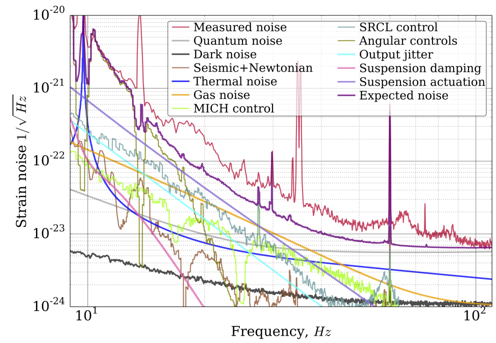

Figure 3: Different types of noise affecting LIGO. This paper focuses on contributions from seismic and Newtonian noise [6].

1.2 How does seismic noise affect LIGO

Seismic noise is a persistent issue for highly precise interferometers, such as gravitational wave detectors. Natural causes of seismic waves are mostly ocean waves and wind, while artificial causes are usually traffic and construction [9]. This noise can affect GW detectors by artificially shaking the arms of the detector, causing false signals. Seismic waves can propagate in all directions, and at different velocities and frequencies, making detecting legitimate signals difficult. Seismic noise comes in at 20 Hz and below, while black holes and binary neutron stars give out signals in the 10-20 Hz band. Lowering noise in the band will allow for clearer detection of signals for black hole mergers and earlier detection of binary neutron star systems, creating the ability to point the telescope at binary neutron star mergers before they happen. Implementing seismic cloaking can allow seismic noise to pass by instrumentation without affecting it, enabling better accuracy in signal detection.

1.3 Newtonian noise

Another factor affecting LIGO is Newtonian noise. Newtonian noise is caused by mass-density fluctuations due to micro-seismic noise, such as from transportation, ocean waves, and construction [3]. 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. This creates noise in highly sensitive instruments such as LIGO.

1.4 Seismic cloaking

Seismic cloaking grew out of the concept of invisibility cloaks, which manipulate electromagnetic waves around an object–making it appear invisible. From there, scientists moved onto thermodynamic cloaking, acoustic cloaking, and then seismic cloaking. All cloaking is done with metamaterials, which are carefully designed building blocks densely packed into a structure. They are usually periodic, but not always [5]. While the majority of metamaterials are artificially made, some natural materials can be manipulated into metamaterials via spacing or other techniques [4].

1.5 Seismic cloaking use in LIGO

This project aims to see if trees can be used as natural seismic metamaterials to reduce seismic noise. Columbi et al (2015) [4] theorized that resonance in forests could be used to attenuate seismic waves. This project will combine theoretical and experimental work by modeling how seismic waves are affected by forests, and measuring different types of trees to discover resonant frequencies. The goal of this project 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.

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

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 [8].

The Rayleigh function [7]

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

seismic wave equation [7]

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

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.

References

[1] J Abadie et al. "Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors". In: *Classical and Quantum Gravity* 27.17 (Sept. 2010), p. 173001. ISSN: 0264-9381. DOI: 10.1088/0264-9381/27/17/173001.

[2] *About — LIGO Lab — Caltech*. URL: https://www.ligo.caltech.edu/page/about (visited on 06/14/2018).

[3] M Beccaria et al. "Relevance of Newtonian seismic noise for the VIRGO interferometer sensitivity". In: *Class. Quantum Grav* 15.98 (1998), pp. 3339–3362.

[4] Andrea Colombi et al. "Forests as a natural seismic metamaterial: Rayleigh wave bandgaps induced by local resonances". In: *Scientific reports* 6 (2016), p. 19238.

[5] Muamer Kadic et al. "Metamaterials beyond electromagnetism". In: *Reports on Progress in Physics* 76.12 (Dec. 2013), p. 126501. DOI: 10.1088/0034-4885/76/12/126501.

[6] D. V. Martynov et al. "The Sensitivity of the Advanced LIGO Detectors at the Beginning of Gravitational Wave Astronomy". In: (Apr. 2016). DOI: 10.1103/PhysRevD.93.112004. arXiv: 1604.00439.

[7] Peter Shearer. *Introduction to seismology*. 1st Ed. Cambridge University Press, 1999. ISBN: 0521660238.

[8] Ping Sheng. "A Step Towards a Seismic Cloak". In: *Physics* 7.112 (Mar. 2014), p. 34. ISSN: 1943-2879. DOI: 10.1103/Physics.7.34.

[9] Stanford Exploration Project. *What is seismic noise ?* 2005. URL: http://sepwww.stanford.edu/public/docs/sep121/paper%7B%5C_%7Dhtml/node2.html (visited on 06/14/2018).