LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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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
from surface waves as they pass through the bandgap filters designed from trees in different arrangements
energy transfer as waves pass through bandgap filters. 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, which each go down an arm. 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 [**aboutLIGO**].

start a new paragraph

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.

nice! I love it

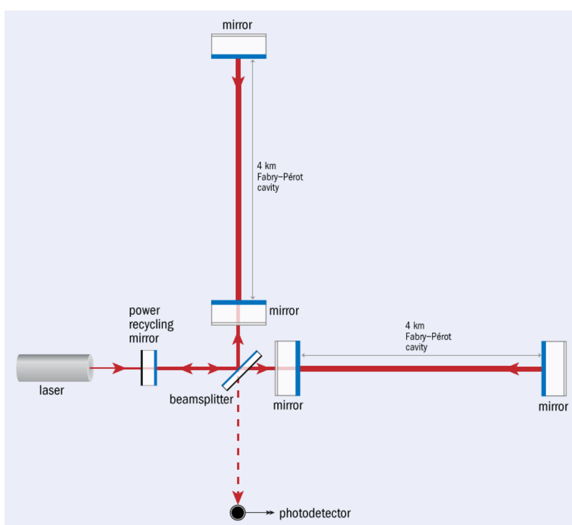

Figure 1: A diagram of the Advanced LIGO detectors [**ligoFig**].

Incorporate what the measurement from the detectors are
1 - delta L == L1 - L2
2 - strain = (L1-L2) / L
3 - Now discuss figure 2

The green trace is from the sensitivity reached using first generation of the LIGO detectors, Enhanced LIGO. After significant improvements to the technology for the upgraded Advanced LIGO,...

1.1 Limits precision

Ground-based gravitational wave detectors look for signals in the tens to hundreds of Hz, making filtering out astrophysical signals over terrestrial noise difficult. There are many sources of noise in the same band as gravitational wave signals, so reduction of noise is extremely important. Figure 2 describes LIGO's current and past sensitivity. Signals below the curves cannot be seen for that configuration. Green is the Enhanced LIGO design, which debuted in 2010. The red and blue lines are for the upgraded Advanced LIGO, which first debuted in 2015, ~~but it still being completed.~~ L1 stands for the Livingston, LA detector, and H1 stands for the Hanford, WA detector. The grey line is the Advanced LIGO design, and is hopefully where LIGO will be once the all the upgrades are complete. The plot shows that it's much easier to detect signals in the low hundreds of Hz than the tens or thousands of Hz. The reason for these curves is because of exterior noise that must be filtered out before detection of astrophysical signals can take place. This can be seen in Figure 3. The red line on top is all measured noise for the detectors, and every other line is either measured or predicted noise from various sources. This study focuses on contributions from seismic and Newtonian noise.

it is "complete; rather we are introducing upgrades :)

we should discuss this part

There are many different types of noise that limit the precision of the detectors ranging from quantum noise to thermal noise to seismic noise.

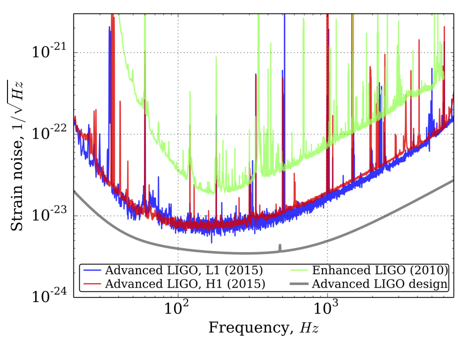

Figure 2: Amplitude spectral density of the detector noise. GW signals that have amplitudes lower than the noise floor cannot be detected with Advanced LIGO [**Martynov2016**].

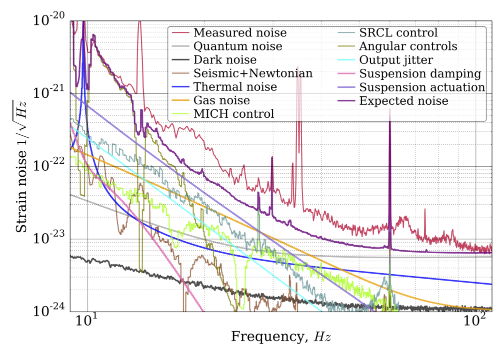

Figure 3: Different types of noise affecting LIGO. This paper focuses on contributions from seismic and Newtonian noise [**Martynov2016**].

1- what is seismic noise (you have this already)
2 - how does a seismic wave effect the differential length measurement (delta L)? you can reference the equation from above
3 - look up what the current suspension system is - i.e. the quadruple pendulum system
4 - discuss how that reduces noise in the 50ish Hz range

1.2 How does seismic noise affect LIGO

I didn't really change up this section at all because I'm having a lot of problems with it. I should have written down more of what you said, because I'm not sure how I need to change it up. I know in general I need more numbers here and less qualitative data, but I know the direction of the paragraph also isn't great. If you could provide some more guidance there on what I should do with this bit, that would be super helpful.

Seismic noise is a persistent issue for highly precise interferometers, such as gravitational wave detectors. ~~This is because astrophysical signals are very tiny, while terrestrial signals are much larger.~~ The change in arm length due to a gravitational wave is less than an atom, I NEED MORE QUANTITATIVE DATA HERE AHHH. Natural causes of seismic activity

you said this part already earlier

look up what the detected amplitude was for one of the first detections and you will have this number. Maybe have this after you talk about the sensitivity curve people generated causes?

are typically ocean waves and wind, while artificial causes are usually traffic and construction [**StanfordExplorationProject2005**]. Seismic waves can propagate in all directions, and at different velocities and frequencies, ~~which makes detecting astrophysical signals difficult.~~

what does artificially shaking mean? how is this propogating wave effect the difference in the arm length?

Natural causes of seismic waves are mostly ocean waves and wind, while artificial causes are usually traffic and construction [**StanfordExplorationProject2005**]. 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.

this is a bit complex in the sense that this sensitivity improvement doesn't necessarily correspond to the way we are able to send out alerts for follow-up with E&M partners though we can discuss this.

1.3 Newtonian noise

What is the difference between these waves and the seismic ones? Are they a different category?

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 [**Beccaria1998**]. 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~~. You have already said this type of sentence earlier

great!

By reducing these types of waves from propagating near the instrument, we can directly increase the low frequency sensitivity of the LIGO detectors.

1.4 Seismic cloaking

Add in a transition sentence linking newtonian noise to seismic cloaking. i.e. one idea is to explore the idea of using 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 [**Kadic2013**]. While the majority of metamaterials are artificially made, some natural materials can be manipulated into metamaterials via spacing or other techniques [**colombi2016forests**]. Implementing seismic cloaking ~~can~~ could allow seismic noise to pass by instrumentation without affecting it, enabling better accuracy in signal detection.

what are the other techniques?

move this sentence to the next section

perhaps we say - seismic cloaking could reduce the amplitude of waves propagating to the insturment? or have them be deflected away? or something like this. i think if you say 'pass by' that still seems as though they are influencing the detectors

1.5 Seismic cloaking use in LIGO

Brule, et. al

The first experiment to explore seismic metamaterials was conducted by Brle, Javelaud, Enoch, and Guenneau 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 [**Brule2014**]. 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 [**colombi2016forests**].

add this paragraph to the section above

This study aims to see if the results of Brle 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. 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.

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 [**Abadie2010**]. 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 [**Sheng2014**].

The Rayleigh function [**Shearer1999**]

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

.

Seismic wave equation [**Shearer1999**]

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

.

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.