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 (< 10 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.

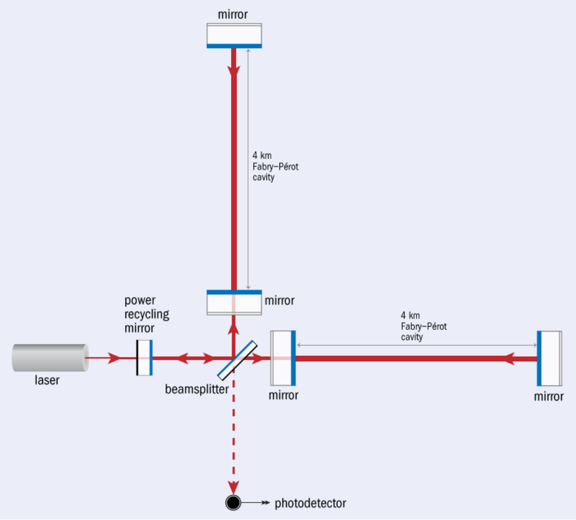

Figure 1: A diagram of the Advanced LIGO detectors [7].

1.1 Limits precision

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

$$\Delta L = L_1 - L_2 \rightarrow strain = \frac{\Delta L}{L}, \tag{1}$$

where L_1 is the length of the x-arm and L_2 is the length of the y-arm. If there is an increase in strain, then the LIGO team must determine the origin, whether astrophysical or terrestrial. 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.

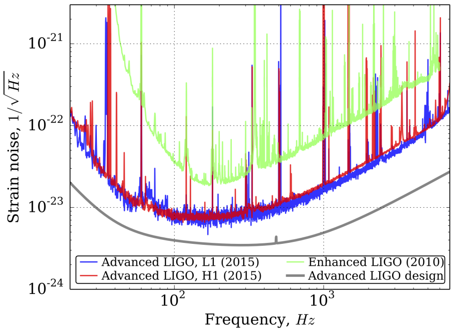

Figure 2: Amplitude spectral density of the detector noise. GW signals that have amplitudes lower than the noise floor cannot be detected with that generation of LIGO [9].

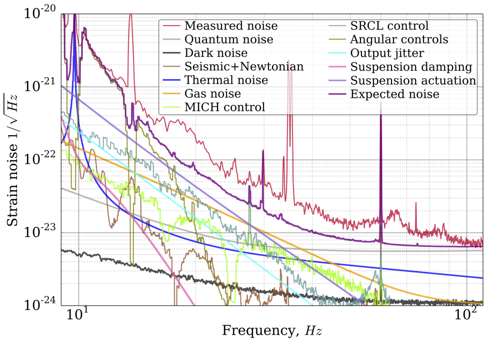

Figure 3: Different types of noise affecting LIGO. The red trace is overall measured noise, while the brown trace is the seismic and Newtonian noise that this paper focuses on [9].

1.2 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.

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].

1.3 Newtonian noise

Newtonian noise is caused by mass-density fluctuations due to micro-seismic noise, such as from transportation, ocean waves, and construction [4]. As Rayleigh waves move through the ground, they create areas of greater and lesser density in the soil. 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.

1.4 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 of 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 the longitudinal resonance inside the trees created two highly attenuating regions between 15 and 130 Hz. They also found that the various sizes and locations of the trees enhanced the abilities of the bandgap filter more than if the trees were spaced uniformly. Columbi theorizes that cloaking could be achieved for ≤ 10 Hz with trees of longitudinal resonant frequency ≤ 10 Hz [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 Computational work

2.1.1 Cloaking

Cloaking works by manipulating waves around an object, thereby rendering it invisible to the waves. This is done by creating bandgap filters where the waves are scattered through the cloak and then cancel each other out due to destructive interference [11]. Cloaking has been studied in electromagnetics, acoustics, seismology, and thermodynamics. An object with an electromagnetic cloak is still susceptible to acoustic waves, as different types of cloaks do not work together.

This section studies the energy transfer as waves pass through bandgap filters. It starts by modeling specific aspects of cloaking, then moving into using acoustic cloaking as an analog for seismic cloaking. Acoustic cloaking is similar to seismic cloaking and does not require solving full elastodynamic equations. This is because acoustic and seismic waves have a number of similarities, and can be modeled similarly. Large scale models of acoustic metamaterials could become seismic metamaterials [11].

COMSOL Multiphysics is interactive software designed to simulate physics problems. As seismic cloaking pulls from a number of different fields, models were first created that tested only a single aspect of cloaking. Seismic cloaking requires negative refracting index, as does all electromagnetic, acoustic, and elastodynamic cloaking [8]. As seen in Figure 4, the waves switch direction at the boundary with the negative refracting index. This is the basis of cloaking.

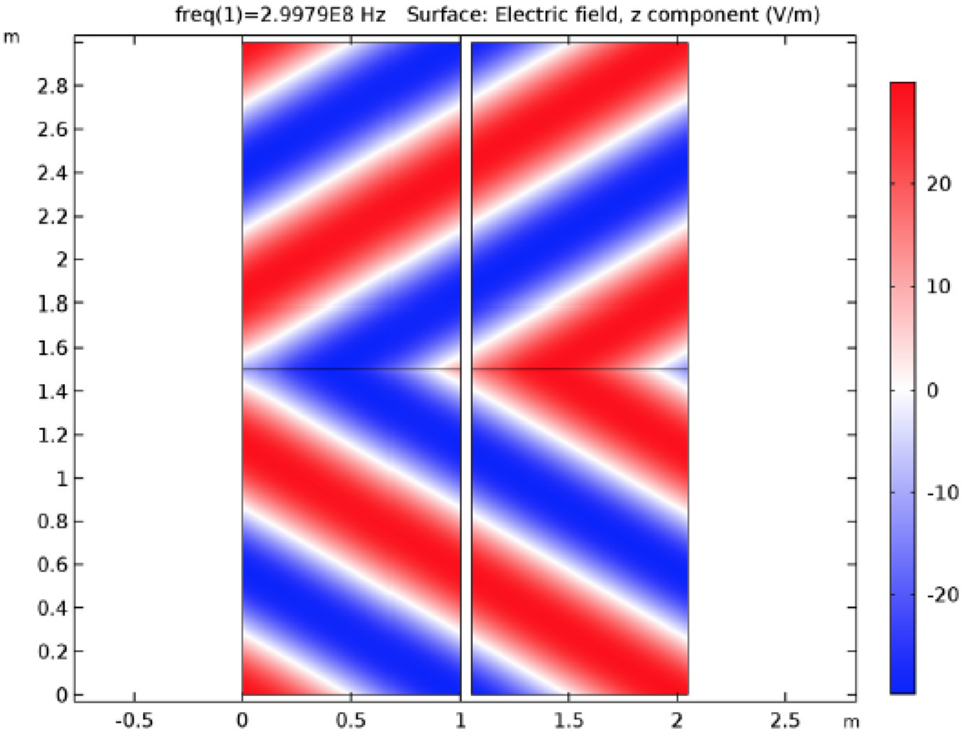

Figure 4: Model of a plane wave traveling through a vacuum (upper) and incident on a metamaterial (lower) with bulk negative permability and permittivity. The block on the left models the wavevector in the material and then adjusts the propagation constant at the boundary for a negative index. The block on the right truncates the domain and acts as an absorbing medium for energy (it is also adjusted for the negative index).

2.1.2 EM cloaking

While electromagnetic cloaking is not as similar as acoustic cloaking to seismic cloaking, it can still hold useful lessons. Figure 5 shows wave propagation through a photonic crystal created from GaAs pillars placed equal distance from each other. Some frequencies of light are not allowed to propagate through the structure. This depends partially on the distance between the pillars and partially on the wave number.

2.1.3 Acoustic cloaking

Starting with acoustic cloaking allows the beginning of quantifying the relationship between the incoming waves and the structure of the cloak. The acoustic cloaking model was initially run with $f = 50, 100, 200, 250, 400$ Hz. The cloak is the most effective at low frequencies, as seen in the comparison between Figure 6 and Figure 11. Interestingly, the cloak mostly evens out the pressure wave to ~ 1.0 Pa at all frequencies, although you can see the beginnings of fluctuations in Figure 8, and it's the most prominent in Figure 11.

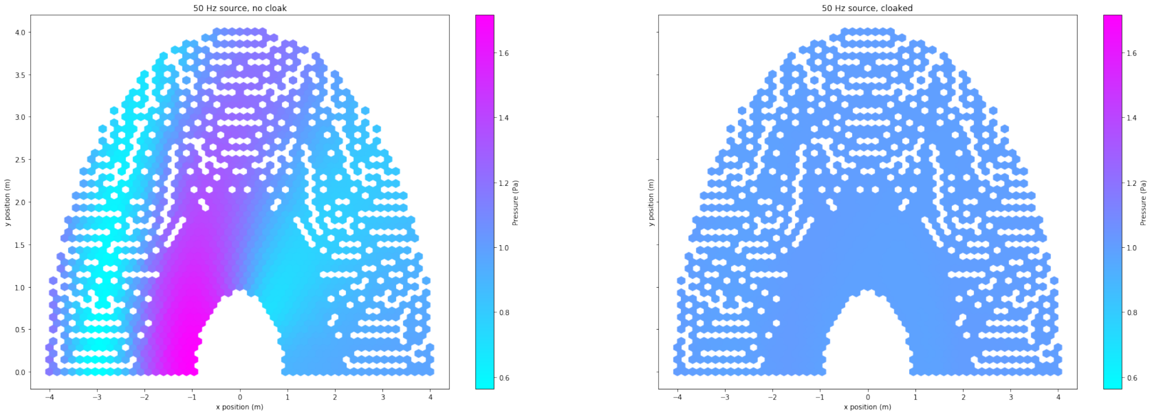

Figure 5: A model of a half circle with and without a cloak. The left image is without a cloak, while the right has a 1 m radius cloak in the inner radius. The incoming wave is at 50 Hz.

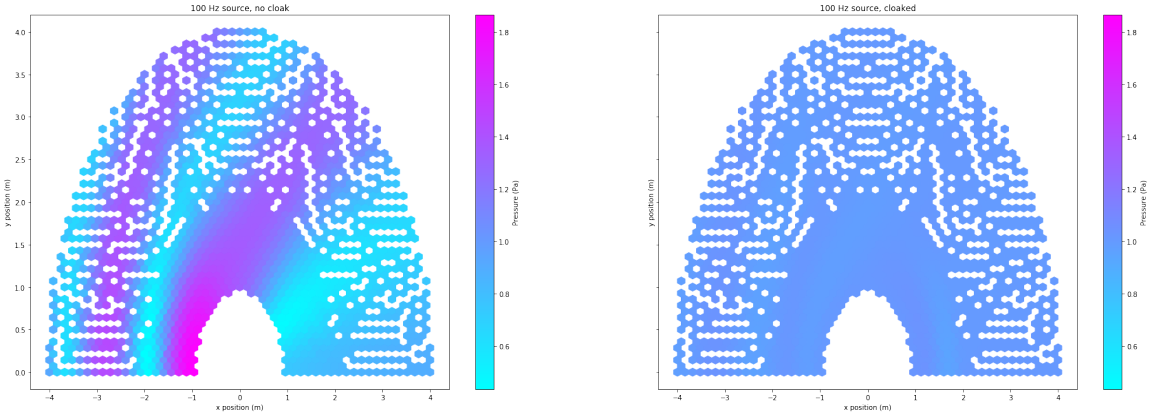

Figure 6: A model of a half circle with and without a cloak. The left image is without a cloak, while the right has a 1 m radius cloak in the inner radius. The incoming wave is at 100 Hz.

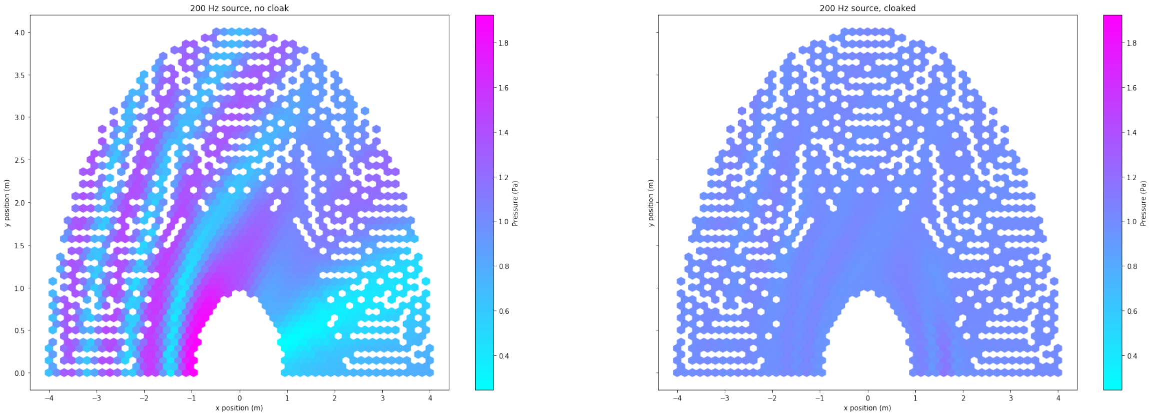

Figure 7: A model of a half circle with and without a cloak. The left image is without a cloak, while the right has a 1 m radius cloak in the inner radius. The incoming wave is at 200 Hz.

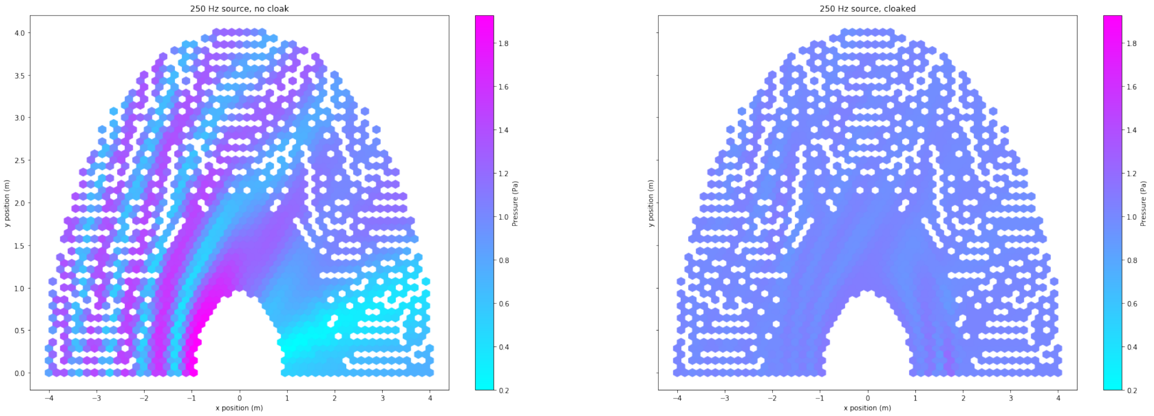

Figure 8: A model of a half circle with and without a cloak. The left image is without a cloak, while the right has a 1 m radius cloak in the inner radius. The incoming wave is at 250 Hz.

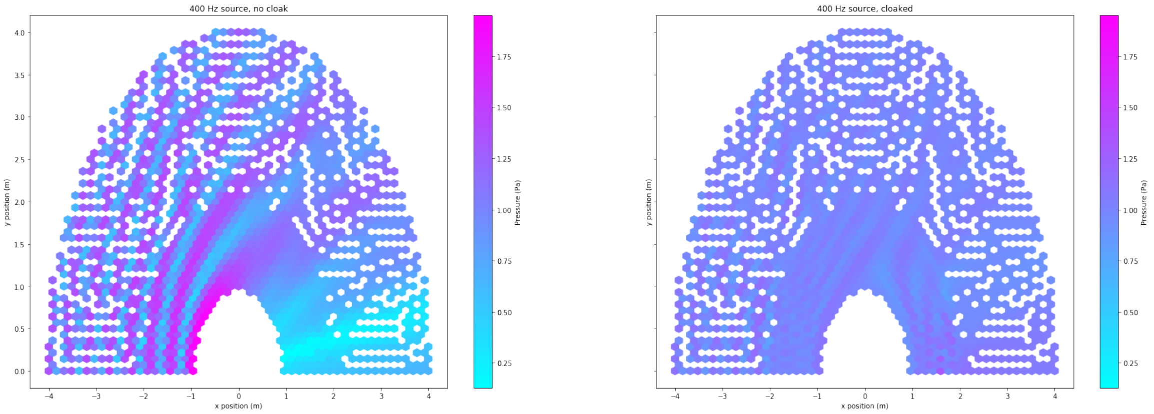

Figure 9: A model of a half circle with and without a cloak. The left image is without a cloak, while the right has a 1 m radius cloak in the inner radius. The incoming wave is at 400 Hz.

All the models were run with the wave propagating in the $+x$ direction. The cloak is made up of 50 layers each 0.02 m thick. The plots show the absolute pressure field, and are plotted with hexagonal binning. The pressure scales for each frequency (the color bar) are identical, although the scale is not identical across the different frequencies. The minimum and maximum for the color bar is set from the minimum and maximum pressure values across both plots for each frequency.

The goal is to be able to get down to ≤ 10 Hz, as that is the noisiest band of seismic noise (see Figure 3), and to lower the floor of the final frequency after the cloak. Effective cloaking at 10 Hz will require redesigning the cloak, as currently the cloaks are not able to hold a full wavelength at 10 Hz, due to the size. Cloaks are able to operate on a subwavelength scale, but at $c_s \approx 400$ m/s, $\nu \approx 40$ m, which is much larger than the $\nu \approx 2$ m found at 200 Hz. Creating a cloak for 10 Hz and below will require a physically larger model, as well as redesigning the cloak. Redesigning the cloak will most likely mean changing the number of layers as well as altering the thickness of the layers.

2.2 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]

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

.

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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2.3 Experimental Work

The experimental portion of this project is measuring how trees can affect seismic noise. This is done with geophones and possiby vibrometers and velocimeters. Data is taken and then digitized and analyzed. A semi-constant source of noise is needed so that data can be taken in front of and behind the "cloak" (the trees) to see how well the trees cloak the detectors from noise. The Los Angeles County Arboretum has a large diversity of plant species, and will be used to take initial measurements. Additionally, Interstate 210 is just north of the arboretum, and can be used as a near constant source of noise.

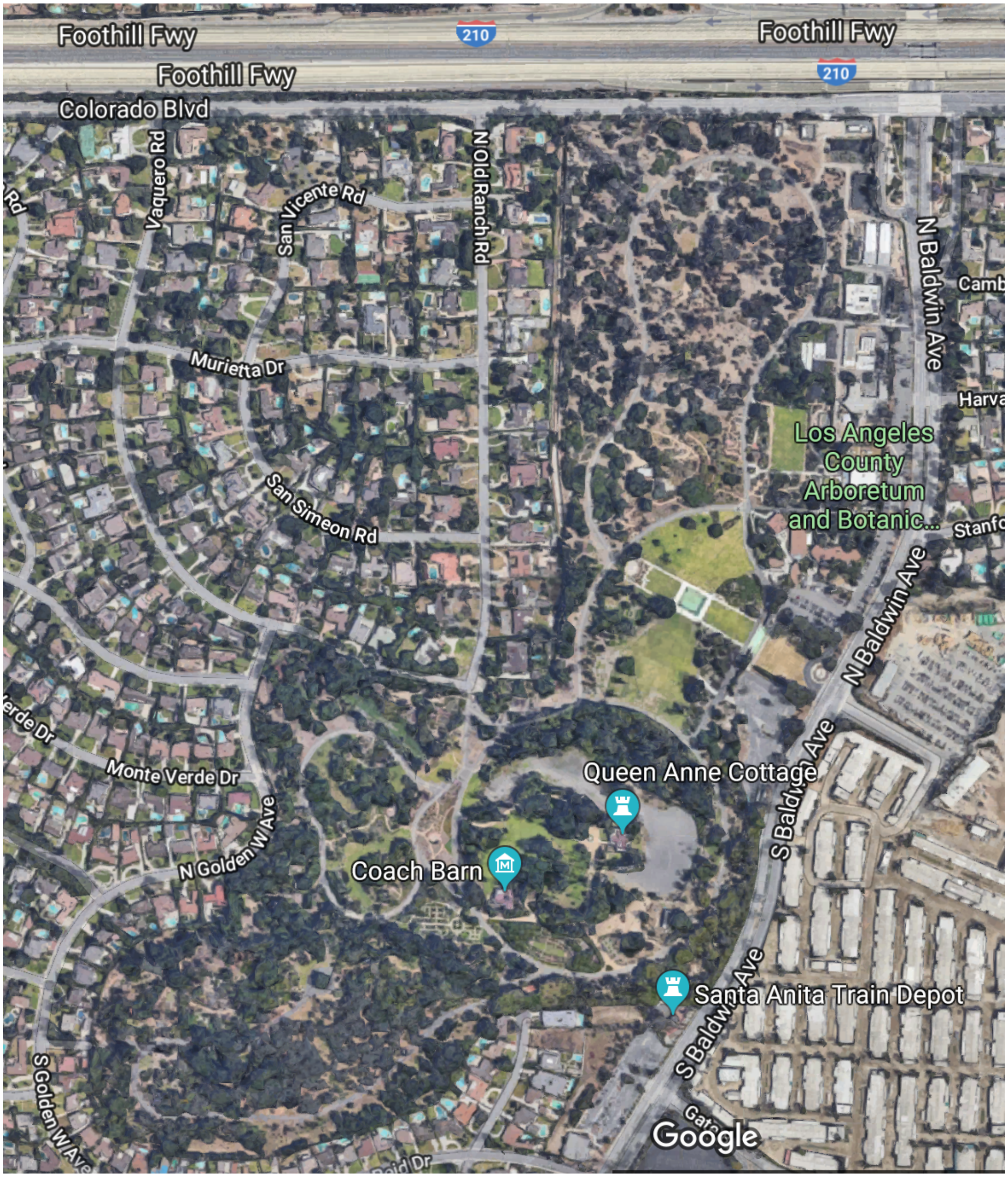

Figure 10: A screenshot of the LA County Arboretum.

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