LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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# Adaptive Feedforward Seismic Noise Cancellation at the 40m Interferometer

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# 1 Motivation

LIGO (Laser Interferometer Gravitational-wave Observatory) uses an interferometer to detect gravitational waves. These interferometers are subject to a multitude of physical forces which we must control in order to extract the signal we want to find. Seismic noise in particular becomes a serious problem for interferometers, such as LIGO, that detect frequencies in the range of <2 Hz [1]. Therefore, it is very important that we are able to determine which signals come from seismic noise and subsequently filter them out. We will accomplish this by using a feedforward technique and implementing IIR wiener filters.

# 2 Theory

## 2.1 Noise in LIGO Interferometers

LIGO Interferometers have a concave mirror at the end of each cavity that reflects the laser beam which is then recombined so that any potential interference patterns can be observed. [1]. There will be no interference pattern unless noise or gravitational waves affect the system. However, many other factors besides just gravitational waves affect the resulting interference pattern of the lasers. These factors are noise that must be filtered out either through the construction of a mathematical filter or physically building a filter to dampen the noise. Many kinds of noise affect LIGO Interferometers, including Seismic, Newtonian, Thermal, and Shot noise. Seismic and Newtonian are most problematic because they affect frequencies LIGO is trying to detect and are more difficult to mechanically control precisely [1]. Therefore, to control these sources of noise, filters using feedback and feedforward are preferred once initial mechanical filters are set in place [1]. Mechanical techniques, including stabilizing the concave mirrors in each cavity through magnetic fields and using oscillators to dampen seismic noise, are already in place. Filters have been constructed, but can still be optimized further.

## 2.2 Feedforward vs Feedback Filtering

Filters can use either feedforward or feedback techniques. We will be focusing on IIR wiener filters using feedforward. Feedforward will help us best optimize the subtraction as opposed to feedback alone, because feedforward is often faster and more precise [2]. This is because, in feedback, the disturbances and noise sources must pass through the system in order to be detected, whereas with feedforward these noise sources are predicted and preemptively filtered out. There is also no time lag that is associated with feedback techniques because the filters are in place before the signal is detected, instead of the system needing to wait for disturbances to occur and then create a filter [2]. Wiener filters in particular are desirable to use for feedforward techniques because they are used to determine the value of an unknown signal given known signals. Using feedback, one can determine the noise of the system and then construct a wiener filter based off of that [4]. Once the filter is created, it will be implemented using feedforward and predict future noise patterns based off of the previously collected noise patterns. Furthermore, these filters will have an extensive impact, minimizing seismic noise through multiple degrees of freedom [6]. Therefore, we will only need to construct one wiener filter to filter out noise from several sources.

### 2.3 IIR Wiener Filters

In this case, IIR wiener filters are ideal because they require fewer parameters than FIR filters, which is important because wiener filters have to create a very precise model of the system, so the fewer parameters required means that there is less room for error. Computational time of the filter is also reduced drastically by using IIR instead of FIR coefficients for high resonance cases because IIR filters can be represented in the frequency domain [6]. This is especially important for a feedforward system, which must predict how to filter the signal prior to receiving it. Also, IIR filters are more likely to achieve the lowest mean-square error because, being Infinite Impulse Response filters, they are an integral, while a FIR filter is just a summation [3]. Therefore, FIR filters can come close to achieving the results of IIR filters, but will never be quite as good. However, IIR filters are difficult to calculate, even using vectfit, and they also can introduce noise into controls of the system because of how each control interacts with others [6]. Therefore, it will be difficult to implement an IIR filter that also optimizes subtraction and introduces minimal noise into other parts of the system.

## 3 Research Goals

The ultimate goal of this project is to create a better filtering technique for the 40m Interferometer at Caltech that will optimize the signal subtraction. After researching static and adaptive feedforward cancellation based on both FIR and IIR filtering techniques, I will construct an IIR filter and apply it in the lab. To achieve this, I will first create an optimal FIR filter based off of previous work. Then, I will use vectfit to map the FIR filter to an IIR filter. This will help me achieve my goal because vectfit repeatedly solves a linear problem until convergence occurs, which is how a FIR (Finite Impulse Response) filter becomes an IIR (Infinite Impulse Response) filter [5]. Using vectfit will allow me to optimize an FIR filter and therefore create a new and better filter for the interferometer.

## 4 Approach

Before I can begin computing a filter of any sort, I will need to learn more about how filters are constructed in matlab, and how Green's function in particular can be used to understand FIR filters. Once I have this knowledge and understand matlab, I should then learn how static and adaptive filters are constructed differently and what I will have to calculate for each one. With all this background knowledge, I will then be able to calculate both a static and adaptive FIR wiener filter. Then, using vectfit, I will need to map the FIR wiener filter to and IIR filter for both the static and adaptive cases. If I have time, I can then also try moving the seismic sensors around in the lab to see how it affects the optimization of the filters I will have calculated.

# 5 Expected Results

The expected outcome of this experiment is that I create a static (offline) and adaptive (online) IIR wiener filter to properly filter the signal from the interferometer and optimize the subtraction further than a FIR wiener filter can do. Secondary applications of this project include possible adaptations of this IIR wiener filter to other interferometers and setups. Hopefully, this will also provide a groundwork for future experiments so that IIR wiener filters can be continued to used successfully.

# 6 Time Plan

Before arriving at Caltech, I will want to learn the basic commands in matlab. I will also want to skim through the matlab reference code on FIR wiener filtering and LMS adaptive filtering. Exploring more of the vectfit website will also be good to do before arriving on campus, so that I will have all the tools I need to start my project right away.

In weeks 1-2, I hope to create a static FIR filter that works as well as the one already implemented. I will also spend this time to ensure that I fully understand how an FIR filter works in relation to Green's function, as well as LMS adaptive filtering and vectfit.

In week 3 I will be creating an adaptive FIR filter from the static filter I have. This part of the project may carry over into week 4, but hopefully not take too much longer than a week.

In weeks 4-6 Knowing I can properly construct a FIR filter in matlab, I will now move on to creating an IIR wiener filter. I will use vectfit to construct a static IIR filter mapped from my FIR filter. This will take more time because IIR wiener filters are harder to create than FIR filters, and there are more references on FIR filters.

In weeks 6-9 I will construct an adaptive IIR wiener filter based off of the static filter I created. I will also begin preparation for my final presentation at the end of this period, as I will have completed my goal after the construction of this adaptive IIR wiener filter.

In week 10, I will either be completing previous tasks that took longer than I am expecting, or I will hopefully be able to have a chance to try moving the seismic sensors in the lab around to find an optimal position for them. This will ideally optimize the subtraction even more than my filters alone could do. I will also finish my presentation and final report during this time.

# References

[1] G. Cella and A Giazotto *Interferometric Gravity Wave Detectors*. Review of Scientific Instruments 82, 101 101 (2011).

[2] John Bechhoefer, *Feedback for Physicists: A Tutorial Essay on Control*. Review of Modern Physics, Volume 77 (July 2005).

[3] Natanael Fontes *An Analysis of the IIR and FIR Wiener Filters with Applications to Underwater Acoustics*. Naval Postgraduate School (1997).

[4] J. Driggers, M. Evans, K. Pepper, and R. Adhikari, *Active Noise Cancellation in a Suspended Interferometer*. arxiv:1112.2224. (December 2011).

[5] https://www.sintef.no/projectweb/vectfit/algorithm/

[6] R. DeRosa, J. Driggers, D. Atkinson, H. Miao, V. Frolov, M. Landry, J. Giaime, and R. Adhikari, *Global Feed-forward Vibration Isolation in a km scale Interferometer*. Quantum Grav. 29 215008 (2012).