Non-Linear Noise Subtraction for Low Frequency

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1 Introduction/Background

The existence of gravitational waves reveals yet another method in which information is transmitted across the cosmos. LIGO (Laser Interfermometer Gravitational-Wave Observatory) [1] utilizes laser interferometers to measure the microscopic deformations in space-time caused by transient gravitational waves. Different sources and features of the same source emit gravitational waves at different levels of frequencies. Ground-based laser interfermometers have a sensitivity that depends on the specific sources of noise at a certain frequency. The lower frequency regime is particularly challenging because of the noise couplings (i.e. disturbances like ground vibrations).[2] Nevertheless, there are interesting sources of gravitational waves at those frequencies to study. For example, the gravitational wave memory from Core-Collapse Supernovae [4] and pre-merger binary star signals are found in the lower gravitational wave frequency regime below 10Hz. For an event such as a galactic supernova, a fraction of the gravitational wave memory might be above the amplitude of the noise floor. Reducing the noise floor as much as possible would make it easier to extract those features. As of right now, there is no official aLIGO [3] calibrated gravitational wave data below 10 Hz. [2]

Generally, contemporary aLIGO noise reduction methods can focus on reducing the impact of noise sources that are linearly coupled with auxiliary channels. Dr. Gabriele Vajente et al.[8] showed that we can reduce the noise contributions to the strain channel (which contains gravitational wave signals) by also reducing noise that are coupled non-linearly and non-stationary. Advancements in noise reduction techniques have allowed physicists to develop a method in which algorithms can be trained to reduce non-stationary noise couplings by using auxiliary channels from LIGO's detectors. Such an algorithm was used to successfully reduce the noise produced by a 60 Hz power line.[8] Therefore, I would like to try to use this algorithm to perform similar noise reductions within the low frequency regime (below 10 Hz).

2 Objective

The main objective of this project will be to modify and apply the known algorithm for subtracting non-stationary noise to perform noise reductions in the lower frequency range. The original code was created by Dr. Gabriele Vajente, who successfully performed a noise subtraction to a 60 Hz power line. I would like to see if it is possible to do this for a lower frequency range that is below 10 Hz by figuring out which LIGO auxiliary channels I can utilize that will be able to perform the subtraction to a gravitational wave channel. Regarding the auxiliary channels, I will be looking at the effect of channels that are related to seismic motion and control systems.

3 Approach

The first step to this project that I have already begun is explicitly deriving the mathematical aspects of the algorithm. I am actively working on this prior to the start of the project in order to gain better proficiency in how to perform the subtraction mathematically. An on-going logbook for this project can be found at this page link: `https://wiki.ligo.org/CSWG/NonLinearNoiseSub_Math`.

The next step is to begin removing the noise that is linearly correlated with the auxiliary channels. After this is done successfully, then I can proceed to remove the part of the noise that is non-linearly correlated. Seeing that there are a number of ongoing LIGO channels, I would first have to calculate if there is any linear coherence between the channels in order to be able to see if we could perform a linear subtraction. This is not a determination of whether or not we would be able to do a non-linear/non-stationary subtraction from those channels. However, this will at least be a starting point to help us pick out some set of channels that might have the possibility of subtracting the non-linear noise from.

Dr. Vajente has already calculated coherences between the CAL-DELTAL_EXTERNAL_DQ target channel and many different auxiliary channels on the webpage "Top 20 Coherences of CAL-DELTAL_EXTERNAL_DQ With Auxiliary Channels" [7], which I will use as a starting point in this project. The target channel is the channel that I want to subtract the noise from. The CAL-DELTAL_EXTERNAL_DQ channel is derived from control signals that are then modified to produce the calibrated strain signals that are corrected below 10 Hz, which is what we are interested in for this project. The downside to using this calibrated signal is that it has less accuracy than the GDS-CALIB_STRAIN channel, which was the target channel that was originally used for subtracting noise between 10 and 30 Hz. [6] However, the GDS-CALIB_STRAIN channel is only useful for subtraction above 10 Hz since the stain signals are not corrected below that range. At this time, CAL-DELTAL_EXTERNAL_DQ channel is the only calibrated strain that is below 10 Hz up to date.

Below is the equation that describes the total strain $h(t)$ with both the linearly and non-linearly correlated parts of the noise that goes into the detector:

$$h(t) = y(t) + H[s(t)] + \sum_{i=1}^{N} \alpha_i [x_i(t)s(t)] \tag{1}$$

where the H is the stationary linear coupling, the α_i is the non-stationary linear coupling, the $x_i(t)$ is the slow modulation witness channel, $s(t)$ is the fast modulation witness channel, and $y(t)$ is the part which is neither linear nor non-linear correlated [5]. As shown in this equation, the non-linearly correlated part requires two different sets of auxiliary channels for filtering. These two auxiliary channels are the fast noise witness channels and the slow modulation witness channels. The fast noise witnesses [6] are the channels that "witness" the fast noise, while the slow modulation witnesses [6] are the channels that "witness" the modulation of the noise couplings. I plan on using the SUS (suspension) and the SEI (seismic) auxiliary channels as starting points for the fast noise witness, while it is suggested that I use the ASC for the slow modulation witness channels. Some of the ASC signals have already been used as the fast witness noise to subtract noise between 10 and 30 Hz. [6]

However, there are thousands of these channels in the LIGO frames to choose from, which means that I will also need a way to narrow down the necessary ones. In order to do this, I need to figure out which specific auxiliary channels to utilize that will be able to perform a noise subtraction for this lower frequency range.

Then, the next step is to understand and utilize the algorithm code, "NON-Stationary Estimation of Noise Subtraction" (NonSENS), created by Dr. Vajente, which was originally used for a 60 Hz Powerline noise subtraction [8]. The Python code needs to be run on a terminal that has access to the LIGO frames, in which the auxiliary channels can be extracted from. Essentially, I will be adjusting the parameters that will aid in seeing a possible noise subtraction in the lower frequency range using the ASC arms.[6]

For more information and details regarding this project, please see this link which documents more information about it: `https://wiki.ligo.org/CSWG/NonLinearNoiseSub_LF`.

4 Project Schedule

Goal	Excepted Date to Complete
In order to begin the project, I would initially make sure that I would be able to run existing NonSENS algorithm example code on a terminal. Then, after being able to successfully run the code, the next step would be to study the algorithm thoroughly in order to gain a more clearer understanding of the operations that is being performed on this non-linear subtraction. This will help me to be able to understand and adjust the code to perform the subtraction on a lower frequency regime.	Prior to start of summer program
With a better understanding of the algorithm, I would also begin to physically find the auxiliary channels in the LIGO frames. As mentioned in the prior section, the webpage "Top 20 Coherences of CAL-DELTAL_EXTERNAL_DQ With Auxiliary Channels" would be my starting pointing since it contains a list of SUS channels that have coherence with the target channel. However, we are not limiting to just the suspension channels, and would therefore need to check for the other auxiliary channels such as the seismic (SEI) channels.	June 25 (End of second week)
Once the location of the auxiliary channels are determined, I would begin to calculate the coherence with the target channel in order to determine if the channel would be able to perform a subtraction in the lower frequency regime. I plan to write a code for the calculation and create an organizational chart that would display the coherences. *This part of the project will probably take the longest to complete since there are a lot of LIGO channels to go through.*	August 13 (End of ninth week)
If I am able to find a list of channels and modulations, I can try to implement them into the algorithm code to verify. Additionally, I would need to adjust the code so that it would performed the subtraction for the 5-10 Hz frequency range. It would be most ideal if I were able to produce this data for a longer observing run (possibly for all of O3).	Last day of program

5 Contributors

- Gabriele Vajente (PhD Department of Physics, California Institute of Technology/Pasadena, CA)
- Michele Zanolin (Phd Department of Physics and Astronomy, Embry-Riddle Aeronautical University/Prescott, AZ)

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