Using adaptive filtering to track noise lines or signals with varying frequency and amplitude

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Abstract

Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo have detected 13 confident gravitational wave (GW) events, however the ones found are only of the compact binary coalescence (CBC) GW type. Continuous waves (CW) and long-transient waves haven't been confirmed by the LIGO observing runs despite us knowing of their existence. One of the issues with the LIGO data that's playing a role in us being unable to confirm these waves is the spectral lines which completely obscure any astrophysical signals at the frequencies where they occur. This project will explore iWave as an alternative method of tracking these spectral lines so they can be factored out of the data more easily as well as exploring the sensitivity of directly tracking weak CW/long-transient signals using iWave.

1 Introduction

On September 14th 2015, Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) detected its first gravitational wave (GW) detection, GW150914 [1]. This event was in the first observing run (O1) LIGO data set (which happened from September 12th, 2015 to January 19th, 2016). After O1 concluded, the second observing run (O2) began in November 30th, 2016 and ended in August 25th, 2017 [2]. O2 was the set where the binary neutron star (BNS) merger GW170817 was detected [3]. The third observing run (O3) had two confirmed mergers – GW190412 [4] and GW190425 [5]. Throughout the entire O1-O3 data set, there have been 13 confirmed GW events, most of them binary black hole (BBH) mergers. There have been no confirmed neutron star - black hole (NSBH) merger detections yet.

One of the most important aspects of LIGO data is detector characterization and noise modeling – without being able to monitor the detector or track the noise accurately, the significance of an event could be incorrectly estimated. From monitoring the physical detector to characterizing glitches, detector characterization is important to making sure the instruments and data aren't flawed. Noise lines can obscure an astrophysical signal at the frequencies in which they occur. These spectral lines are a problem because they can't be factored out easily with the current noise modeling/dampening methods. Some of these lines aren't very well understood either - some might have wandering frequencies and/or varying amplitudes, which makes them even more difficult to track.[6]

Adaptive filtering is a dynamic approach for characterizing the features in input data, including noise lines or signals with wandering frequency and amplitude. This method is very helpful when the input signal changes over a period of time. It could prove helpful in the LIGO detector data for tracking these spectral lines since they can change over the data set. There is also the phase locked loop (PLL), which uses an oscillator to produce an output signal at a frequency and phase related to the input signal by a variable called the z-transform. The line-tracking adaptive filter that we will be using for this project, iWave, is a hybrid of a traditional PLL and an adaptive filter. This allows us to combine the wandering frequency/amplitude aspect of adaptive filters with the oscillation frequencies of PLLs to help us better track these spectral lines over a time series.

There are more types of GWs than just the BBH and BNS compact binary coalescence (CBC) LIGO-confirmed types. Continuous waves (CW) are produced by a single spinning massive object (like a neutron star). There are also long-transient GW signals that can be produced by a post-merger remnant from a BNS merger. Burst GWs aren't very well understood since no one has made a good model for them, however, once detected, they will be able to reveal much about the universe. Stochastic background GWs are small waves that pass by from all parts of the universe and are the most difficult to track [7]. There are currently techniques that are used to search for CW and long-transient GWs like the hidden Markov model tracking (which, like iWave, can track wandering signals and has been used for tracking both noise lines and signals [8–10]). Such methods mainly work in the frequency domain while iWave could prove to be an alternative method for doing so that works directly on the time series.

This proposal will cover the objectives of this research, algorithms of iWave and how it applies to the LIGO data, the approach to the objectives, and finally a proposed schedule for covering these objectives.

2 Objectives

This project has three main goals: tracking the noise lines, cleaning narrow-band data, and studying/tracking these other GW types. The first goal is to track the spectral lines that haven't been well studied/characterized in the past using iWave. This will allow us to achieve the second goal of cleaning the data where these lines exist. The third goal is to find a way so we can better see these long-transient and CW signals within the data sets.

3 Algorithms

The change between the input and the output of any adaptive filter is determined by the z-transform over a certain time period τ. For iWave in relation to this project, this change is determined by the equation:

$$z_0(\Sigma) = \sum_{n=-\infty}^{0} x_n e^{n\Sigma} \tag{1}$$

Where Σ is related to τ through the equation $\Sigma = w - j\Delta$ because $\Delta = 2\pi f \tau_s$ and $\tau = \tau_s/w$ (where w is the weighting factor of the transform and τ_s is the sampling period) [11].

In terms of the input and output, this z-transform relationship can be modeled by:

$$y_n = x_n + e^{-\Sigma} y_{n-1} \tag{2}$$

however, to avoid the divergence of the output equation as the n input term increases, iWave scales the input term by $(1 - e^{-w})$ to make the relation like this [11]:

$$y_n = (1 - e^{-w})x_n + e^{-w} e^{j\Delta} y_{n-1} \tag{3}$$

4 Approach

At the beginning, we will be trying to work iWave with the publicly available GW data. In order to test if it works, we will use it to verify some highly confirmed lines (for example, the 60 Hz line) within a chosen frequency band. We will track those highly confirmed lines using iWave and compare the cleaned and uncleaned spectrograms of the data.

For the next stage, we will try to use iWave to identify some unknown lines in the data and where certain lines in the spectrum appear over certain time periods. We will compare our results to other studies on the same data to see if there are any discrepancies.

Lastly, we will test if it could be sensitive to some of the weak injected signals, e.g., CW and long-transient signals. We will check the root-mean-square (rms) error between the injected and recovered signals to see, once again, how accurately iWave can recover a signal. This will be important because it will help us see how much iWave can be a more powerful asset than the filtering methods we currently have.

5 Schedule

I propose this preliminary outline for this project:

- finish setting up an environment on the cluster; reading literatures in more detail; setting up tools; running some tests on iWave (Weeks 1-2)
- finish 1st stage of Approach section — compare lines; analyze output of iWave (Weeks 3-4)
- finish 2nd stage of Approach section — study unknown noise artifacts; see how well iWave performs cleaning the data (Weeks 5-6)
- finish 3rd stage of Approach section — test how iWave responds to injected signals (Weeks 7-8)
- finish final report; give final presentation (Weeks 9-10)

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