Sifting Through Detector Noise Using Time Series Analysis

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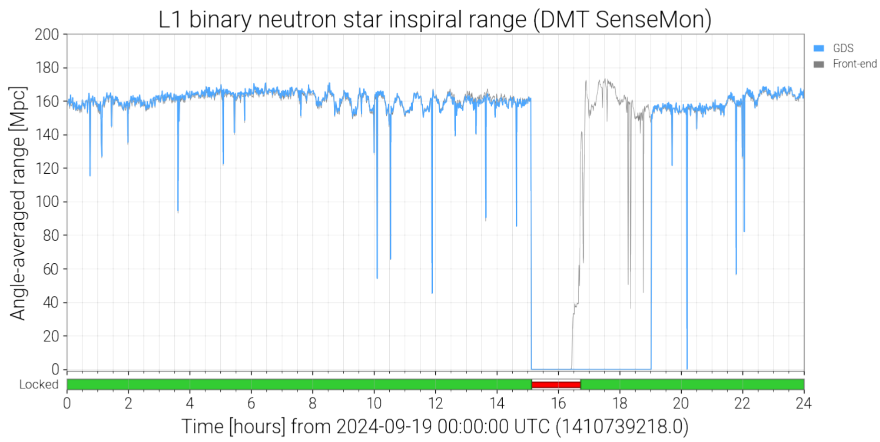
1. Introduction

Gravitational waves were first predicted by Albert Einstein in the early 1900s [1]. Sometimes thought of as “ripples in spacetime”, gravitational waves are produced by extreme astrophysical events, like the merging of two black holes or neutron stars. It was not until recently that the first observation of a gravitational wave was made. On September 14, 2015, the Laser Interferometer Gravitational-Wave Observatory facilities in Livingston, Louisiana (LLO) and Hanford, Washington (LHO) observed a merger of two stellar mass black holes [2], which produced measurable gravitational waves.

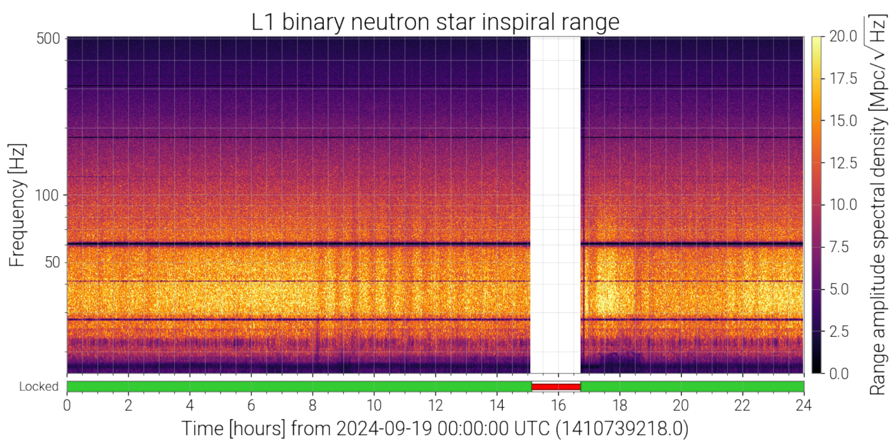
Gravitational waves are difficult to detect because they are incredibly weak. The gravitational wave amplitude, often referred to as the gravitational wave strain, can be on the order of $10^{-21}\ \mathrm{Hz}^{-1/2}$ at 30 Hz [3]. Due to their elusive nature, detection requires extreme sensitivity. Both LIGO facilities operate as modified Michelson interferometers in order to achieve the sensitivity required to detect gravitational waves. Some of these modifications include increased arm lengths, optical cavities, and filter cavities, all of which allow us to reach the precision required to measure space-time fluctuations due to gravitational waves. With such large facilities and cutting-edge precision, the potential for noise is seemingly insurmountable.

The group known as detector characterization is the primary group responsible for understanding how noise can impact the interferometers. In general, detector characterization is the process by which noise sources are monitored, identified and addressed. This includes studies of LIGO data quality to identify and mitigate noise sources to improve detector sensitivity [4]. There are hundreds of sensors (ranging from accelerometers, microphones, and seismometers) placed throughout the detector to help track potential noise sources. One of the ways that detector sensitivity is tracked is via the binary neutron star (BNS) range. The BNS range represents the distance at which a gravitational wave signal from the inspiral of two neutron stars with an SNR of 8 can be detected [5].

Since the beginning of the fourth observing run, the BNS range at LLO has had frequent oscillatory behavior with periods of roughly 30 minutes. Oscillations are also observed in many auxiliary channels [6]. The direct coupling of this noise has not yet been identified and that is the main objective of this project. Due to the wide variety of potential noise sources, identifying the channels of these oscillations is difficult. In the following section, I will describe my plans to better understand this behavior.



(a) top: Visualization of the BNS range on September 19th 2024. 30 minute oscillations are visible from roughly 8 UTC to 13:30 UTC on this day.



(b) bottom: Time-frequency spectrogram where the color represents the amplitude spectral density of the BNS range. During the oscillations, we can see ”stripes” corresponding to changes in noise from 30 Hz to 50 Hz.

Figure 1

2. Objectives

The 30-minute oscillations that appear in the main gravitational wave data at a frequency roughly between 30 and 50 Hz at the Livingston LIGO facility are the primary target of study. In this project, I will analyze data over the entire span of the fourth LIGO observing run in which these oscillations are present. Identifying the source or sources of these oscillations requires exploration of many channels and how they interact with each other. Due to the elusiveness of the source, multiple auxiliary channels are believed to be contributing to the behavior. Identifying possible auxiliary channels, or at the minimum, ruling out channels, is the main objective. If significant progress is made, regression algorithms will be performed to model the noise to try to understand the behavior of this noise.

3. Methods

There are numerous auxiliary channels that appear to manifest some form of the half-hour oscillatory behavior. Due to this, it is unclear as to which channels or systems are the primary contributors to the noise that is seen in the main gravitational wave data. Correlation analysis will be used to help identify which channels are driving the noise behavior. Narrowing down the potential auxiliary channels is the goal.

We will initially start with an auxiliary channel, such as a temperature sensor or accelerometer, and the main gravitational wave data channel. Using time-lag analysis, we can determine whether an auxiliary channel precedes or drags behind the noise in the gravitational wave channel by sliding their time series against each other for various time shifts to determine better fits. A preceding channel is more meaningful to us because it may be an initial driver of the noise that we see. If it drags, that means it may couple with another source of noise or witnesses the noise that contributes to the oscillations we see in the gravitational wave data.

Once we have identified a subset of interesting auxiliary channels, we will use regression algorithms to model the noise. Regression algorithms that have been used in the past in various detector characterization studies include Least Absolute Shrinkage and Selection Operator (LASSO) and Ridge regression [7]. It is possible that these regression methods may be insufficient, so other regression techniques may be explored to glean more connections between the channels.

4. Timeline

I will begin this project by familiarizing myself with detector characterization tools and analysis methods. After this, the first goal is to write code to perform the time-lag correlation analysis on the auxiliary channels and the gravitational wave data channel. If and when interesting channels are identified, regression algorithms will be performed on this subset of auxiliary channels to model the noise. Then conclusions will be drawn, a final report will be written, and a presentation will be given.

References

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