Characterizing Periodic Low-Frequency Noise During O4 at LIGO Livingston

Lanie DeMarcay[1], Jane Glanzer[2],

[1]Davidson College, Davidson, NC 28035, USA

[2]LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

1. Introduction

Gravitational waves, often thought of as "ripples in spacetime", are generated by asymmetrically accelerating massive objects such as black holes and neutron stars. First predicted by Albert Einstein in his general theory of relativity [1], these waves contain critical information on the behavior of some of the most energetic events in the universe. The first direct detection of gravitational waves occurred nearly a century after they were first theorized on September 14, 2015, when the Laser Interferometer Gravitational-Wave Observatory (LIGO) observed the spiraling and merger of a binary black hole system [2]. This marked the growth of an entirely new subsection of gravitational astrophysics, and since that first detection over a decade ago, the LIGO, Virgo, KAGRA Collaboration (LVK) have cataloged dozens of gravitational phenomena dramatically expanding our understanding of the universe[3].

LIGO operates two observatories: one in Livingston, Louisiana (LLO) and one in Hanford, Washington (LHO) [2].The facilities use modified Michelson interferometers to measure small changes in optical path lengths due to space time fluctuations, measuring gravitational waves (GW) as a time series. The event produces a change in the differential arm (DARM) lengths such that, $\Delta L_{\text{free}} = \Delta L_x(t) - \Delta L_y(t)$, which is related to the gravitational wave strain, $h(t) = \Delta L_{\text{free}}(t)/L$. The calibrated gravitational wave strain, $h(t)$, is not directly measured; it is reconstructed from the interferometers digitized error signal, which encodes differential arm (DARM) displacement as fluctuations in the laser power at the gravitational wave readout port [4]. The GW strain being measured by these interferometers are incredibly small, on the scale of 1/1000th of the diameter of the nucleus of an atom, and therefore require extraordinarily precise instrumentation [5]. Due to this extreme sensitivity, LIGO data is susceptible to noise from a variety of environmental and instrumentation factors such as passing trains [6] or scattered light [7, 8].

Understanding and mitigating these noise issues is referred to as Detector Characterization (DetChar). The DetChar team monitors the status of the detectors, investigates data quality, examines sources of instrumental noise, and ensures that noise artifacts are not misidentified as an astrophysical signal [9]. The "auxiliary channels" in

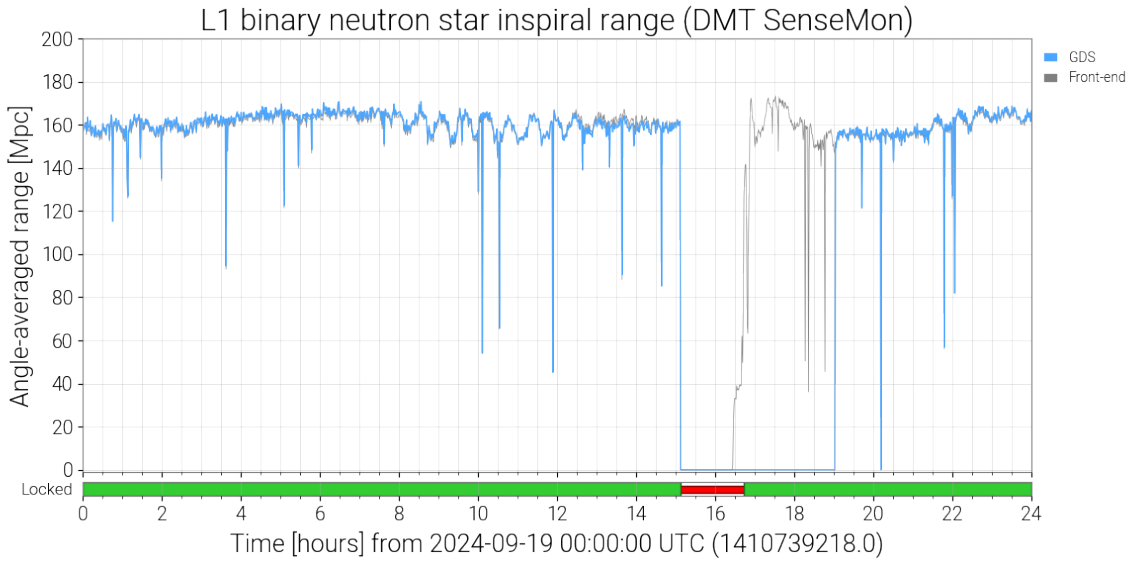


Figure 1: Time series of the binary neutron star (BNS) inspiral range for the LIGO Livingston detector on September 19, 2024. The detector exhibits approximately 30-minute periodic oscillations from 08:00 UTC to 13:00 UTC.

the detectors are essential for DetChar work such as the accelerometers, seismometers, magnetometers which record the state of the physical environment and the control systems, and they are routinely analyzed for correlations with the gravitational-wave strain channel.

One important metric for quantifying LIGO's sensitivity is the binary neutron star (BNS) range, defined as the distance to which a pair of 1.4 solar mass neutron stars can be detected with a signal-to-noise ratio (SNR) of 8 and is defined as:

$$R = \frac{1}{\rho_0}\left(\frac{5\pi}{24c^3}\right)^{1/2}(GM)^{5/6}\pi^{-7/6}\frac{1}{2.26}\left[4\int_0^\infty \frac{f^{-7/3}}{S_n(f)}\,df\right]^{1/2} \tag{1}$$

[10]. Because of the weighting of $f^{-7/3}$, low-frequency noise is particularly damaging to the BNS range and can significantly impact LIGO's detection rate.

During the fourth LIGO observing run (O4), the BNS range at the Livingston Observatory (LLO) exhibited approximately 30-minute periodic oscillations [11], which manifested as excess noise in the 30–50 Hz band of the main gravitational-wave strain channel. The correlated behavior observed across many auxiliary channels prompted a systematic investigation into the origin of these oscillations.

Identifying the origin of such oscillations is important for two reasons. First, if the cause can be understood, the oscillations may be mitigated or elimimiated, improving the quality of GW strain data. This is especially important because the excess noise appears in the 30-50 Hz frequency range where the interferometers are particularity sensitive to the mergers of high mass binary black holes. Second, understanding this noise source contributes to the broader knowledge base of how environmental and

instrumental effects impact LIGO data. This project hopes to trace the origin of these oscillations using time-lagged cross-correlation analysis of auxiliary channels and coherence measurements between auxiliary channels and the gravitational-wave strain.

2. Objectives

The goal of this project is to identify the source, or at least narrow down the location, of the 30-minute BNS range oscillations observed at LLO during the O4 period [12]. Building on the previous summer's work, we will first modify the existing time-lagged cross correlation (TLCC) code to include negative correlations between the strain and auxiliary channel data. We will then expand the analysis to cover additional auxiliary channels: the EX ALS system, the EY station, and the corner station. For any channels that show interesting results, we will follow up with coherence and amplitude modulation analyses to better understand how the noise relates the gravitational-wave strain.

3. Methods

This project will be an extension of last summer's work by Gabriel Grant and Jane Glanzer though LIGO SURF 2025, where the goal was to better understand the approximately 30-minute periodic oscillations that appear in the BNS inspiral range at LLO. The first question we will explore in this project is whether any auxiliary channels in the interferometer, sensors that monitor the state of the detector and its environment, begin oscillating before the interesting behavior appears in the gravitational-wave data. If a channel consistently leads the strain, then it could reveal insights as to whatever is driving the noise.

Pre-existing Python scripts developed by Grant and Glanzer identify correlations between the strain channel and auxiliary channels by first filtering both time series to the 30–50 Hz band and computing a band-limited RMS to track how signal amplitude evolves over time. The normalized cross-correlation is then computed as a function of lag k:

$$\rho[k] = \frac{\sum_t (y_t - \bar{y})(a_{t-k} - \bar{a})}{\sqrt{\sum_t (y_t - \bar{y})^2}\sqrt{\sum_t (a_t - \bar{a})^2}} \tag{2}$$

where y_t is the strain RMS time series, a_t is the auxiliary channel RMS time series, and k is the time lag. The lag at which $\rho[k]$ is maximized indicates the delay at which the two channels are most strongly correlated. My first step this summer will be to expand this code to include cases of negative correlations. We will then collect the calibrated strain data and all relevant auxiliary channels for the 19 days over the O4 period in which the 30-minute oscillations were clearly present. This code will flag any channel with a correlation coefficient of at least 0.3 at a lag between 0 and 1800 seconds. In this setup, a positive lag means the auxiliary channel precedes the strain. Once the negative correlations are integrated, we will to expand the set of channels we are examining

to include the arm-length stabilization (ALS) first at the end-X station. From there, we plan to extend the project to cover to the end-Y station and the corner station, including the input test mass chambers and the gravitational-wave readout chamber, HAM6. For any channels that show interesting time lags, we may explore whether there is a threshold for when the noise only show up in the strain once the auxiliary channel exceeds a given amplitude level.

In addition, I will compute the coherence between the strain channel and auxiliary channels as a complementary frequency-domain analysis. The coherence is effectively the cross-correlation evaluated in the frequency domain, and is defined as:

$$C_{xy}(f) = \frac{|S_{xy}(f)|^2}{S_{xx}(f), S_{yy}(f)} \tag{3}$$

where $S_{xy}(f)$ is the cross-spectral density between the strain and auxiliary channels, and $S_{xx}(f)$ and $S_{yy}(f)$ are their respective auto-spectral densities. The coherence reveals at which specific frequencies an auxiliary channel shares common variability with the strain channel. Channels with high coherence at the oscillation frequency are strong candidates for further investigation as potential witnesses or sources of the noise.

4. Timeline

I will begin the ten-week project by familiarizing myself with the existing time-lagged cross correlation (TLCC) code base and the relevant detector characterization tools and data access systems. Once comfortable with the code, the first goal is to modify the code to include negative correlations and re-run the full analysis over the 19 O4 days where the oscillations were present. From there, we will expand the channel search in stages, starting with the EX ALS channels, then moving to the EY station, and finally the corner station. As interesting channels are identified at each stage, we will perform the coherence and amplitude modulation follow-up analyses on those auxiliary channels. Once all analyses are complete, conclusions will be drawn, a final report and presentation will be written.

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