Investigations of Binary Neutron Star Range Oscillations at LIGO Livingston

Gabriel Grant[1], **Jane Glanzer**[2]
[1]Minnesota State University Moorhead, Moorhead, MN 56563, USA
[2]LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

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 (LIGO) 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 (GW), 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 four kilometer 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 [4]. With such large facilities and cutting-edge precision, the potential for noise is seemingly insurmountable.

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 [5]. There are hundreds of auxiliary sensors, including accelerometers, microphones, temperature sensors, and seismometers, placed throughout the detector to help track potential noise sources. These auxiliary channels are not sensitive to gravitational waves, as they only measure the environment and monitor different parts of the detector. 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 of 1.4 stellar masses with an SNR of 8 can be detected [6].

The BNS range is an integral of frequency over the power spectral density of strain noise. $\mathcal{M}$ is the chirp mass and ρ_0 is the SNR [7].

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

Since the beginning of the fourth observing run (O4), the BNS range at LLO has had frequent oscillatory behavior with a period of roughly 30 minutes. These oscillations are also observed in many auxiliary channels [8]. The direct coupling of this noise has not yet been identified and that is the main objective of this project. This is important to address, as it significantly affects the range and sensitivity with which we can measure gravitational events. During these oscillations, the BNS range can vary anywhere from 5 to 15 megaparsecs within this 30 minute window [5]. These oscillations do not occur consistently; usually disappearing from weeks to months at a time. These oscillations affect the sensitivity of the gravitational wave strain data primarily from 30 to 50 Hz. Noise within 30-50 Hz affects the sensitivity to measure higher mass binary black hole mergers. Due to the wide variety of potential noise sources and amount of auxiliary channels that oscillate, identifying the source of these oscillations is difficult.

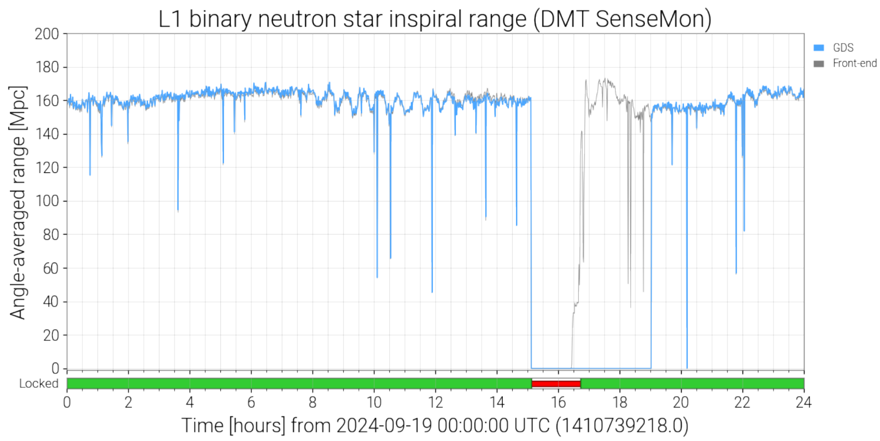
These oscillations have been appearing since the start of O4, and many tools have been used to try and understand this behavior. Regression algorithms that have been used in the past in various detector characterization studies, including Least Absolute Shrinkage and Selection Operator (LASSO) [9]. These are tools that help to model and determine couplings between sensors. These have been used across a wide range of channels already; however, the results have been inconclusive. The problem stems from many auxiliary channels exhibiting this 30-minute periodicity, making it difficult to determine to understand the coupling mechanism. Cross-correlation is a time-lag analysis technique that has not yet been tried and may be able to filter out a majority of sensors that are witnesses of the noise, rather than the source.

2. Methods

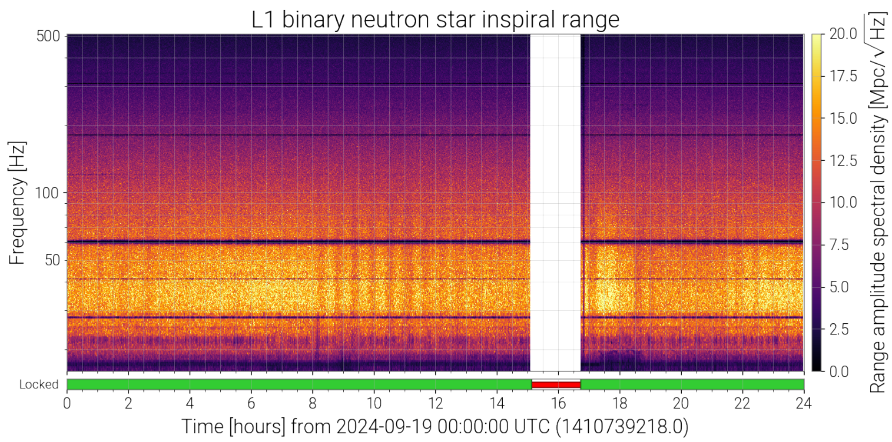
2.1. Band-Limited Root Mean Square (BLRMS)

Band-limited root-mean-square (BLRMS) are taken of the GW strain and auxiliary channel data to study signals within a certain frequency range. The GW strain was most affected in the 30-50 Hz range, so this was our choice of frequency range for the BLRMS. Figure 2 gives another visual to the frequencies where the noise appears. Many auxiliary channels across multiple subsystems were exhibiting the 30 minute period oscillations.

For analysis described in Section 2.3, we looked at many auxiliary channels from various subsystems at the End-X station. Facility Management Control (FMC) contains temperature and relative humidity sensors. Physical Environment Monitoring (PEM) is a collection of accelerometers, seismometers, and microphones. The suspension (SUS) subsystem is a collection of optical sensing actuators that measure relative motion between the test mass and the surrounding cage. Hydraulic External Pre-Isolator (HPI)



(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 range amplitude spectral density 1. During the oscillations, we can see "stripes" corresponding to changes in noise from 30 Hz to 50 Hz. A brighter color represents a frequency band with higher contribution to the range due to lower strain noise.

Figure 1

is first line of defense against ground motion (0.1 to 3 Hz) using hydraulic actuators. Internal Seismic Isolation (ISI) is passive and active seismic isolation within the vacuum chamber (0.1 to 30 Hz). The ISI are in vacuum, while HPI is not. ISI has both active and passive isolation. Arm Length Stabilization (ALS) is a locking system that uses auxiliary lasers to help sense and control arm cavities. If some auxiliary channels are highly correlated, that could suggest some coupling within that subsystem.

2.2. Spectrograms

Spectrograms are plots that describe how frequency behaves as a function of time. Using spectrograms, we can observe whether the frequency changes over a certain period.

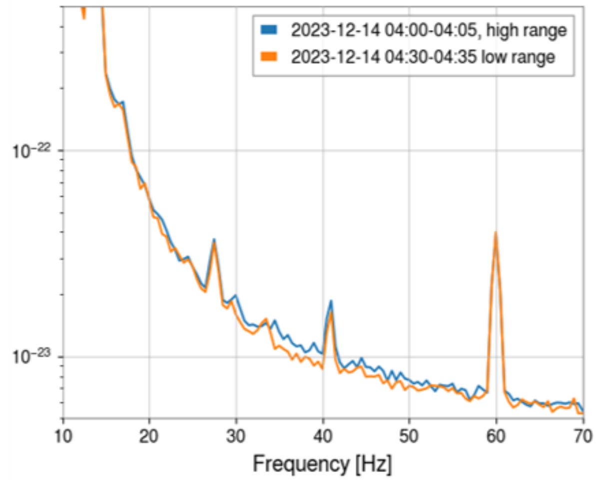


Figure 2: ASD Spectra of excess noise. We can see the gap between 30 and 50 Hz.

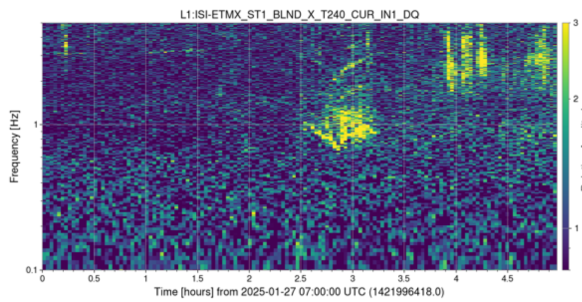


Figure 3: Spectrogram of an ISI seismometer in the End-X station that has no evidence for oscillations between 0.1 to 0.25 Hz.

Looking at Figure 1, which is a spectrogram of the BNS range, we can observe some vertical lines ranging from 30 to 50 Hz. This indicates some noise is concentrated there with a period of 30 minutes. Spectrograms were then created on auxiliary channels to check if they were observing similar behavior.

The BNS range was observing the noise in the 30-50 Hz range most strongly, however, low frequencies below 1 Hz were unexplored. Low frequencies have the potential to modulate into higher frequencies, or upconvert [9]. Spectrograms display the sensors' behavior across a wide range of frequencies and could show behavior that would not be readily apparent in BLRMS plots. Spectrograms were created for seismometers at all stations to check if there were low-frequency oscillations present. The spectrograms showed no oscillations between 0.1 and 0.25 Hz, ruling out low-frequency noise 3.

2.3. Cross-Correlation (Time-Lag Analysis)

Cross-correlation is a data analysis technique that measures how similar two signals are to each other at different time lags [10]. In our case, our two signals are the gravitational wave strain and the auxiliary channel time series data. Cross-correlation slides the time series against each other to determine at what time-lag they are most similar. A lag is the time delay that a time series is set at when comparing the two, and can be positive or negative. A correlation value is generated along with the lag 2.

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

A negative time-lag, or a preceding auxiliary channel, is more meaningful to us because it may be an initial driver of the noise in the GW strain data. If a lag is positive, it means that the signal is "starting" or drags after the signal being tested against. This possibly indicates that the channel is observing the reactions to the noise rather than observing the source itself.

The cross-correlation program was written in Python using the GWpy [11] and SciPy [12] packages. GWpy was used to band pass the GW strain and auxiliary channels and SciPy was used for cross-correlation. A collection of auxiliary channels in the End-X station was individually cross-correlated against the GW strain. The cross-correlation script used Pearson-correlation style normalization on both the GW strain and auxiliary channels time-series. This allowed consistent comparison between channels and different days. For any given day, a five-hour window was chosen in which the GW strain was stable and then started to exhibit oscillations. The goal was to identify which auxiliary channels started to oscillate before they appeared in the strain data.

3. Results

Nineteen days of the fourth observing run were analyzed using the cross-correlation algorithm. Roughly 150 of the same auxiliary channels were cross-correlated against the strain for each day. Auxiliary channels that had a time-lag of -1800s or less and a correlation of 0.3 or greater, were noted in Figure 4 and Figure 5. FMC channels have routinely higher correlations and consequently have more occurrences within these 19 days. `L0:FMC-EX_AHU_FAN2_DISCH_RH` is a relative humidity sensor with 7 counts out of 19 and the auxiliary channel with the highest number of counts. This sensor is located at the air handler output after mixing cold return air from inside the facility with outside air. It is followed by temperature sensors and more relative humidity sensors. A striking temperature sensor, `L0:FMC-EX_VEA_302C_TEMP`, mimics the GW strain closely and appears to start oscillating a couple of cycles beforehand, as seen in Figure 6. Aside from FMC, PEM and ISI had some notable channels: `L1:ISI-ETMX_ST2_BLND_Y_GS13_CUR_IN1_DQ` and `L1:PEM-EX_ACC_EBAY_FLOOR_Z`, which is a seismometer in the internal seismic isolation system and an accelerometer near the electronics bay. However, these channels were picked out only four times in the 19 days.

The days each auxiliary sensor was caught by the filtering were compared to see if there was any overlap. FMC channels were the most active, followed by PEM and ISI. Notably, the ISI seismometer and PEM EBAY accelerometer are seemingly working

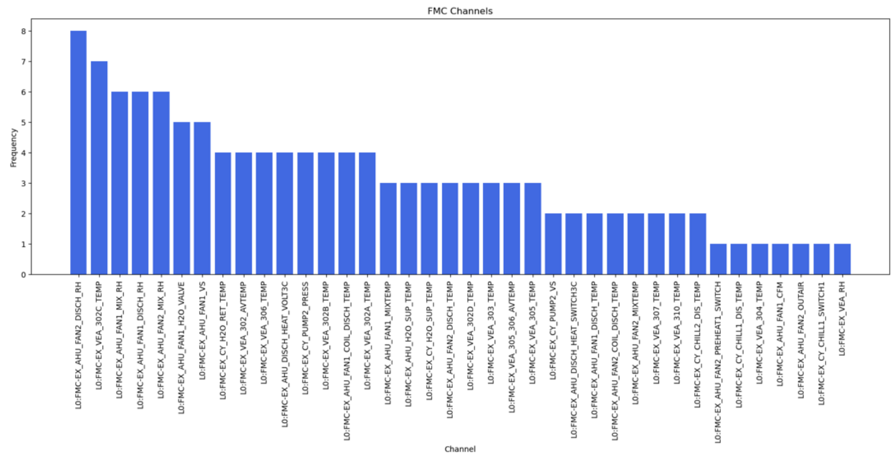


Figure 4: Bar graph that shows the frequency of FMC channels being chosen through the filtering.

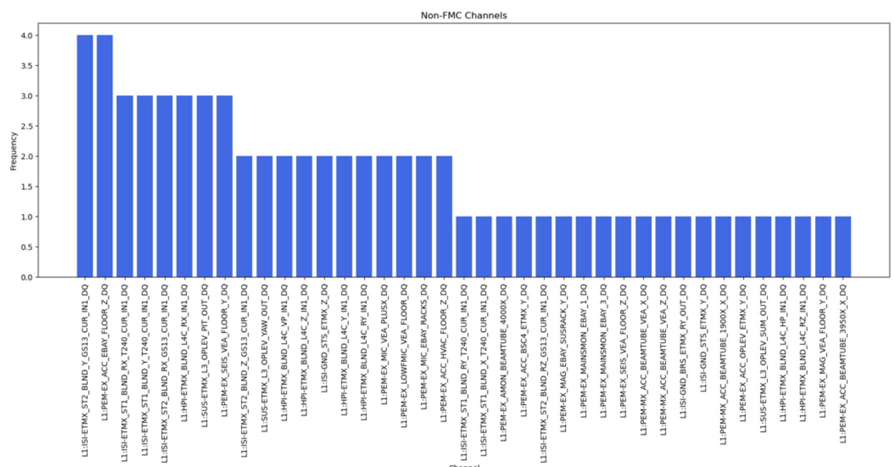


Figure 5: Bar graph that shows the frequency of nonFMC channels being chosen through the filtering.

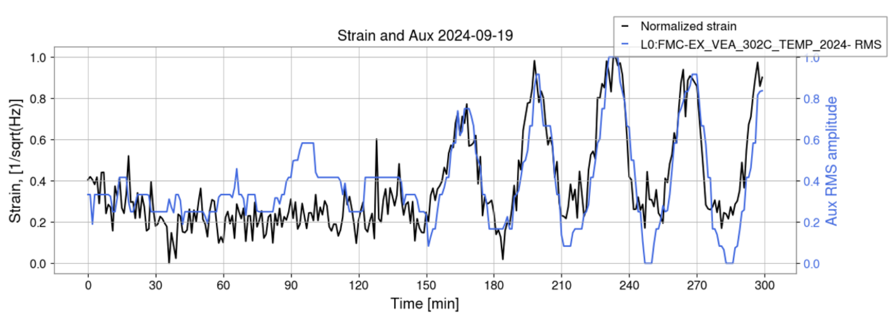


Figure 6: Comparison between a 30-50 Hz BLRMS of the strain data with an End-X temperature sensor.

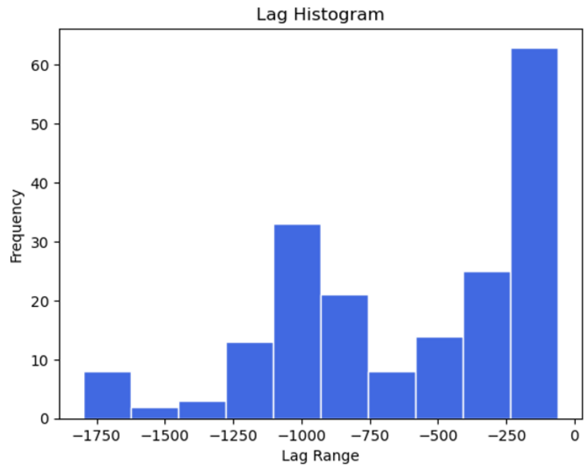


Figure 7: Histogram that shows the number of channels of channels at given time lags with a correlation threshold of 0.3.

independently of each other as they are never picked out on the same day. It is important to note that these two auxiliary channels were only picked out on four out of nineteen days. Because of this, we also suspect that there are multiple coupling mechanisms at play that reducing detector sensitivity. September 18th, 2024 had the most active auxiliary channels that were caught by the cross-correlation.

Figure 7 shows the behavior of the negative lags. Most lags are between -250 seconds and a second, suggesting a quick response. There is another spike of channels at the -1000 seconds mark, which is around 15 minutes.

4. Conclusion

The source of the BNS oscillations remains unknown. The source of the noise has not yet been identified, but the FMC subsystem is routinely being caught by the cross-correlation algorithm. Relative humidity sensors and temperature sensors are correlated most frequently with the gravitational wave strain. Seismometers and accelerometers also show some correlation.

There is evidence of multiple coupling mechanisms within the detector. The PEM accelerometer and ISI seismometer mentioned in Section 3 are not oscillating on the same days. Since the FMC channels pop up so frequently, we speculate that the HVAC fan may be causing airflow or structural vibrations that are being caught by the accelerometers. The electronics bay is right next to the air handling unit, so this is possible. Furthermore, since relative humidity sensors are being routinely picked up, humidity may be a factor in this noise. With so many subsystems at play, multiple coupling mechanisms seems likely. Future work is needed to untangle the subsystems from the noise.

5. Future Steps

Future steps would be to perform some follow-up on these auxiliary channels with the Livingston commissioners and widen our net to the End-Y and corner station. Although early investigations suggested that the source of the noise was at the End-X station, we have not completely ruled out the source being at other stations.

Many of the channels that are observing the oscillations are in physical proximity to each other in the End-X station, possibly indicating a source or a coupling. Current evidence points towards the air handling unit at the End-X station; however, interesting behavior is being seen in the electronics bay and seismometers as well. Communications will take place with the commissioners to determine what kind of physical tests can be performed. Another avenue to be explored is to develop some method to track how the amplitude of the oscillations in the auxiliary channels change over time, as we have only looked at the timing of the oscillations rather than the behavior itself. The sources of these BNS and auxiliary oscillations are evasive, so we must perform a comprehensive analysis throughout the entire facility to make sure that we do not miss something important.

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