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Poissonian analysis of gravitational wave interferometers

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Abstract. Glitches are non-Gaussian transient noises that impact the ability to identify true gravitational wave signals. This study aims to analyze the statistical behavior of the main types of glitches during an observational run using computational methods, investigating whether their temporal distributions follow a Poisson pattern. This analysis may provide insights into their physical origins, facilitating their mitigation and contributing to the improvement in the quality of gravitational wave detections.

Resumo. Os "glitches" são ruidos transitórios não gaussianos que afetam a capacidade de identificar sinai reais de ondas gravitacionais. Busca-se então, por meio de métodos computacionais, analisar o comportamento estatístico dos principais tipos de glitches ao longo de uma corrida observacional, investigando se suas distribuições temporais seguem um padrão de Poisson. Essa análise pode oferecer pistas sobre suas origens físicas, facilitando sua mitigação e contribuindo para a melhoria na qualidade das detecções de ondas gravitacionais.

Keywords. Gravitational waves – interferometers – data analysis

1. Introduction

Gravitational waves represent a phenomenon of remarkable interest and relevance in contemporary physics. Originally conceived as a consequence of the Theory of General Relativity, these oscillations in the fabric of spacetime arise from supermassive and violent cosmic events, such as black hole mergers, neutron star collisions, and supernova explosions.

The direct detection of these phenomena marked a historic milestone in astronomy, achieved for the first time in 2015 by the Laser Interferometer Gravitational-Wave Observatory (LIGO). Since then, multiple detections have been made, providing an abundance of data on some of the most extreme cosmic events that previously could not be properly studied.

However, the quest to capture and interpret gravitational waves is fraught with challenges. Terrestrial interferometric detectors excel in detecting the slightest distortions in spacetime caused by the passage of gravitational waves. However, during the measurement interval known as the "observational run," the interferometers detect not only gravitational wave oscillations but also a range of transient disturbances commonly referred to as "glitches." These anomalies, characterized by their non-periodic and often unpredictable nature, pose a significant challenge to the reliable detection and interpretation of signals emitted by gravitational waves, as they can mimic the morphology of true signals within the detector.

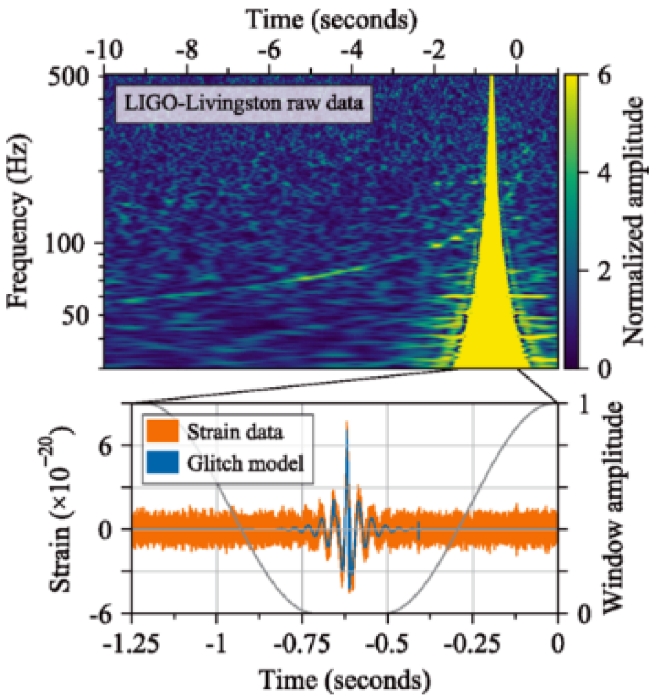

Figure 1. The signal of the GW170817 event contaminated by a glitch by Abbott.

1.1. Data

It is essential to characterize the LIGO detectors and monitor their behavior. To achieve this, there are databases that analyze and categorize observed glitches using the signal morphology in time-frequency space. In this project, we are utilizing a glitch database provided by the Gravity Spy, Glanzer et al. (2023), Machine Learning model for LIGO glitches. This model classifies all transient noise events identified by the Omicron pipeline. The Omicron pipeline is triggered when it detects an excess of power on a multi-resolution spectrogram of data between 10 Hz and 2048 Hz.

During the event of the first binary neutron star merger, there was a real case of the impact of glitches. Figure 1 shows the characteristic chirp signal of a merger, where the frequency increases with time, but with a significant glitch at the end. In this case, the glitch was observed only at Livingston and had no known cause, as reported by Abbott et al. (2017).

2. Methodology

To perform the behavioral analysis of glitches, we use the Poisson distribution, which is suitable for describing the occurrence of independent events at a constant average rate. In this case, the distribution can be used to predict the expected number of glitches within specific time intervals, referred to as bins, considering that these glitches occur independently in the detection system.

Our methodology is based on the analysis of real observational data, considering only the periods when the detectors were operational, i.e., actively collecting data (**Duty Cycle**). At this initial stage, we are studying glitches from the LIGO Livingston detector (which is more sensitive than the Hanford detector and therefore registers a higher number of glitches) during the O3a period, where the Duty Cycle is 76%, corresponding to 138.5 days.

Using the observational data, two main initial graphs are created: one describing the occurrence of glitches over time (GPS time) in terms of central frequency, and another, a histogram, showing the statistical distribution of observed glitches compared to the distribution predicted by the Poisson model under the same conditions. Initially, the method cannot be applied to all 22 glitch morphologies classified by Gravity Spy, as some do not have a sufficient amount of observed data to build statistics with an adequate level of significance.

3. Results

Non-Poissonian glitches, characterized by systematic deviations from a Poisson distribution, can signal the presence of interferences arising from anthropogenic activities, such as machinery operation or ambient vibrations, or from specific natural processes. A primary objective of investigating non-Poissonian glitch characteristics is to establish potential correlations with human-induced or external factors, thereby facilitating the mitigation of such noise.

Thus, when we applied the method to the Extremely Loud glitch morphology, we were able to obtain the graphs described in Figures 2 and 3 below.

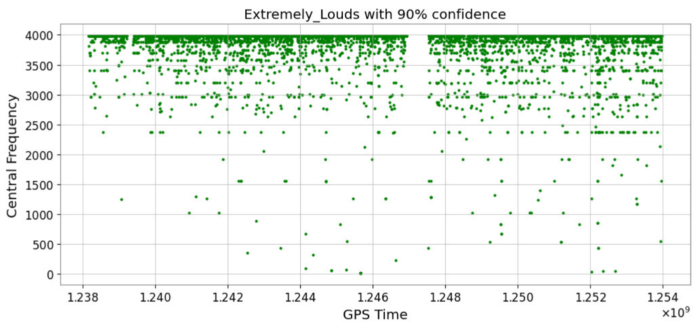

Figure 2. Central frequency / GPS time for an Extremely Loud category glitch

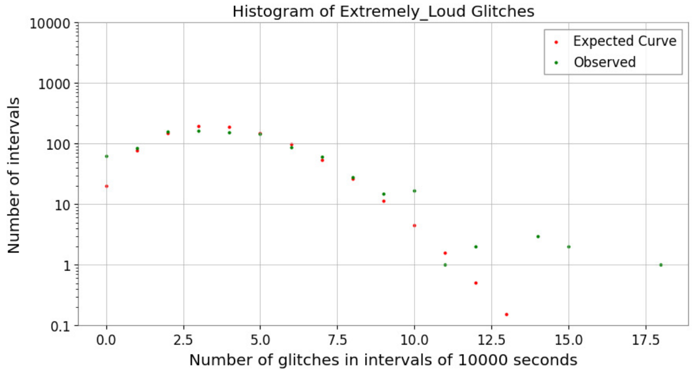

Figure 3. Comparative Histogram between the Observed Experimental Curve and the Expected Statistical Curve from the Poisson Distribution for the Extremely Loud Glitch Category

4. Conclusion

The initial results of this study highlighted qualitative discrepancies between the observed distribution of "Extremely Loud" glitches and the expected Poisson distribution, suggesting the presence of non-Poissonian external influences affecting the glitches, meaning that the occurrence of glitches in the signals may be influenced by external or systematic factors.

Future development may also include expanding the dataset to incorporate more glitch categories and other observational runs. This will help to better understand broader patterns and influences affecting glitches in gravitational wave interferometers. Additionally, the research may contribute to studying improvements in noise mitigation strategies based on the insights gained, enhancing the quality and reliability of gravitational wave data.

In summary, although only small progress has been made so far, the continuation of research and development is essential to fully understand and address glitch behavior. The goal is to improve the sensitivity and precision of gravitational wave interferometers, paving the way for more accurate observations and discoveries in the field of gravitational wave astronomy.

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