Investigating data quality metrics for stochastic gravitational-wave detection

Caltech LIGO SURF 2021

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I. INTRODUCTION

Ever since their initial detection in 2015, gravitational waves (GWs) have been at the forefront of scientific research. GWs are notably ripples caused by disruptions to the fabric of space-time typically traced back to high-energy events, such as binary black hole mergers, compact binary coalescence, and bursts. First predicted by Albert Einstein in his general theory of relativity, GWs have the potential to provide unprecedented insight into astrophysical phenomena and the primordial universe [1].

The Laser Interferometer Gravitational-Wave Observatory (LIGO) has the ability to directly detect the GWs permeating from high-energy events and has been doing so since the first successful GW detection on September 14th 2015. LIGO is a large interferometer consisting of two, four kilometer arms oriented in an L-shape. A laser beam is split using a beam splitter and the two resulting beams are sent down the arms of the detector. If the light beams go undisturbed by GWs, the light from both arms will arrive back at the detector at the same time and cancel eachother out, resulting in no GW detection. If a GW is present, it will create a slight disturbance and the two beams will return to the detector at different times. In this instance, the two beams of light will not cancel due to the varying phases, providing evidence of the presence of a GW. There are LIGO detectors in Livingston, Louisiana and Hanford, Washington.

While the primary sources of GWs are isolated astrophysical events, many detected GWs can be attributed to the stochastic gravitational-wave background (SGWB) [2]. The SGWB is stochastic data composed of the weak GW signals from a large number of unidentified events [4]. For instance, the superposition of GW signals from a population of binary black holes would appear stochastic. The SGWB can also be credited to stochastic processes that occurred in the primordial stages of the universe. We expect a successful detection of the SGWB to occur in the near future.

Stochmon is a data-quality monitor which specializes in the analysis of LIGO and Virgo low-latency stochastic data [3]. The monitor has a variety of tools that provide us with useful analysis, such as estimates for the sensitivity at which stochastic data is being collected and analyzed as well as coherence estimates for the two LIGO locations and the noise stationarity of the detectors.

A. Problem

The improvement of Stochmon will lead to a direct improvement in the analysis of stochastic data, the quality of data, and the overall detection of the SGWB. With the current instrumentation, the detection of the SGWB, and GWs in general, is imperfect. This is especially evident in frequency bands where strains are corrupted by noise.

An improvement in Stochmon would improve future stochastic data analysis. This would provide the opportunity for more research to be conducted on the SGWB and its corresponding sources. It would also aid researchers in detecting any problematic data more efficiently and in turn they would have more accurate and meaningful data.

This improvement in stochastic data analysis could potentially lead to a deeper understanding of the primordial universe and the stochastic events which may have occurred around the time of the Big Bang [5]. Additionally, the stochastic data analysis could provide the ability to achieve a deeper understanding of what the universe is composed of and allow for a method of detection free of scientific models.

As of right now, Stochmon exists and is operational. However, it has not been integrated and is not actively being improved or monitored. We want to ensure that Stochmon is updated and that the necessary improvements are implemented to ensure the most efficient detection of gravitational waves.

II. OBJECTIVES

One of the main objectives of this project is to improve Stochmon and its tools to more effectively monitor potential data-quality issues. Improved monitoring allows for the identification of imperfect data and may lead to the development of better data collection and analysis. Additionally, a goal of this project is to characterize the features in the LIGO data that have the potential to impact the stochastic sensitivity. A deeper understanding of the data leads to the identification of new ways to improve and analyze stochastic data.

We aim for an improvement of the Stochmon system and its ability to investigate the performance of LIGO's detectors in detecting the SGWB. An improvement must first be identified through an analysis of the current efficacy of the Stochmon system. Prior to beginning the project, the assumption is that all of the elements of Stochmon can be updated in some way to achieve a higher quality of stochastic data analysis. Another objective is to ensure that Stochmon and its tools are well integrated with other existing online data monitoring tools. These updates must then also be integrated so that they can be utilized during the next LIGO detection run. The project may be considered a success if we are on the path to improving Stochmon and the data it monitors.

III. APPROACH

The approach for this project is entirely contingent on what elements of Stochmon ultimately need improving and how those updates can be accomplished. The first step is to identify the components of Stochmon which are the most beneficial and need the most revision. After the initial identification, the next step would be to identify the ways in which the component could be improved and how those improvements could be implemented. The length of each step in the process is dependent on what approaches are taken and how intensive those approaches may be. While working on improvements, we will be working closely with the original developers and maintainers of Stochmon. They will provide us with guidance and support throughout the process.

Stochmon consists of many tools which aid in the stochastic data analysis which can be improved. Stochmon provides a detailed analysis of cross-correlated data between the Hanford and Livingston LIGO locations. This H1-L1 coherence is determined by dividing the cross power of the two detectors by the product of the auto powers [3]:

$$coh(f) = \frac{|\overline{S_{12}(f)}|^2}{\overline{S_1(f)}\;\overline{S_2(f)}} \tag{1}$$

Knowing the coherence aids in the cross-analysis of data and therefore in the process of separating the stochastic data from any disruptive external artifacts or noise from instrumentation.

Stochmon also provides an analysis of the cross amplitude density plots for both detectors [3]:

$$a(f) = |\widetilde{s}_I^{*}\widetilde{s}_I(f)|^{1/2} \tag{2}$$

One of Stochmon's main features is the analysis of sensitivity. The strain sensitivity (σ_h) is the sensitivity of what is measured with the detector. The energy sensitivity (σ_Ω), which is the cosmological quantity used in publications, is determined and is then compared to the aforementioned strain sensitivity [3]:

$$\sigma_\Omega(f) = \frac{10\pi^2}{3H_{100}^2}\frac{f^3}{\gamma(f)}\sigma_h(f)^2 \tag{3}$$

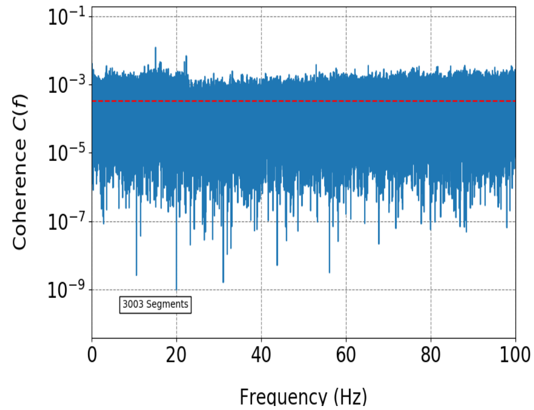

FIG. 1. The coherence between Livingston and Hanford with 1mHz frequency resolution. The dashed red line signifies the expected level of coherence. Figure provided by the Stochmon summary page.

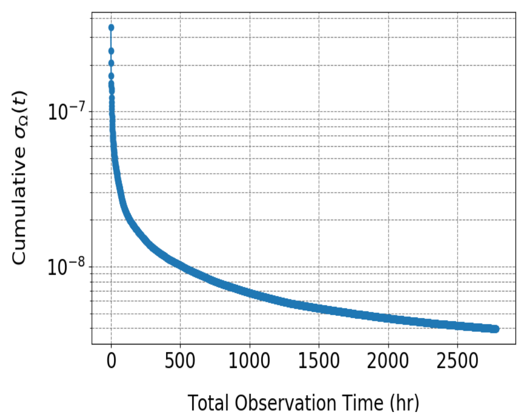

FIG. 2. Energy sensitivity vs. observation time. Figure provided by the Stochmon summary page.

An analysis can then be performed by taking a weighted average of both the sensitivity of time and frequency [3]:

$$\sigma = \sum_{t=1}^{n}\sum_{f=1}^{m}(\sigma(f,t)^{-2})^{-1/2} \tag{4}$$

The analysis of sensitivity provides a deeper understanding of the detectors' strengths and weaknesses, as well as how they can be improved.

IV. PROJECT SCHEDULE

All ten weeks of the program have been split into three sections in order to ensure maximum efficiency and comprehension. Week one places an emphasis on onboarding. This includes getting everything set up from a technical perspective to ensure the rest of the project runs smoothly. The first four weeks will center around learning. In this stage, the goal is to develop a deeper understanding of the project's content, such as studying the analysis of stochastic data. This also includes learning the complimentary information which will aid in participation, such as what code will be implemented. This stage includes reading papers and inquiring about any withstanding questions or confusions. The second stage involves carrying out the actual research, which will take place during weeks five through eight. In this stage, all of the knowledge gained during the first stage will be applied to the research detailed throughout the rest of this proposal with the goal of achieving the desired objectives. Finally, weeks nine and ten will be devoted to writing the final report and preparing a final presentation on the completed research.

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