Stochmon: A LIGO Data Analysis Tool

Gabriela Hernandez[1, a]

[1] *Georgia State University, 33 Gilmer St SE, Atlanta, GA 30303*

(Dated: August 16, 2013)

Stochmon is a data-quality monitor for LIGO-Virgo stochastic analyses. It provides sensitivity estimates and diagnostic plots to track potentially problematic data-quality issues in real time. With *Stochmon*, LIGO-Virgo researchers will get a (blind) preview of the results of stochastic analyses, which will facilitate planning while providing useful feedback for detector characterization and commissioning efforts.

I. INTRODUCTION

Detecting gravitational waves is one of the most exciting areas of study in physics. Predicted by Albert Einstein's theory of general relativity, gravitational waves are associated with the distortion of space-time. There exist four primary categories of gravitational-wave sources: spinning isolated neutron stars, merging compact binary coalescence, bursts from objects such as supernovae, and the stochastic background [1]. The advantage of observing gravitational waves emitted by isolated neutron stars and compact binary coalescences is that they are both easily modeled. Bursts, on the other hand, are never the same. They are difficult to model due to the uncertainty in predicting the waveform.

The stochastic gravitational-wave background (SGWB) is the unresolved and faint gravitational radiation emitted by a large number of independent events [2]. The SGWB is random yet persistent and can be created through two different mechanisms. In astrophysical models, events such as compact binary coalescence creates faint chirps at the moment of their collision, and the superposition of these chirps creates a SGWB. In cosmological models, the SGWB is created in the early universe. Measuring a cosmological SGWB may allow us to probe extraordinarily high energy scales, which are otherwise inaccessible. Despite the randomness of the SGWB, it can be analyzed statistically by integrating a large amount of data [2].

The SGWB is analogous to the cosmic microwave background. The cosmic microwave background, the residual thermal radiation filling the observable universe, and the SGWB both enable us to learn about the early universe. However, the cosmic microwave background only permits us to look back around 380,000 years after the Big Bang, marking the moment when the universe became transparent to photons. The SGWB could potentially allow us to look back much closer to the instant the universe was created since the early universe is nearly transparent to gravitational waves. It is believed that the SGWB from the early universe could answer questions regarding the primordial universe, perhaps shedding light on the inflationary period or even pre-Big-Bang models [3]. However, the cosmic microwave background is much easier to detect than the SGWB, because the force of gravity is so weak.

The SGWB created by compact binary coalescence and the SGWB created by the early universe differ in expected detectability, and the SGWB created by the early universe is probably more challenging to detect. Consequently, short-term effort is focused on identifying the SGWB created by relatively nearby objects, such as compact binary coalescences [1].

II. LIGO

Detecting the stochastic gravitational wave background, or the SGWB, has proven to be quite difficult. However, many laboratories around the world have made significant advancements in creating instruments that may one day be able to directly to observe the SGWB. The California Institute of Technology and the Massachusetts Institute of Technology operate LIGO, the Laser Interferometer Gravitational Wave Observatory. Three observatories have been built thus far, two in Hanford, Washington, one of which is in the process of being shipped to India, and another in Livingston, Louisiana. With the upgraded Advanced LIGO set to begin taking data in 2015, the direct observation of the SGWB may be just around the corner.

It is possible to detect gravitational waves by exploiting the deformation of space-time. LIGO does this with a giant L-shaped instrument, in which two mirrors are suspended by wires on each end. High powered laser beams are bounced back and forth between the two mirrors and a beam splitter. When gravitational waves pass through LIGO, it creates an incredibly small change in distance between the two arms of the L. The slight change in distance changes the phase between light in the two arms, which modulates the light incident on a photodiode, revealing the form of the gravitational wave [4]. Compiling about one year's worth of data, statistical analysis of the SGWB can now begin.

Various feedback control systems are used to keep the suspended masses tightly on resonance, but seismic activity can knock the detector out of lock, thus ending data-taking until lock is restored. Another common is-

[a] Electronic address: `ghernandez5@student.gsu.edu`

sue with collecting useful scientific data is the presence of non-stationary noise, which contaminates the data while harming sensitivity.

The noise detected by the observatories varies at either location, but the SGWB signal is identical at both locations. Researchers differentiate between noise and the SGWB by averaging large amounts of data so that noise begins to shrink. The signal shows up as excess cross-correlation.

III. STOCHMON

In order to monitor stochastic-search data as it becomes available, I am creating a website under the supervision of Dr. Eric Thrane that acts as a stochastic monitor, entitled *Stochmon*. *Stochmon* includes a computer program that generates diagnostic plots in order to optimize the detection of the SGWB. This web based interface includes standard plots which are updated automatically by the UNIX tool, cron.

IV. PROGRESS

Below is a list of the features I implemented in *Stochmon*.

- I created an Apache Subversion (SVN) repository for version control within the stochastic group

- I added amplitude spectral density plots for the two detectors. Figure 1a shows an example of amplitude spectral density, defined as

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

  Here, $\tilde{s}_I(f)$ is the Fourier transform of the strain time series from detector I. Researchers may examine plots such as Figure 1a in order to observe new lines emerging, or excess broadband noise compared to design sensitivity.

- Next I examined sensitivity. There are different metrics when discussing sensitivity: strain sensitivity σ_h and energy density σ_Ω. Strain is what we actually measure with the detector and it is useful because it can be used in a control room setting. Energy density, on the other hand, is the cosmological quantity that we ultimately include in publications. The two are straightforwardly related by the following equation:

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

  Here, H_{100} is Hubble's constant and $\gamma(f)$ is the overlap reduction function arising from gravitational-wave interference.

  Regardless of the metric used, a stochastic analysis works by performing a weighted average on both time and frequency:

$$\sigma = \sum_{t=1}^{n}\sum_{f=1}^{m}\left(\sigma(f,t)^{-2}\right)^{-1/2} \tag{3}$$

  Here, n is the total number of data segments and m is the total number of frequency bins.

  Examining Equation 3, it is apparent that we can carry out only one of the sums in order to see how sensitivity is dependent on frequency $\sigma(f)$ or time $\sigma(t)$. The quantity $\sigma(f)$ can be used to identify spectral features such as electronic noise lines. The quantity $\sigma(t)$ can be used to see, for example, if there was an hour out of the last day characterized by bad noise.

  – Figure 1c and Figure 1d represents $\sigma_h(f)$. By integrating over long stretches of time, $\sigma_h(f)$ falls with time. We show two plots from two different amount of integration times to demonstrate how it has fallen.

  – Figure 3 represents $\sigma_\Omega(f)$. The spikes are due to the overlap reduction function.

  – Figures 2c and 2d represents $\sigma_\Omega(t)$. There are two different time variables that we can consider: science time and clock time. Science time (Figure 2c) is the measure of the accumulated amount of science quality data. It does not include gaps caused by, for example, a commissioning break. Clock time, on the other hand (Figure 2d) is a measure of absolute time since the data has been running. It does include data-taking gaps. If the detector performance does not change over time, then $\sigma(t)$ falls like $t^{-1/2}$ in a science time plot. In both figures we also include $\sigma_0(t)$, the uncertainty associated with each segment. Note, $\sigma_0(t)$ (red) is for just one segment, whereas $\sigma(t)$ (blue) integrates over all previous segments.

- I calculated the cross-amplitude spectra, the amplitude common between the two detectors (Figure 1b):

$$a(f) = |\tilde{s}_1^\star(f)\tilde{s}_2(f)|^{1/2} \tag{4}$$

  Because cross amplitude spectra is obtained from a product of two Fourier transforms, it has complex values. The absolute value is taken such that plotted values are real.

- I added a plot of coherence to observe the correlation between the two detectors. Equation 5 describes the coherence between the detectors.

$$coh(f) = \frac{\overline{|S_{12}(f)|}^2}{\overline{S_1(f)}\,\overline{S_2(f)}} \tag{5}$$

Here, S_{12} represents the cross power while S_1 and S_2 represent the auto power.

In order to see coherence falling with time, I included plots for two different integration times (Figure 2). The red line indicates the expected value for uncorrelated data.

- In Figure 4a, I created a plot that tracks how much data is analyzed per unit clock time (duty cycle). The duty cycle tells researchers what fraction of the time the detectors are both on.
- I added a nonstationary plot that tracks the fraction of segments failing a non-stationarity cut as a function of clock time. Figure 4b shows the percentage of failed segments every day.
- *Stochmon*'s input is configurable, meaning it can either create plots with initial LIGO data (from the S6 trial) or simulated advanced LIGO data. I have been performing preliminary testing of Stochmon with the simulated data. However Figure 3b shows an example plot generated with actual S6 data.

V. CONCLUSIONS

Future plans include:

- After about a year of integration, *Stochmon* will determine projected sensitivity.
- *Stochmon* will contain a non-stationarity monitor. This will tell us the fraction of data which contains a sudden jump in noise that may be due to a glitch.
- Transition to real data: many subtleties to work out
  - Detector is sometimes out of lock.
  - Catching up if *Stochmon* goes down.
  - Working out retroactive vetoes.
- *Stochmon* will have a more robust design.
- Alpha testing with engineering run once *Stochmon* is able to take in real data.

After continued operation, the detection of gravitational waves has the potential to yield revolutionary discoveries. *Stochmon* will help researchers monitor gravitational-wave data, which will help them detect and remedy problematic data faster, which in turn, will enable them to get meaningful results sooner.

[1] W. Gear et al. (2013), http://www.astro.cardiff.ac.uk.
[2] B. Allen and J. D. Romano, Phys. Rev D p. 81 (1997).
[3] E. Thrane, Phys. Rev D **87**, 9 (2013).
[4] J. Giaime et al. (2013), http://www.ligo-la.caltech.edu.

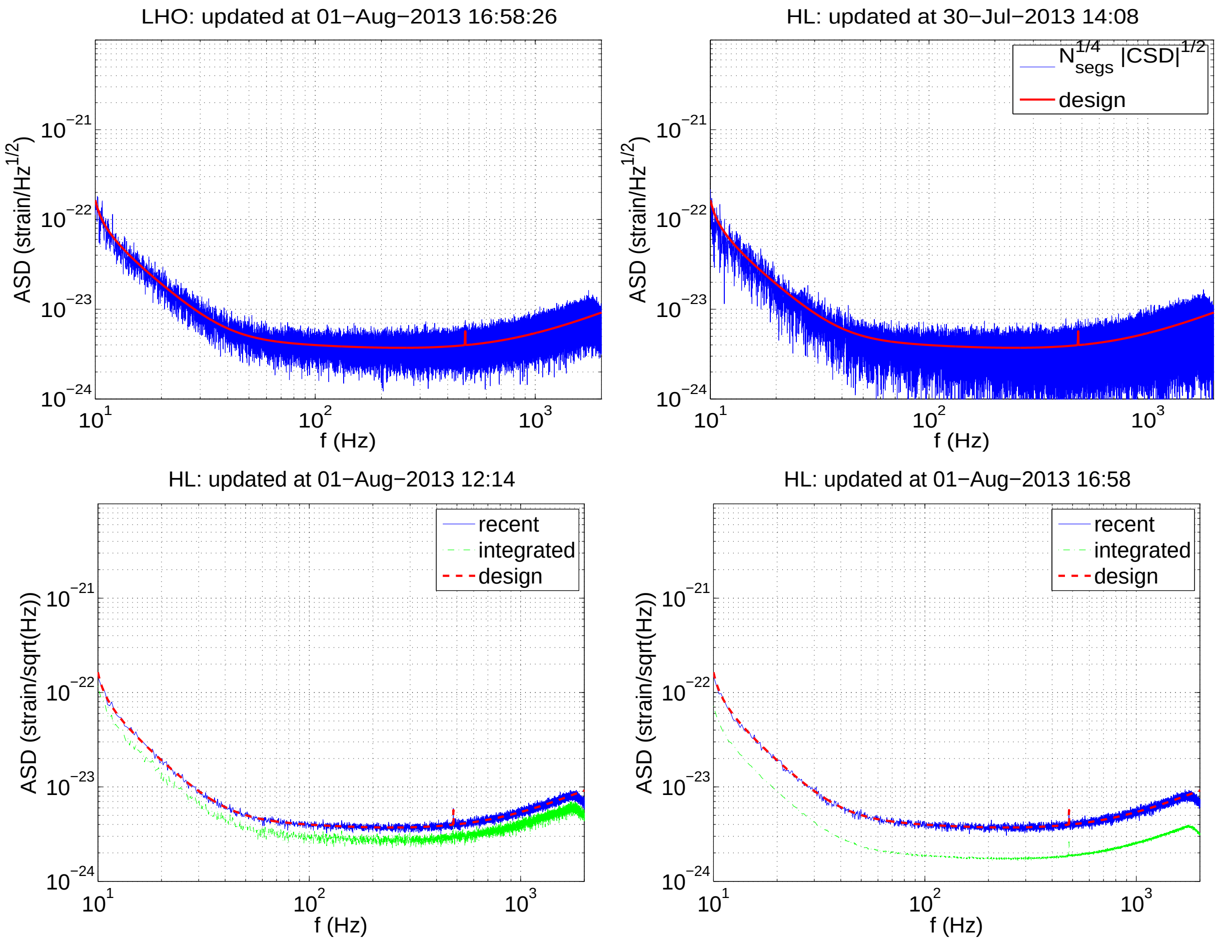

FIG. 1: Top-left: plot of auto-power spectra from the Livingston Observatory. The blue curve shows strain noise, and the red line shows design sensitivity. Top-right: plot of cross-power spectra vs frequency from the Livingston and Hanford Observatory. The blue curve represents strain noise, and the red curve represents design sensitivity. Bottom-left: integrated sensitivity falling with time. The blue line represents strain noise, the red line represents design sensitivity, and the green curve represents integrated data. Bottom-right: this plot is the same as the bottom-left plot, but with additional integrated data.

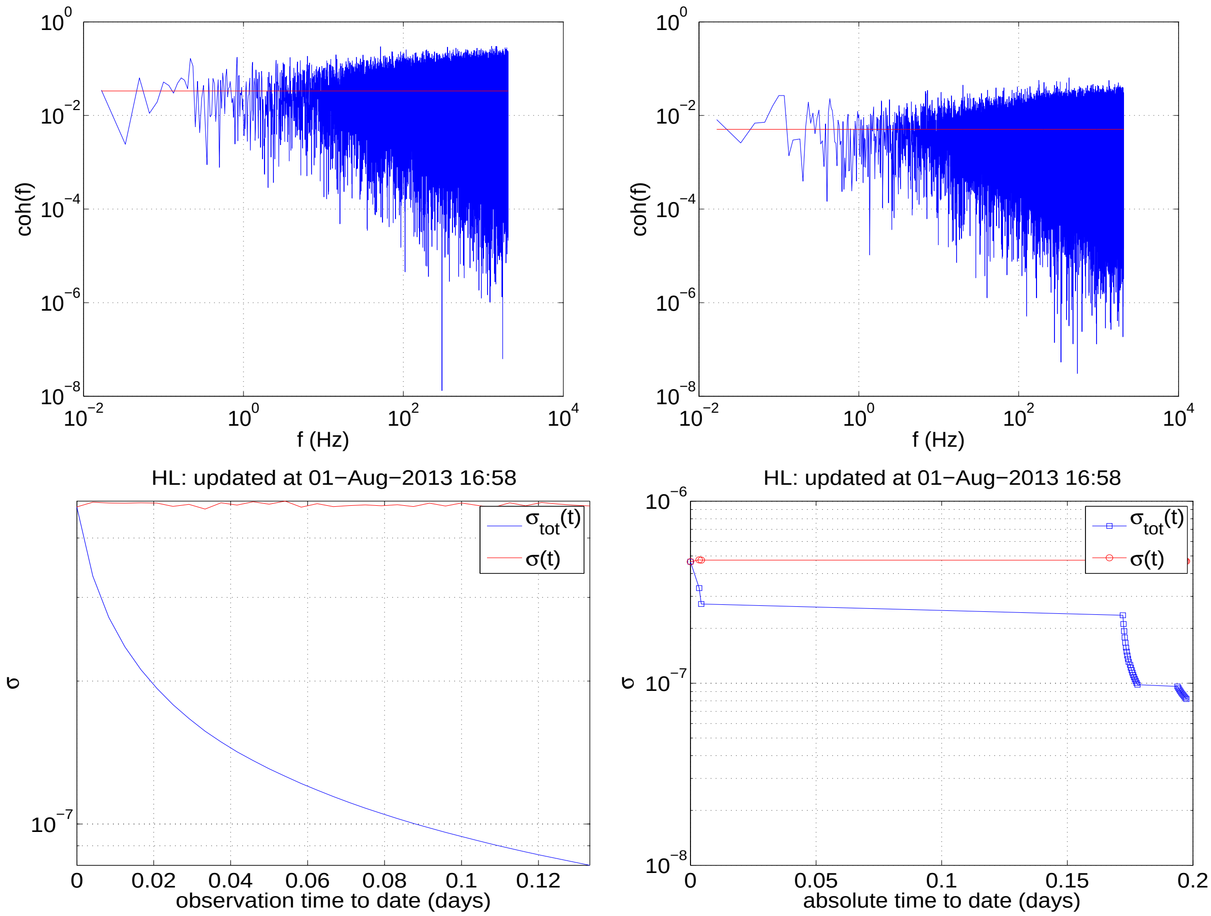

FIG. 2: Top-left: plot of coherence vs frequency. The blue curve shows the coherence between the two detectors, and the red line shows the expected value for uncorrelated data. Top-right: this plot is the same as the top-left plot, but with additional integrated data. The plots may be examined by researchers in order to observe excess coherence indicative of correlated noise. Bottom-left: plot of $\sigma(t)$ and $\sigma_{tot}(t)$ vs accumulated science time. Bottom-right: same as bottom-left but with clock time.

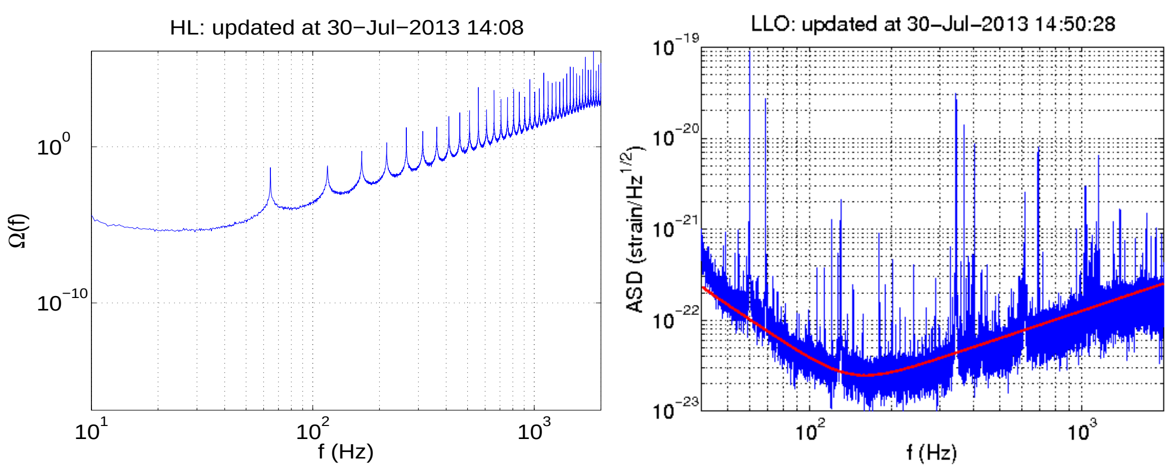

FIG. 3: Left: plot of $\Omega(f)$. $\Omega(f)$ is the energy density of the universe due to the stochastic gravitational wave background. The spikes in the plots are due to the overlap reduction function. Right: plot of auto-power spectra with data from the S6 trial.

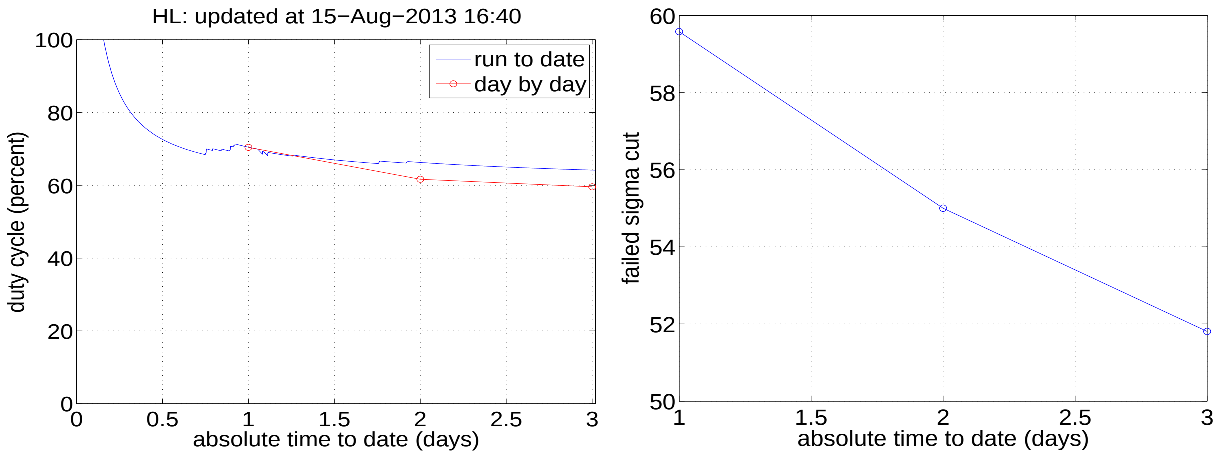

FIG. 4: Left: plot of the duty cycle vs clock time. The red curve represents the duty cycle day by day, and the blue curve represents the duty cycle run to date. Right: plot of percentage of segments that fail the stationarity cut vs clock time. The current typical percentages (around 50) are too high, and we are working to debug this issue.