Tracking Spectral Noise Lines in Advanced LIGO Data

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Abstract

The Advanced LIGO detectors are expected to make gravitational wave observations possible within the next few years. However, sharp spectral noise lines continue to obscure the data, and it is unknown if or how these lines wander over time. Therefore, we are developing a method that will track the frequencies of the various noise sources which appear in our data. Using Python for scripting, we utilize various signal processing techniques to extract information about the frequencies present in our time series. We then heterodyne to examine how a given spectral line wanders in frequency over time. Preliminary results using data from Advanced LIGO's Engineering Run 7 are included. In the future, this method will be automated to constantly examine new data in quasi-real time, providing beneficial insight for improving the quality of the data and the sensitivity to gravitational waves from spinning neutron stars and other astrophysical sources.

1 Introduction

Gravitational waves are ripples in space-time, first predicted by Einstein's theory of general relativity in 1916. They can be produced by a number of sources, including compact binary coalescences, galactic supernovae, non-axisymmetric spinning neutron stars, and the stochastic gravitational wave background left over from the Big Bang. Now, nearly a century after the existence of gravitational waves was predicted, the Advanced LIGO detectors are expected to finally make gravitational wave observations possible.

LIGO is designed to detect gravitational waves using a laser interferometer, which measures with high precision the time it takes light to travel between suspended mirrors[1]. If a gravitational wave passes by, the distance measured by the light will change, and a photodector will produce a signal. The LIGO instruments are modeled after Michelson interferometers with Fabry-Perot arm cavities. The detectors are operated in unison at the different locations to rule out false signals. The first generation of LIGO ran from 2002 to 2010, and although it did not detect anything, it proved that the experiment was technologically possible[2]. Advanced LIGO is predicted to be ten times more sensitive due its additional suspension cables, and should soon be able to detect gravitational waves. However, the data are confounded by various sources of noise.

There are two components to LIGO strain noise: a broadband component and sharp spectral lines. One of the sources of the largest line features is the electrical power system, which operates at a frequency of 60 Hz and which produces spectral lines in the LIGO strain data at 60 Hz and all multiples (harmonics). Another chief source is the vibration of the suspension cables which hold up the mirrors. These noise lines, of which there are about a dozen, are called violin modes, and they typically produce spectral lines in the data around 500 Hz (and all harmonics). Other sources of line features include calibration and dither lines, which are deliberately placed in the data by moving the mirrors. (The calibration and dither lines are very close to pure sinusoids, so their harmonics do not show up noticeably in the data.) We would like to determine if and how the frequencies of the lines drift. Thus, we are developing a method for tracking the frequencies of these noise sources.

2 Methods

2.1 Scripting and Data

We use Python[3] for scripting, making extensive use of a package called GWpy[4], which provides specific tools for studying data from gravitational-wave detectors. Preliminary data were taken from Advanced LIGO's ER7 run (specifically June 7, 2015), from both the Livingston (L1) and Hanford (H1) detectors.

2.2 Signal Processing

In order to identify the frequencies present in our time series, we utilize various signal processing techniques available in numpy[5] and scipy[6]. These include the fourier transform, spectrogram, and power spectral density (PSD), all of which provide information about how the power of a signal is distributed over its different frequencies. (In order to reduce spectral leakage, a

Blackman window is applied.) These techniques can give us further insight into the noise that we detect. We use a high resolution PSD to identify the exact frequencies of our spectral noise lines.

2.3 Heterodyning

Heterodyning is a signal processing method that involves multiplying an incoming signal by a complex exponential, and then integrating over time. Thus, we are essentially computing the integral $H(g) = \int_0^T e^{2i\pi gt} \sin(2\pi ft)dt$, and then dividing by T to get an average. (This is described step-by-step in the Appendix.) The first exponential, with frequency g, is chosen based on the lines identified from our PSD, and the second, with frequency f, represents only one fourier component of a signal time series (in our case, LIGO strain data). This technique allows us to pick out frequencies f close to g, suppressing all others because the heterodyne averages to zero for them. We examine the heterodyne magnitude and phase plots to determine how the signal frequency changes over time. If the heterodyne and signal frequencies are one and the same, the phase should be constant. However, if they are different (that is, if the signal frequency wanders over time), then the phase will vary.

3 Results

The results of our preliminary analysis of Advanced LIGO data are shown in Figures 1-8. Time series plots of H1 and L1 data are shown in Figures 1 and 5, respectively. H1 and L1 power spectral densities, which give us the frequencies and magnitudes of the spectral noise lines, are shown in Figures 2 and 6. Plot of heterodyne magnitude and phases from H1 and L1, which illustrate how the frequencies of our spectral noise lines wander over time, are shown in Figures 3-4 and 7-8. So far our observations are not necessarily in line with what we expected. The phase of the first violin mode in both detectors is not constant, so the frequency is likely wandering, but it is unclear exaclty how. We also suspected that the power line would wander significantly, but based on cursory analysis, its phase appears constant, which would suggest that its frequency is not drifting. We need to heterodyne at many more frequencies and on much more data before we can offer conclusive results.

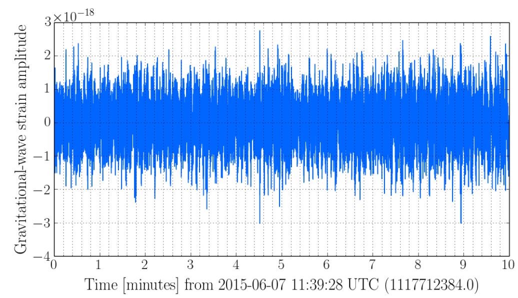

Figure 1: Ten minutes of ER7 H1 data.

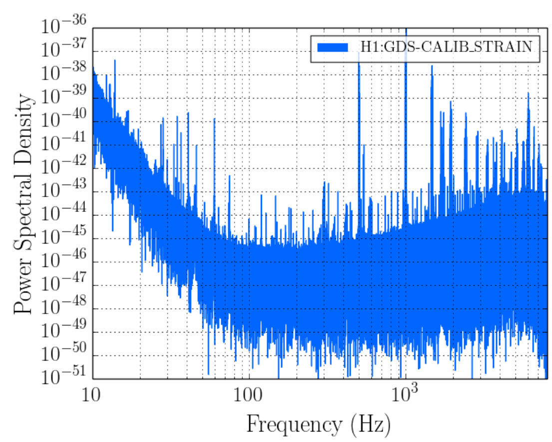

Figure 2: PSD of H1 data.

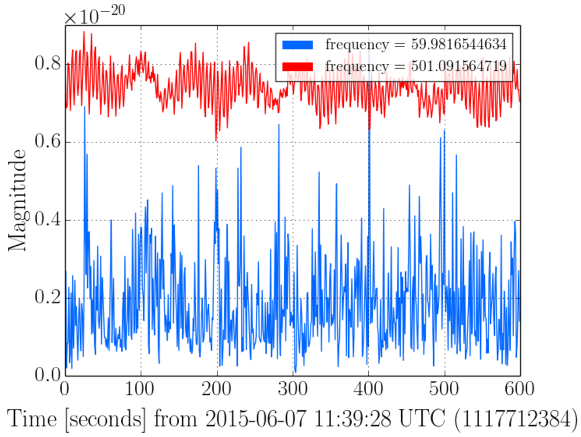

Figure 3: Heterodyne magnitudes of H1 data at various frequencies.

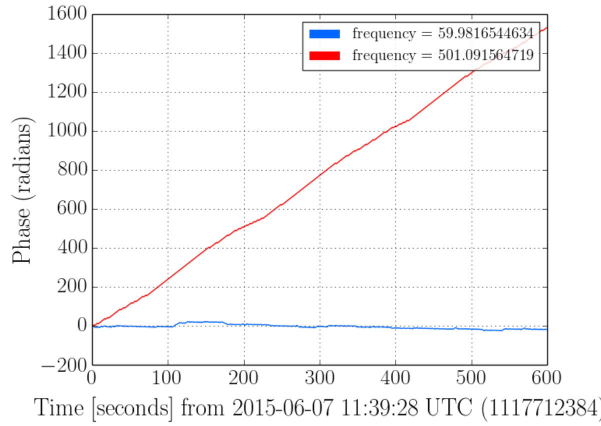

Figure 4: Heterodyne phases of H1 data at various frequencies.

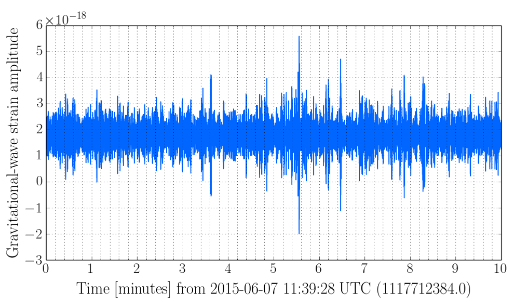

Figure 5: Ten minutes of ER7 L1 data.

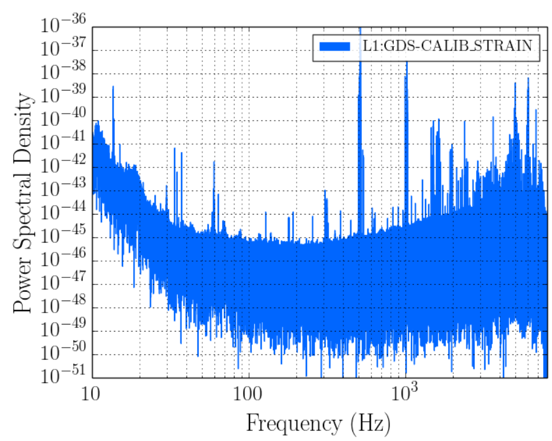

Figure 6: PSD of L1 data.

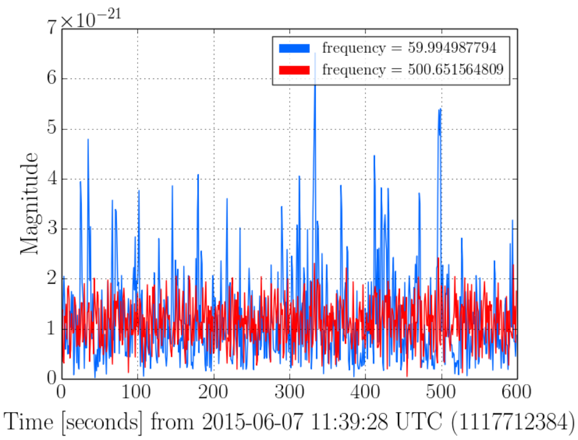

Figure 7: Heterodyne magnitudes of L1 data at various frequencies.

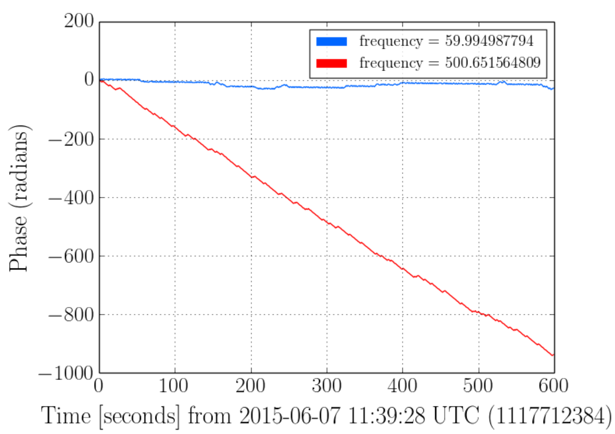

Figure 8: Heterodyne phases of L1 data at various frequencies.

4 Conclusions

Further analysis is needed to verify the relationship between the changing phase and the wandering frequency, as well as to understand the heterodyne results from the Advanced LIGO data. We will examine more data as well as more spectral noise lines over the next few weeks. The final step will be to automate the entire process so that the code runs through all incoming Advanced LIGO data minute by minute. For this, we will set up a Condor job in "cron mode" to execute the script at specific scheduled time intervals. All of the plots will be displayed on the LIGO Summary Pages[7].

5 Acknowledgments

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6 Appendix

We want to evaluate the integral

$$H(g) = \int_0^T e^{2i\pi gt} \sin(2\pi ft) dt. \tag{1}$$

This can be rewritten as

$$H(g) = \int_0^T \cos(2\pi gt) \sin(2\pi ft) dt + i \int_0^T \sin(2\pi gt) \sin(2\pi ft). \tag{2}$$

This can be expanded so that

$$H(g) = \int_0^T \frac{1}{2}[\sin(2\pi gt + 2\pi ft) - \sin(2\pi gt - 2\pi ft)] + i \int_0^T \frac{1}{2}[\cos(2\pi gt - 2\pi ft) - \cos(2\pi gt + 2\pi ft)]. \tag{3}$$

Then, because we can assume that oscillatory functions integrate to zero if T is much larger than a period, the sum terms disappear, and only the difference terms remain. Thus, we are left with

$$H(g) = \frac{i}{2} \int_0^T \cos(2\pi gt - 2\pi ft) - \frac{1}{2} \int_0^T \sin(2\pi gt - 2\pi ft). \tag{4}$$

Evaluating the integral, we get

$$H(g) = \frac{i}{2}\frac{\sin(2\pi gt - 2\pi ft)}{2\pi g - 2\pi f}\bigg|_0^T + \frac{\cos(2\pi gt - 2\pi ft)}{2(2\pi g - 2\pi f)}\bigg|_0^T. \tag{5}$$

Taking the limits, we get

$$H(g) = \frac{\cos(2\pi gT - 2\pi fT) - 1 + i\sin(2\pi gT - 2\pi fT)}{4\pi(g - f)}. \tag{6}$$

We let

$$a = Re\left(\frac{\cos(2\pi gT - 2\pi fT) - 1 + i\sin(2\pi gT - 2\pi fT)}{4\pi(g - f)}\right) \tag{7}$$

and

$$b = Im\left(\frac{\cos(2\pi gT - 2\pi fT) - 1 + i\sin(2\pi gT - 2\pi fT)}{4\pi(g - f)}\right). \tag{8}$$

To find the magnitude, we want

$$r = (a^2 + b^2)^{1/2}. \tag{9}$$

In this case,

$$a^2 = \frac{\cos^2(2\pi gT - 2\pi fT) - 2\cos(2\pi gT - 2\pi fT) + 1}{16\pi^2(g - f)^2}, \tag{10}$$

and

$$b^2 = \frac{\sin^2(2\pi gT - 2\pi fT)}{16\pi^2(g - f)^2}. \tag{11}$$

Thus,

$$r = \left(\frac{1 - \cos(2\pi gT - 2\pi fT)}{8\pi^2(g - f)^2}\right)^{1/2}. \tag{12}$$

Or, letting

$$g = f + \Delta f, \tag{13}$$

we have

$$r = \left(\frac{1 - \cos(2\pi\Delta fT)}{8\pi^2\Delta f^2}\right)^{1/2}. \tag{14}$$

To find the phase, we want

$$\phi = \text{atan}\,\frac{b}{a}, \tag{15}$$

which equals

$$\phi = \text{atan}\left(\frac{\sin(2\pi gT - 2\pi fT}{\cos(2\pi gT - 2\pi fT) - 1}\right) \tag{16}$$

or

$$\phi = \text{atan}\left(\frac{\sin(2\pi\Delta fT}{\cos(2\pi\Delta fT) - 1}\right). \tag{17}$$