

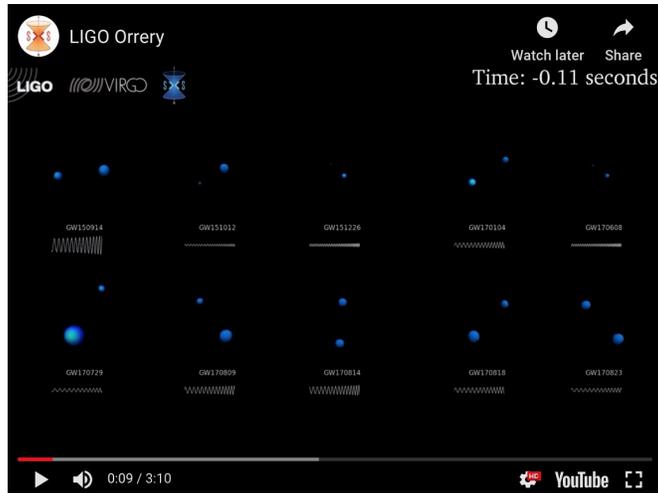
MATLAB LIGO Analysis

⚠ This is a preview of the published version of the quiz

Started: Nov 6 at 9:14pm

Quiz Instructions

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<https://youtu.be/gmmD72cFOU4>



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LIGO Orrery



Learning goals

Describe the nature, origin, and observations of gravitational waves.

Access big science open data.

Verify from the data a claim leading to a Nobel prize in physics.

Apply frequency analysis and signal filtering methods to time series data.

Visualize time series data using a power spectrum and a periodogram.

Use cross correlation to identify a coincidence of signals in noisy time series data.

Introduction

This exercise explores filtering and cross-correlation in signal analysis applied in the discovery of direct evidence for [gravitational waves](https://en.wikipedia.org/wiki/Gravitational_wave) (https://en.wikipedia.org/wiki/Gravitational_wave). Gravitational waves are simultaneously distortions in the curvature of space-time propagating at light speed. Read about [the first observations of gravitational waves](https://en.wikipedia.org/wiki/First_observation_of_gravitational_waves) (https://en.wikipedia.org/wiki/First_observation_of_gravitational_waves) that you are about to reconstruct. The source of the waves is a binary black hole system. Radiation associated with the acceleration of the co-orbiting compact sources causes loss of orbital kinetic energy and in-spiral motion ending in merger. According to numerical models based on Einstein's [General Theory of Relativity](https://en.wikipedia.org/wiki/Introduction_to_general_relativity) (https://en.wikipedia.org/wiki/Introduction_to_general_relativity), the merged hole initially has rotating lobes which lose energy in a so-called ring-down phase resulting in a spherical gravitational-wave-quiet object. The video above illustrates reconstructions of various source pairs observed by the LIGO-VIRGO collaboration as of 2019. Watch [an animation](https://www.ligo.org/science/Publication-) (<https://www.ligo.org/science/Publication->

[S6CBCHM/50.0_14.0_EOBNRv2_10hz_padded.mp4](#)) of a model binary generating waves during in-spiral and ring-down phases.

Each LIGO detector measures the difference in light travel time along two orthogonal arms, in effect the difference in length of the arms, through the interference of laser light waves. Light from a laser source is split into two coherent beams by a beam splitter at the corner of the [interferometer](#), (<https://en.wikipedia.org/wiki/Interferometry>) reflected from mirrors at the ends of the arms (in practice, multiple reflections are used), and recombined to produce the [interference](#) (https://en.wikipedia.org/wiki/Wave_interference) pattern. The length difference is disturbed by and depends upon the polarization and direction of an incident gravitational wave. The length difference sensitivity of order 10^{-21} m represents an average over the internal thermal motion of the atoms in the mirrors. The thermal noise in the light source, mirrors, and photo detectors, and noise resulting from excitation of a variety of [mechanical resonances](#) (https://en.wikipedia.org/wiki/Mechanical_resonance) limit the sensitivity.

In the analysis, the strain (fractional length change) time series data is resolved into a sum of various frequency components using [Fourier analysis](#) (https://en.wikipedia.org/wiki/Fourier_analysis). Analysis is restricted to a band of frequencies below ~ 1 kHz. Frequency components corresponding to mechanical resonances within the range are removed using a [notch filter](#) (https://en.wikipedia.org/wiki/Band-stop_filter) technique. The residual strain difference amplitude is of order 1 part in 100,000 of the raw data signal amplitude. Within the residual strain data, evidence for gravitational radiation resulting from in-spiraling black holes is observed as a coincidence of chirps in two detectors, each chirp a signal of increasing amplitude and frequency reflecting the in-spiral, terminated by the merger. Since a gravitational wave propagates at light speed, the observed slight difference in arrival times at the two detectors provides information about the direction of the source relative to an axis through the detectors.

Get the data

LIGO data is available online. Visit <https://www.gw-openscience.org/events/GW150914/> (<https://www.gw-openscience.org/events/GW150914/>) to collect the data for the first observation of gravitational waves resulting from a black hole merger at an estimated distance of 420 Mpc. The Milky Way galaxy is about 100 kLY or 30 kpc across and the nearest large galaxy (Andromeda) is about 0.78 Mpc so the source was likely in a quite distant galaxy.

Figure 1 shows the observed strain (fractional change in length) for the Hanford, Washington (H1) and Livingston, Louisiana (L1) interferometers after LIGO collaboration analysis filtering. Use the "click for DATA" links below the plots to download the data for both of the detectors. The direct links are <https://www.gw-openscience.org/GW150914data/P150914/fig1-observed-H.txt> (<https://www.gw-openscience.org/GW150914data/P150914/fig1-observed-H.txt>) and <https://www.gw-openscience.org/GW150914data/P150914/fig1-observed-L.txt> (<https://www.gw-openscience.org/GW150914data/P150914/fig1-observed-L.txt>). The goal of this exercise is to recreate/verify these published results.

Further down, find "Strain Data at 4096 Hz" and links to the raw strain data for 32 seconds centered on the event. The 4096 sampling rate data is a smoothed version of the 16384 samples per second data also

available. Click the "data.txt.gz" links for each of the detectors and unzip/uncompress these 4096 sampling rate files.

Analysis

Download the Live Script [LigoAnalysis2Detectors.mlx](#) ([LigoAnalysis2Detectors.pdf](#) ) and run the script on the files you have downloaded. You will have to alter the script slightly to run on both files and perform the cross correlation described below.

After importing the strain data, the script performs a Fourier transform to express the strain versus time samples as a sum of harmonic functions. The square of the amplitude of each function is a measure of the power at the corresponding frequency. (Read about [spectral estimation](#) (https://en.wikipedia.org/wiki/Spectral_density_estimation).

The power spectrum exhibits peaks associated with instrumental effects. These are eliminated using [notch filters](#) (https://en.wikipedia.org/wiki/Band-stop_filter%20), which, in effect, set to zero the amplitudes of frequencies within the range of each peak. A [band pass filter](#) ([https://en.wikipedia.org/wiki/Filter_\(signal_processing\)](https://en.wikipedia.org/wiki/Filter_(signal_processing))) is also used to additionally restrict the frequencies to a range expected for black hole merger gravitational wave signals. The chirp signal becomes evident in the time series data after filtering. It can also be observed in a [periodogram](#) (<https://en.wikipedia.org/wiki/Periodogram%C2%A0>).

It is possible for noise to fake a chirp signal at a low rate. The near coincidence in time (and amplitude) of chirps in the two detectors is used to suppress such signals - the fake rate for coincidences during the observation time is negligible. A simple method to search for a coincidence of a signal common to but at different times within two noisy uncorrelated time series data streams is to perform a [cross-correlation](#) (<https://en.wikipedia.org/wiki/Cross-correlation>). A cross-correlation amounts to taking the sum over all times of the products of the two signals. The resulting value is computed as a function of relative time shift. When the signals align in time, each signal point, whether positive or negative, contributes a positive value to the cross correlation while random values outside the signals average to zero. When the signals do not align, each point in each signal is matched with a random value which will contribute to the sum a value as often positive as negative.

The Hanford and Livingston chirp signals are expected to be separated in time by at most a light travel time between the two detectors, the time difference providing information on the angle of incidence relative to the line between the detectors. The script uses the simple cross correlation method to estimate the time difference. A more elaborate chirp finding algorithm is <https://arxiv.org/pdf/gr-qc/0509116.pdf> (<https://arxiv.org/pdf/gr-qc/0509116.pdf>).

After you have studied the script and readings, answer the following questions.

Question 1	10 pts

LIGO Noise

Examine the power spectra of the raw time series data. Which line frequency and harmonics noise peaks appear in the LIGO data?

- 60 Hz
- 30 Hz, 60Hz
- 60 Hz, 120 Hz, 180 Hz
- none

Question 2**10 pts****Time delay of LIGO signals**

The difference in arrival time of the L1 and H1 signals may be inferred from the position of the peak in the cross correlation. If a gravitational wave arrives perpendicular to a line connecting the two detectors (call that $\theta = 0$ degrees where θ is the polar angle relative to an axes through the two detector locations), both detectors should register the signal at the same time. If the wave travels along the line at light speed ($\theta = 90$ degrees), the signals should have a time difference equal to the distance (~3000 km) between the detectors divided by light speed. At what angle in degrees relative to the line did the wave arrive?

- 0 deg
- 30 deg
- 70 deg
- 44 deg

Question 3**10 pts****Error on time difference**

Zoom in on the cross-correlation plot and note the full-width-at-half-maximum (FWHM) of the highest (absolute magnitude) peak. We can crudely estimate the standard error σ on the time delay determination given by the position of the peak by supposing it is a gaussian with $\text{FWHM} = 2.35\sigma$ where σ is the standard deviation. What is the resulting estimated error? (The LIGO analysis official gave an error of about 0.5 ms.)

- 3 ms
- 1 ms
- 7ms
- 15 ms

Question 4**10 pts****Change in the filter**

The analysis uses a bandpass filter with a pass range of 35 Hz - 350 Hz. Change the range to 35 Hz -700 Hz. The analysis also uses a conservative range $w/6$ for the half width of the notch filters where w is the base width of the peak determined by the MATLAB *findpeaks* function. Change the notch filter half widths to $w/2$ as well. With both changes in effect, determine an answer to the following question.

Are both chirps still evident in the spectrograms of frequency versus time and is the relative time delay unchanged within the error estimated in the previous question? (Choose True if all are true, otherwise choose False.)

- True
- False

Not saved

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