University of Washington Bothell

B PHYS 433 A

Characterizing Transient Noises to Probe for Gravitational Wave Signals

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Final Research Report

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Introduction

The universe is an infinite scope of knowledge and opportunities for discovery. Many scientists around the globe are racing for new discoveries in order to understand the area of astronomy and cosmology. Astronomy is the study of stars, galaxies, planets, and other celestial objects interact in space. Cosmology is the study of the origin and evolution of the early universe, such as the all famous 'Big Bang'. The Laser Interferometer Gravitational-wave Observatory (LIGO) is one of the most sensitive experiments ever developed, detecting vibrational strains to about a width of a proton. The first detection of a gravitational wave (GW) signal was from a binary black hole merger on September 14, 2015. First predicted by Albert Einstein's Theory of General Relativity in 1916, gravitational waves are ripples in space that stretch and squeeze space-time due to collisions of extremely massive objects, usually black holes or neutron stars. However, transient noise, also known as glitches, mimic astronomical gravitational wave signals and decreases the sensitivity of the detectors. Glitches occur due to a variety of reasons, including environmental noise or instrumental artifacts. In this research, the goal is to improve the quality of the collected data and eliminate as much noise as possible in the interferometers. Where my research question then asks if these triggers have been seen in Advanced LIGO of solved or unsolved glitches? Characterizing transient noise sources in the detectors, known as detector characterization, relies on methods used to depict and remove noisy data in the analysis time. One of the methods I will be using is comparing the h(t) Omega pipeline scans to the Gravity Spy classes. h(t) Omega scans are detected gravitational wave signals outputted in a time-frequency and Signal-to-Noise ratio (SNR) plot. Gravity Spy is a citizen science project that helps improve machine learning algorithm to detect glitches. By looking at the data from both LIGO observatories, the detector network is able to identify signals from some of the most exotic objects in our universe more precisely. The search for gravitational waves opens a new era of exploring the universe and enables astrophysicists to observe events that an ordinary telescope can't.

0.1 General Relativity

Before Einstein, the universe and it's feature of space and time was seen as changeless. It was then in 1905, Einstein's groundbreaking work determined that the laws of physics are the same for all non-accelerating observers and that the speed of light in a vacuum is independent of the motion of all observers. This was known as Einstein's Theory of Special Relativity. Due to this theory introduced one of the most significant frameworks and concepts of space and time. When Einstein

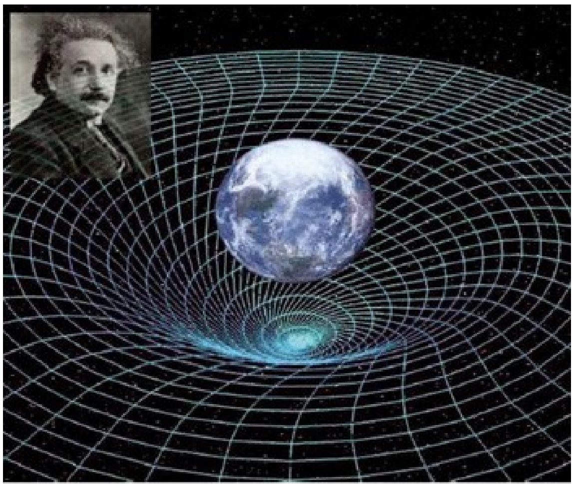

Figure 1: Massive objects bending spacetime. Credits: NASA.

spent an additional 10 years in order to include acceleration in the theory, he then published his Theory of General Relativity in 1916. In it determined that massive objects cause the 'fabric' of spacetime to distort, which is felt by gravity. The more massive the object is, the more it curves spacetime.

However, Einstein wasn't the first to discover the tug of gravity and its theory. Sir Isaac Newton was first to quantify this theory of gravity from his famous three laws of motion. The force tugging between two bodies depends on how massive each one is and how far apart the two lie. The difference, however, shows that Newton's law works perfectly well on small scales – such as calculating how fast an object drops from a tall building to the ground. But when distance and speed is very large, or very massive objects are involved, Newton's laws become very inaccurate. Thus, Einstein utilizes Special Relativity towards celestial objects moving at a constant velocity in spacetime. Einstein discovered that space and time intertwined with each other in a continuum known as spacetime. This means that events that occur at the same time for one observer could also occur at separate times for another. If an object accelerates in space, then the theory breaks down into General Relativity.

Nonetheless, General Relativity shows that observers in any frame will agree how spacetime is curved by objects whether they are moving relative to the object or not. Einstein realized that massive objects causes distortion in spacetime and that this distortion is what causes acceleration between objects, calling it gravity. This acceleration is similar to when an object rolls on a curved surface, such as a hill – but in this case the amount of acceleration is much higher for objects with higher mass because greater mass causes deeper, longer curvature. Putting in terms, "spacetime tells matter how to move; matter tells spacetime how to curve."

Figure 2: Laser Interferometer Gravitational wave Observatories. Credits: LIGO CalTech.

0.2 LIGO

Gravitational waves lie at the heart of general relativity in that violent events, such as the collision of black holes and neutron stars are thought to be able to create ripples in spacetime. A revolutionary experiment, known as the Laser Interferometer Gravitational wave Observatory (LIGO), uses interferometry to detect such catastrophic signals.

There are two LIGO observatories housed in Handford, Washington and Livingston, Louisiana. Which consists of two four kilometer arms, both in x and y positions. LIGO is known to be the largest and most sensitive physics experiment ever developed that utilizes interferometry to detect gravitational waves. Rather than using optical or radio telescopes to see the electromagnetic radiation, LIGO uses gravitational waves, which is a different type of wavelength spectrum to understand the universe.

0.3 Michelson Interferometer

In order to 'feel' these distortions from space, LIGO's experiment uses the basic Michelson Interferometers, an observational device that was invented in the 1880's. For LIGO, the interferometers are the largest ever built with 4km (2.5 mile) arms in a form of an L-shape. This is important because as scientists are searching for gravitational waves because the longer the arms, the further the laser light travels, thus increasing the sensitivity of the instruments.

In a Michelson Interferometer, a concentrated laser beam passes through a beam splitter that divides the laser light into two orthogonal directions, x and y.

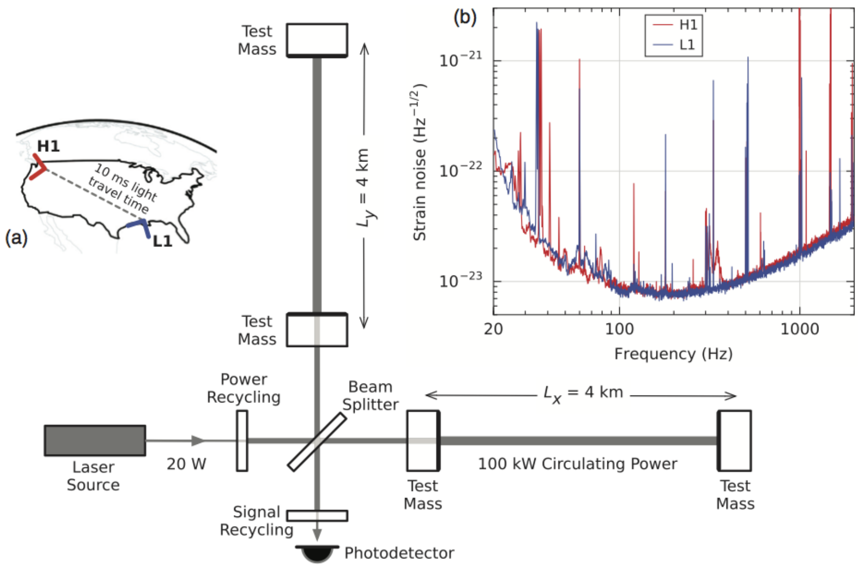

Figure 3: Basic Michelson Interferometer. Top right shows the location of Handford and Livingston observatories. Top left shows the sensitivity curve of LIGO. Credits: LIGO CalTech.

Each beam of light travels down an arm of the detectors until it reached the end where it consists of a reflecting mirror. The mirror reflects each beam back to the beam splitter where the two beams merge. During the merging, the light beams cross one another before getting measured. The photodector is on the opposite side of one of the arms where it measures the beam's intensity.

When the beams travel at the same distance and the mirrors are stationary, then the photo detector will not measure any beam of light. However, if the arms are adjusted, then the photodector will experience a much intense or faint beam of light, depending how the arms change. This process is called constructive interference pattern because when a peak of one wave merges with a peak of another wave, coming at the same time, will create a much larger wave. Destructive interference is when the peak of one wave meets the valley of another wave, canceling each other out and returning nothing.

Nonetheless, the significance of the Michelson interferometer and LIGO is to vibrations of gravitational waves to light intensity in which scientists can measure the time, frequency and signal-to-noise ratio of the gravitational wave. This experiment is extremely sensitive in that the detectors are designed to measure distant changes to about 1/10,000th the width of a proton.

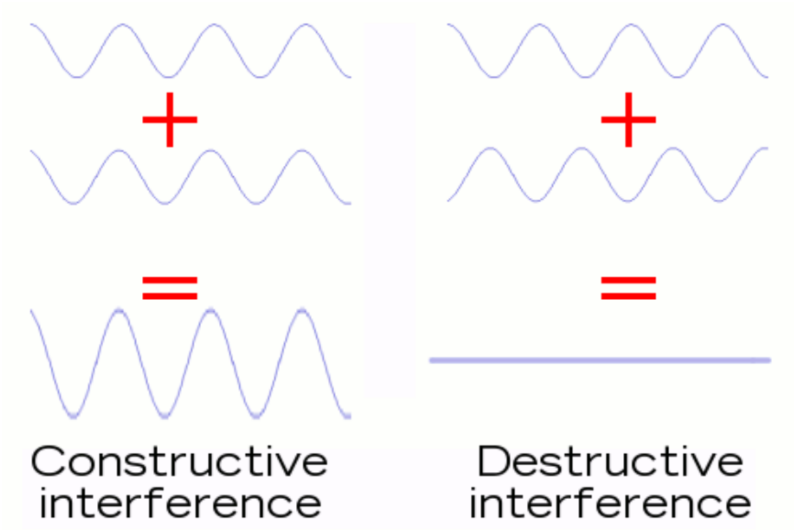

Figure 4: Interference patterns when two waves merge. Credits: LIGO CalTech.

Detector Characterization

As part of the LIGO Scientific Collaboration (LSC), I connect with over thousands of scientists in over dozens of institutes world wide. In addition, I am part of the Detector Characterization (DetChar) group that analyzes the quality of the data coming in and out of the interferometers in real time and off-line. Scientists and researchers, like myself, uses various resources t detect transient noises, glitches, measure from the detectors through template matching. By analyzing data from the Physical Environmental Monitor channels (PEM), Gravity Spy, LIGO's Summary page, which consists of the detector's information, and coherence between other observatories, probing gravitational waves will be much easier. Since the end of LIGO's Second Observing Run (O2) and Virgo's first scientific run, I have been working on the automated event candidates from the Data Quality Report (DQR) checklist. By template matching using the information given from various sources, my results are shown below.

0.4 Experimental Question

Are any of the Compact Binary Coalescence (CBC) triggers similar to the known glitches seen in Advanced LIGO?

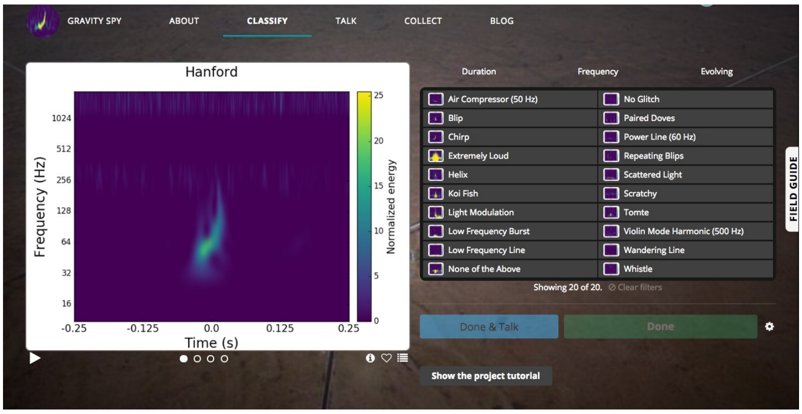

Figure 5: Gravity spy - citizen science project that helps classify glitches detected by LIGO's interferometers. Credits: Zooniverse, Gravity Spy.

Experimental Method

With the detectors currently off, LIGO has detected and gathered an abundance of data from the second observing run (O2). Some of which, captures the most recent triggers that are potential candidates for future gravitational waves, are analyzed more thoroughly. My responsibility as a student researcher is to perform independent checks on four of the most recent Compact Binary Coalescence (CBC) triggers. In order to do so, I compare the $h(t)$ Omega scans of these events to the Gravity Spy classes. Omega scans are a detector characterization tool to help measure the Signal-to-Noise-Ratio (SNR) of transient noises during detections. This helps scientists distinguish the difference between a gravitational wave signal, which looks like a 'chirp' versus a glitch in the data. Gravity Spy is a citizen science program that helps LIGO in classifying glitches to improve machine learning for gravitational wave signals. For each event I determine if it looks like one of the known categories of solved or unsolved glitches seen in the Advanced LIGO detectors? My results are then recorded in the O2 event detection checklist. Omega scans are a 'burst-type' search pipeline that detect glitches efficiently. The Omega scan is labeled using time measured in seconds on the x-axis, frequency measured in Hz on the y-axis and the signal measured is normalized to demonstrate how 'loud' the noise is.

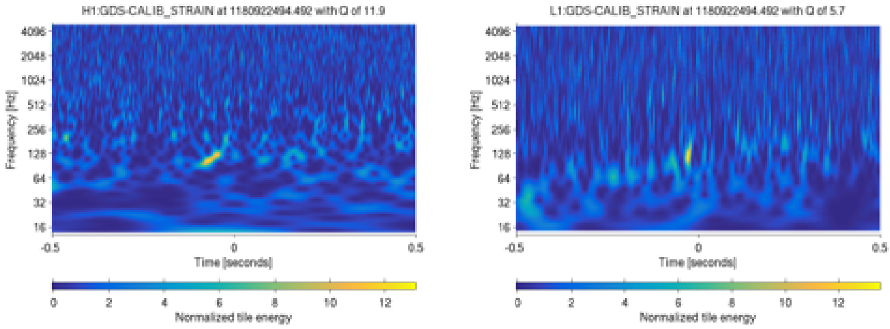

Figure 6: Right is the Handford observatory detection, left is the Livingston detection of the binary black hole gravitational wave signal. Credits: Zooniverse, Gravity Spy.

Results

0.5 GW170608

By looking at the data measured and the coherent signals from both Handford and Livingston observatories, one can confirm that this is a gravitational signal from the collision of two black holes. At a certain GPS time, measured from both observatories, it was detected that at $GDS - CALIB\_STRAIN$ at 1180922494.492 is a confirmed chirp signal.

The Primary black hole mass is roughly around 15 solar masses, while the secondary black hole mass was around 7 solar masses. When merged, the total solar mass summed up to be 18 to 24 solar masses. The merging happened on June 8, 2017 in which the duration of the merger lasted around two seconds, with that created measured the strain frequency peak of about 610 Hz and the strain wavelength peak at 662 km.

Fact Sheet of GW170608

Observed by	H1, L1
Source Type	BBH
Date	June 8, 2017
Duration	2s
Distance	0.7 to 1.5 b.l.y
Total Solar Mass	18 to 24
SNR	13
f at peak GW strain	453 to 610 Hz
λ at peak GW strain	492 to 662 km

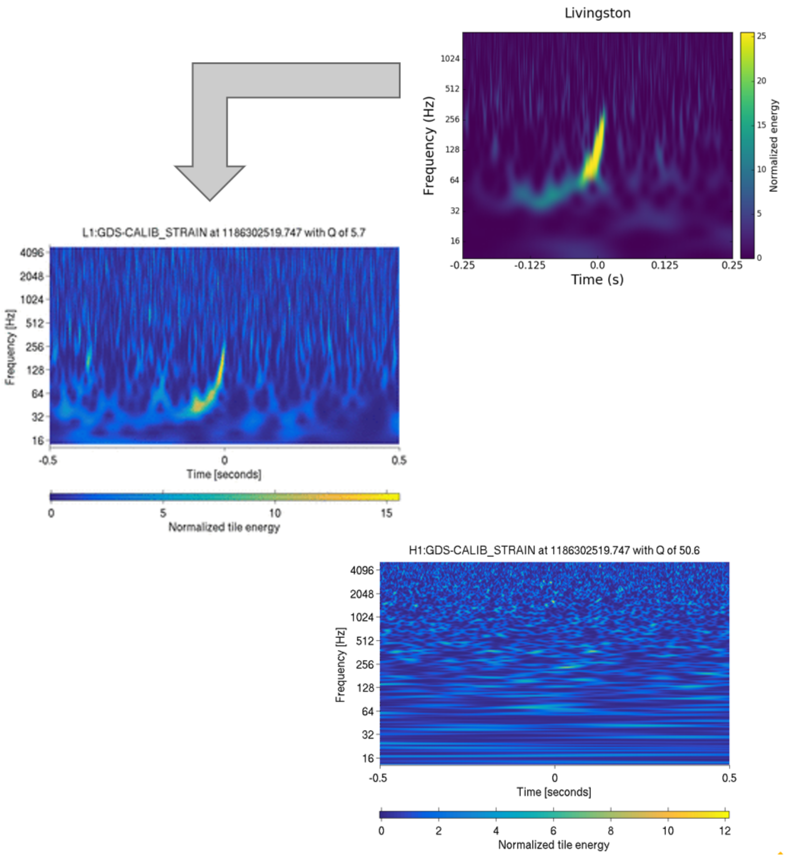

Figure 7: Demonstration of a signals from Gravity Spy (top right) in relation to the Livingston Spectrogram signal (middle). Handdford (bottom) experienced a very faint signal, impossible to see with the human eye unless quality and parameters are changed.

0.6 LVT170809

For this trigger, it was detected on August 9, 2017 as a binary black hole merger. With roughly about 93% acceptance rate as a gravitational wave signal. The reason why it is an LVT - LIGO Virgo Trigger - rather than a GW - Gravitational Wave - is due to the loudness (SNR) and measurement of the detection. For this observation, Livingston was able to detect a loud signal that looked like a 'chirp' signal of a gravitational wave. However, for Handford, the signal was still very faint and unable to detect after adjusting the quality and parameters of the spectrogram to about Q = 50.7.

From Livingston's observation, the duration of the black holes merging that was measured was about 2.5 seconds with a total solar mass of 73. Making this one of the largest binary black hole merger ever detected.

Fact Sheet of LVT170809

Observed by	H1, L1
Source Type	BBH
Date	August 9, 2017
Duration	2.5s
Distance	3.8 m.l.y
Total Solar Mass	73
SNR	11
f at peak GW strain	N/A
λ at peak GW strain	N/A

0.7 GW170814

This detection happened on August 14, 2017 - the last binary black hole detection from O2 before O3 (observing Run 3) Advanced LIGO turns back on at the end of 2018. What makes this source unique is that all three of the observatories, LIGO and Virgo, detected the same signal given a GPS time at 1186741861.527 UTC. The duration of this signal lasted .26 to .28 seconds with the source being about 2.2 billion light years away. The primary mass was 36 solar masses, while the secondary mass was about 28 solar masses. Thus, the total solar mass of the binary black hole merger was about 59. Which gave a strain frequency peak of 155 to 203 Hz and a wavelength at peak strain of 1480 to 1930 km.

Fact Sheet of GW170814

Observed by	H1, L1, V1
Source Type	BBH
Date	August 14, 2017
Duration	.26 to .28s
Distance	1.1 to 2.2 b.l.y
Total Solar Mass	53 to 59
SNR	18
f at peak GW strain	155 to 203 Hz
λ at peak GW strain	1480 to 1930 km

0.8 GW170817

The last observed signal happened on August 17, 2017. This signal was also measured by all three observatories, LIGO and Virgo. This is the first multi-

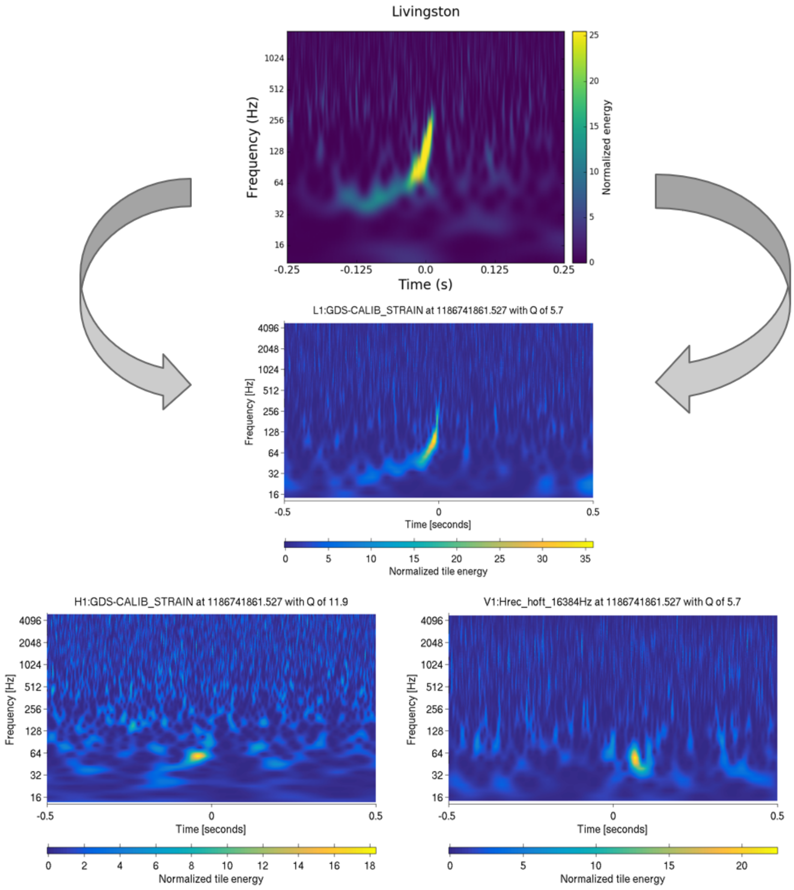

Figure 8: Demonstration of a signals from Gravity Spy (top) in relation to the Livingston Spectrogram signal (middle). Handdford (bottom left) experienced a very faint signal, same as Virgo (bottom right). But all observatories experienced the same detection.

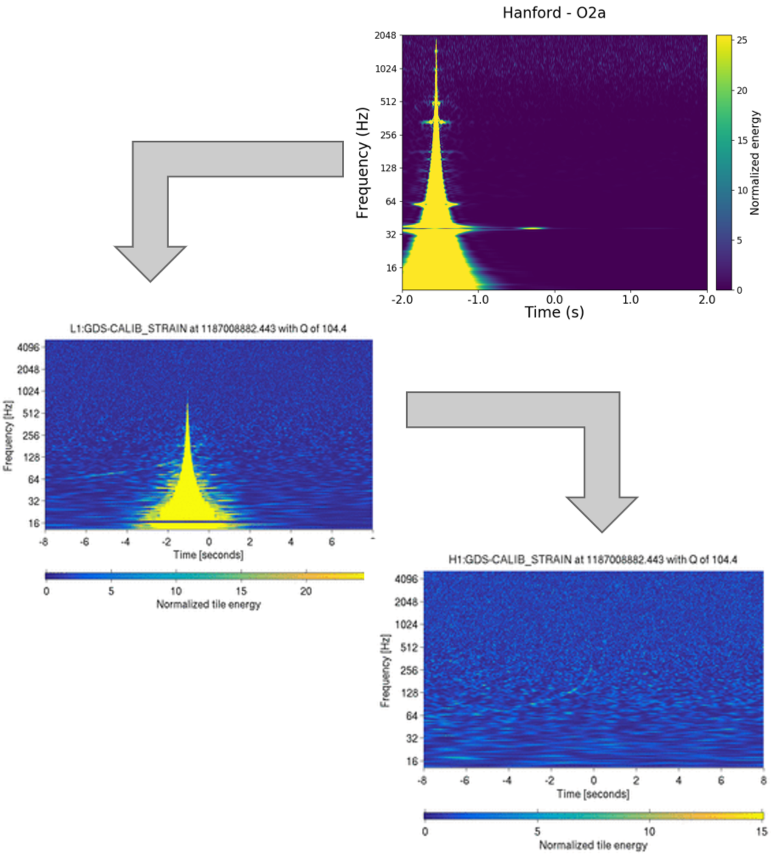

Figure 9: Binary neutron star from Livingston with glitch overlying the detection (middle). The glitch from Livingston template matched with a Gravity Spy signal (top). Handford (bottom) showed a clean gravitational wave signal.

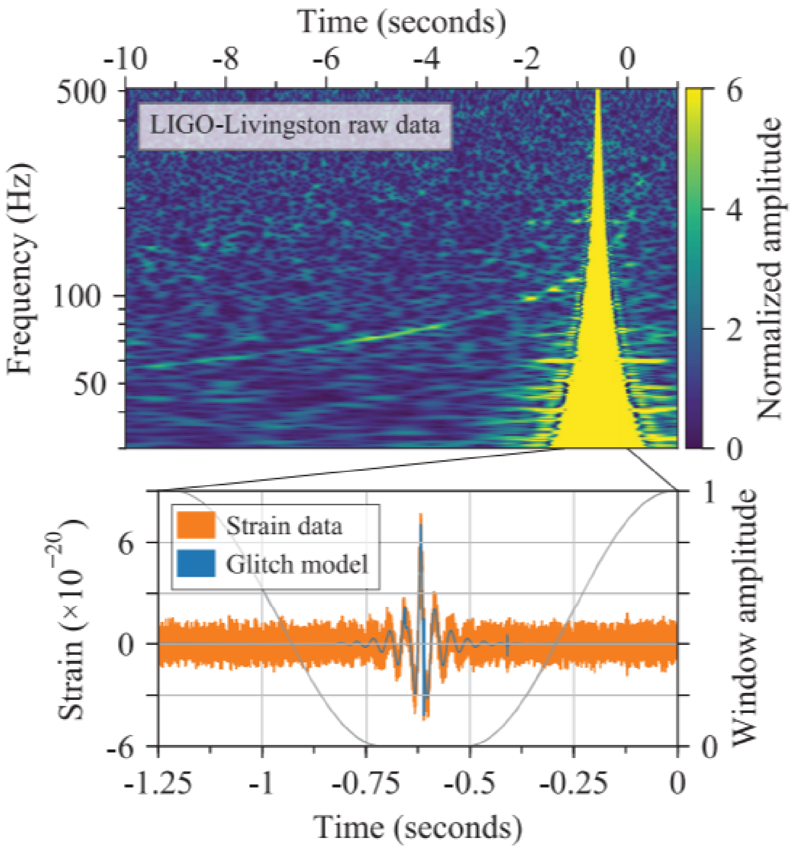

Figure 10: Demonstration of the glitch model template (blue) and the glitch (orange) overlapping one another to cancel out the noise. Credits: LIGO

messenger detection in such that the observatories detected gravitational waves and electromagnetic radiation from space and ground based telescopes. This source is the first binary neutron star merge that consisted of a primary mass of 2.26 solar mass and a secondary mass of 1.36 solar mass, summing the merging masses to be 3.29 solar mass. The duration of the merging lasted roughly 60 seconds as the number of electromagnetic observatories that followed the trigger was 70. during the merging, telescopes also observed gamma-rays, X-rays, ultraviolet, optical infrared and radio waves in addition to gravitational waves.

Although all three observatories detected the signal, it was, however, in Virgo's blind spot. Livingston also measured a sharp glitch during the merger that overlapped the signal. Therefore, by template matching and utilizing the glitch waveform model, one can cancel out the transient noise and observe the gravitational wave more clearly.

```
from gwpy.timeseries import TimeSeries
data = TimeSeries.fetch_open_data(
    'H1', 'Sep 14 2015 09:45', 'Sep 14 2015 09:55')
```

```
specgram = data.spectrogram(2, fftlength=1, overlap=.5) ** (1/2.)
```

```
plot = specgram.plot(norm='log', vmin=5e-24, vmax=1e-19)
ax = plot.gca()
ax.set_yscale('log')
ax.set_ylim(10, 2000)
plot.add_colorbar(
    label=r'Gravitational-wave amplitude [strain/$\sqrt{\mathrm{Hz}}$]')
plot.show()
```

Figure 11: GWpy Spectrogram code. Credits: Gwpy Documentation, LIGO.

Fact Sheet of GW170817

Observed by	H1, L1, V1
Source Type	BNS
Date	August 17, 2017
Duration	60 s
Distance	85 to 160 m.l.y
Total Solar Mass	3.3
SNR	32.4
Num. of EM observed	70
Also observed λ	Gray, Xray, UltViol, Optical, Inf, Radio

Data quality report: contains notes from scientist that observed and recorded basic information of the signal, such as time.
GraceDB: Data base that contains the calculations of the CBC triggers, such as mass and other factors. Two types of tables: Coinc tables and Single Inspiral Tables for each trigger/ event.
Fact sheet: contains information of the events as well, similar to GraceDB.

Future Work

Write a script using python/GWpy that intakes GPS time and generates the following:
a. Spectrogram
b. Normalized Spectrogram
c. Over-dense, short duration Spectrogram
d. Calculate the time-dependent coherence between two channels e. Spectrograms of the Rayleigh Static

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