Gravitational Waves (Project 3)

1. Motivation

The detection of gravitational waves (GW) marks a revolutionary leap in our understanding of the universe, particularly in observing cosmic events such as black hole mergers. This report centers on the gravitational wave event GW150914, the first confirmed detection, observed by the LIGO Hanford and Livingston detectors. The objective is to analyze the time-series data, filter noise, and visualize the strain data to better understand the signal characteristics. Additionally, we generate an audio representation of the detected wave signal, allowing for an accessible interpretation of gravitational wave data.

2. Methods

Using Python and the GWpy library, we performed the following steps:

1. **Data Acquisition**: We accessed time-series data around the event time for GW150914, spanning 32 seconds, from the LIGO Hanford detector.
2. **Frequency Analysis**: We plotted the Amplitude Spectral Density (ASD) to observe the strain sensitivity over a range of frequencies and highlighted the powerline frequencies (60 Hz, 120 Hz, and 180 Hz).
3. **Signal Filtering**: To enhance the signal clarity, a bandpass filter (50–250 Hz) was applied, along with notch filters to eliminate the powerline frequency noise.
4. **Comparison of Hanford and Livingston Data**: Using a 6.9 ms time shift, we aligned the filtered signals from both detectors and plotted them for comparison.
5. **Q-transform Analysis**: To analyze the time-frequency evolution of the signal, we used a Q-transform, visually illustrating the signal's energy over time and frequency.
6. **Audio Representation**: We converted the strain data to an audio file by normalizing the amplitude and adjusting the sample rate, creating a "chirp" sound corresponding to the detected gravitational wave.

3. Results

3.1 Frequency Analysis

The Amplitude Spectral Density (ASD) plot (Figure 1) displayed strain sensitivities from 10 Hz to 2000 Hz. The noise peaks at powerline frequencies (60, 120, and 180 Hz) were prominent, confirming the necessity of applying notch filters. The bandpass filter, set from 50–250 Hz, targeted the frequency range where gravitational waves are most detectable and eliminated higher-frequency noise.

3.2 Filtered Data Comparison

The filtered time-series data for the Hanford and Livingston detectors (Figure 2) revealed a clear and aligned signal after applying the 6.9 ms time shift. The amplitude of the strain aligns well between the two detectors, confirming the consistency of the gravitational wave signal across both observatories.

3.3 Q-transform Analysis

The Q-transform (Figure 3) provided a time-frequency representation of the event. The gravitational wave signal is clearly visible in the Q-transform plot, with energy concentrated in the frequency range of 50–250 Hz, which aligns with expectations for a black hole merger signal. The signal peaks sharply, highlighting the "chirp" characteristic, where both frequency and amplitude increase until the final merger.

3.4 Audio Conversion

The audio conversion successfully transformed the time-domain data into a .wav file. By amplifying and normalizing the strain data, we created a sound that reflects the “chirp” pattern of the gravitational wave as the black holes spiral towards each other and merge. This audible interpretation reinforces the signal's time-domain characteristics, where the frequency and amplitude of the wave increase until the merger point.

4. Calculation

4.1 Estimation of Black Hole Masses and Distance

We can estimate the total mass of the merging black holes using the relationship between the orbital period just before merging and the system’s mass. Given an orbital period (Δt) of approximately 0.01 seconds and their orbital distance a is twice the Schwalzschild radius $Rsch\ =\ 2GM/c^{2}$ and orbital velocity $v\ =\sqrt{GM/a}$, we can get $\Delta t\ =\ 2\pi a/v\ =(2\pi 4GM/c^{2})/(c/2)\ =\ 16\pi GM/c^{3}$the mass of the two black holes can be derived from: $M_{black\ holes}\ =\ \Delta t\cdot c^{3}/16\pi G$This calculation provides an estimated total mass of approximately 40.39 solar masses. This result aligns with the expected mass range for the binary black hole system involved in gravitational wave event GW150914.

4.2 Distance Estimation

The distance D to the merger event is estimated based on the observed gravitational wave strain h. Since the strain h decays with the distance traveled by the wave, and is proportional to the Schwarzschild radius $D\ =\ Rsch$, we use the relationship:$D\ =\ Rsch/h$where h≈10^{-21} The Schwarzschild radius Rsch for the estimated black hole mass is calculated as follows: $Rsch = 2GM_{blackholes}/c^2$. The calculated Schwarzschild radius is 59.64 km, which, when divided by h, results in a merger distance of approximately 1932.86 mega parsecs (or about 6.3 billion light-years).

4.3 Estimation of Released Energy

The energy released as gravitational waves, ΔEgw, corresponds to the difference between the initial and final mass of the black hole system. If we assume that the mass converted into gravitational wave energy during the merger is approximately 0.1 of the total black hole mass, approximately 4.039 M☉was radiated away as gravitational wave energy.

Using Einstein's mass-energy equivalence:ΔE_{GW}=4.039M☉$\cdot c^2 \approx 7.23\cdot 10^{47}$joules.

This enormous amount of energy reflects the powerful gravitational waves produced during the black hole merger, contributing to the detection of this event.

5. AI usage

In this project our team utilized google Gemini (an advanced AI model), which is offered as a feature in colab, in hopes of more efficiently debugging our code and further supplementing it.

6. Conclusion

This analysis of GW150914 has demonstrated how data processing and filtering can clarify the gravitational wave signals from the surrounding noise. The time-shifted and filtered data from the Hanford and Livingston detectors were consistent, further validating the authenticity of the detected signal. The Q-transform effectively highlighted the temporal evolution of the signal, and the generated audio file provided a novel way to interpret the data. This approach of combining data visualization and sonification makes gravitational wave research more accessible and underscores the power of multi-modal analysis in understanding cosmic events.