Could LIGO Have Heard the Event GW150914 Before Its Upgrade?

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(Dated: July 2016)

Abstract

Event GW150914, which represents the merger of two black holes with masses of 29 and 36 $M_{\odot}$, was observed by the Advanced LIGO on September 14, 2015. [1]. In this research, we applied software injection and recovery to LIGO bulk data from S5 and S6 run using the GW150914 template and proved that events with such magnitude would not have been observed by the initial LIGO or the Enhanced LIGO in the S5 or S6 run due to the higher background noise level. In order to be recognized as an event, it would have been required to be at least one times larger in magnitude.

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† This research paper is a student project of the Pioneer Academics Program

I. BACKGROUND

Gravitational waves were first predicted by Einstein in 1916 as a result of mathematical interpretation of the field equations of general relativity [1]. They are the waves created by changing gravitational fields. For example, in a binary star system, as two stars orbit around each other, the magnitude of gravitational fields around them changes according to the stars' different positions, creating an oscillating pattern; thus, gravitational waves are emitted. Theoretically, any changing quadrupole mass distribution, such as two circling figure skaters, can create gravitational waves [2]; however, since gravitational waves have extremely small magnitudes, they are only detectable when they come from some massive sources, including binary systems, gravitational pulsars, bursts from cataclysmic events, etc. [3].

In the general theory of relativity, gravity is described as "a consequence of the curvature of spacetime, caused by the uneven distribution of mass/energy [4]." In other words, the presence of a mass curves space and time around it, creating a force-like effect– gravity. Likewise, gravitational waves can also distort spacetime; they change the length of physical objects as they pass through, which is the basis of their detection. Since they do not interact with matter, they are able to travel from distant space and time and bring back valuable signals.

An earlier attempt of gravitational wave detection was made by an American physicist Joseph Weber in the 1960s. His device, the Weber Bar, utilized resonance of an aluminum bar to amplify the tiny disturbance caused by gravitational waves. Weber claimed success around 1968, but the peer reviews conducted later disproved his findings [5]. In 1982, Taylor and Hulse published the result of their eight year-long observation of binary pulsar system PSR B191316. The energy loss of the system they discovered provided indirect evidence of gravitational wave radiation [6]. Also, after the failure of resonant detectors, many countries turned their attention to the interferometric detectors. By the early 2000s, several interferometric detectors were set up by different countries, including TAMA 300 in Japan, GEO 600 in Germany, Virgo in Italy, and LIGO in the United States. In September 2015, the Advanced LIGO team announced their success of the first direct observation of gravitational waves from two merging black holes [1].

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is comprised of two separate observatories located in Livingston, Louisiana and Hanford, Washington to locate the source of the signal. They are designed based on the Michelson Interferometer [7]. Each experimental site has two L-shaped, 4km-long arms; a beam splitter placed at the corner splits one laser beam from the source into two. The light beams travel along the arms and are reflected back by the mirrors at the end of the arms. The lengths of two arms are precisely adjusted so that the two light beams could cancel each other through fully destructive interference when they meet again at the corner. However, if the arms are disturbed by any external factor and their length were relatively changed, the light beams will not get back at the same time since the distance they travel changes. Thus, they would create an interference pattern received by a photodetector; then scientists would be able to find the evidence of gravitational waves by analyzing this signal [1].

LIGO program is operated by Caltech and MIT. Its construction started in 1995, and it started its first science run in 2002. In the next five years, the initial LIGO had finished five science runs; all were relatively short except S5 which lasted from 2005 to 2007. Then, the Enhanced LIGO was installed and started operating in late 2009. Compared to the initial LIGO, the Enhanced LIGO has increased the laser power and added output mode cleaner, in-vacuum readout hardware, and active seismic isolation in Livingston Observatory. These changes cost around two million dollars. The Enhanced LIGO started the sixth science run (S6) in 2009; S6 also continued for about two years and did not find any convincing evidence [8]. From 2012 to 2015, the Enhanced LIGO was upgraded again to the Advanced LIGO, which cost 620 million dollars. The Advanced LIGO had achieved a great improvement in strain sensitivity through a series of upgrades including higher laser power, lower seismic cutoff frequency, 290,000 more data channels, etc. [9]. Therefore, in September 2015, shortly after Advanced LIGO began its first run, it successfully detected event GW150914, the gravitational wave signal of a merger of two black holes with the masses of 29 and 36 $M_{\odot}$. This result was published by the LIGO team in physical review letters in February 2016 [1].

II. ANALYSIS

The objective of this research is to determine whether the initial LIGO and the Enhanced LIGO would be able to detect event GW150914 by creating and analyzing software injections into background noise data detected in S5 and S6. The LIGO Open Science Center has opened all of the bulk data from S5 and S6, as well as a time domain template of event GW150914, to the public [10]. All the data sets used in this research are 100% legible data according to the accessory data quality channels, and each set contains 4096s of data with 4096 Hz sampling frequency.

The first step is to inject the template of GW150914 into selected datasets. In a python script, we read a data set as hdf5 file and the template as a txt file, then extracted the strain data in the time domain from both files and made them into two separate lists. Since the bulk data and template have the same sampling rate, the strain magnitude in each list corresponds to the other in time. We started at a random point in the background strain list and added the value of the template to the original strain value. Thus, the template of the event was injected into the background noise at a random point for later investigation. Then, we also changed the flag of data quality channel in the hdf5 file to note the location of the injection.

Then, we loaded the data set containing the injection into another python script, which ran cross correlation using the same template, to try to discover the injection. This script was modified from a tutorial script from LIGO Open Science Center [11]. It used matched filter technique to maximize the correlation between the data and the template. After reading the data and template file, it sliced off the injection site as well as an additional 50s before and after the injection according to the changed data quality channel; it also took a noise slice, which is eight times the length of the injection slice, from where there is no injection. Then, it zero-padded the template set to make it the same length as the background noise and took the Frontier transform of both sets to obtain the data in the frequency domain. It also set the template to zero where the frequency is below 25Hz because LIGO noise is very high at low frequency. Next, it analyzed the power distribution of the noise slice and divided the data by noise power in each frequency bin. Then, it applied the matched filter between data and template, transferred the output back to the time domain, and calculated the signal to noise ratio(SNR), plotting an SNR versus time graph. A more elaborated explanation and codes can be found on the LIGO Open Science Center website [12]. All the Python scripts used in this research are also available online [13].

III. RESULT

As stated above, the injection segments were all made 101 seconds long with a one second injection in the middle and 50 seconds of noise around; thus, a successful recovery should get a distinguishable higher SNR at the location of the signal.

In this research, we have tested 195 datasets from the S5 run and 191 from S6 using the procedure introduced above; all datasets were selected randomly and evenly distributed throughout the year.

Overall, in both S5 and S6 datasets, the injection recovery has failed to extract the signal from background noises. As Fig. 1 shows, the common background noise fluctuates around four while there are usually a few spikes that go over five. With the signal in the middle, the middle spike was generally not the highest one, and in such case, the computer would not be able to pick out the injected signal from generic noises, and the recovery is counted as failed. While the noise level could fluctuate for various factors– seasons, time of the day, different observatories, improvements of instruments due to the debugging during runs, etc.– the aggregate success rate of the recoveries was about 3.6% for S5 and 5.8% for S6. Even in the rare success cases, as shown in Fig. 2, the signal did not stand out enough to be distinguishable from other random spikes. Therefore, we can conclude that neither the initial LIGO nor the Enhanced LIGO was able to detect events as loud as GW150914.

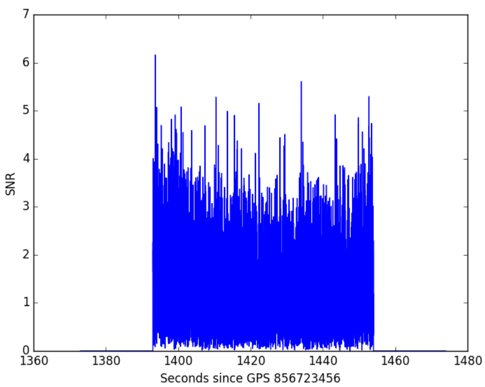

FIG. 1: A typical recovered SNR vs. Time graph from S5 run when the recovery has been considered failed

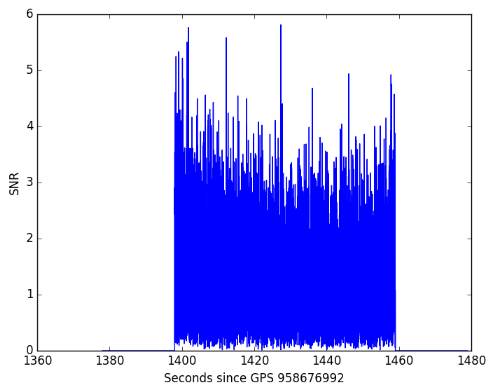

FIG. 2: A typical recovered SNR vs. Time graph from S6 run when the recovery has been considered successful

Then, we amplified the template by integer factors from two to five in the injection step and repeated the recovery process for all the datasets. As Fig. 3 (factor vs. success rate for S5) shows, in S5 run, with the noise level of roughly around four and five, the success rate of recovery jumped to 43% percent when the template was two times larger and got to 90% when the template was multiplied by four. Similarly in S6, as in Fig. 4 (factor vs. success rate for S6), when the template's magnitude was doubled, the success rate became 65%, which shows a decent possibility of finding the signal. The percentage reached 88% when the multiple factor was three, and it was stabilized over 90% as the factor became four or larger. While S6 was recorded after initial LIGO was upgraded to Enhanced LIGO, data from S6 was expected to have a lower noise level and a higher success rate of recovery. Indeed, S6 did present more successful recovery in general than S5 in every factor; however, when the template is the same magnitude as the original GW150914 event, the slight enhancement barely makes any difference.

Factor	Success rate	average SNR
1	3.56691919192%	9.37535930416
2	43.0082070707%	9.43334590869
3	73.2638888889%	10.5848069605
4	89.6305818182%	12.96209169285
5	90.22916666665%	17.28891779275

FIG. 3: Table of corresponding recovery success rate and average SNR when the template was multiplied by different factors with S5 datasets

Factor	Success rate	average SNR
1	5.82176690901%	8.034962502415
2	65.2126018947%	8.23002202697
3	87.6514650804%	11.92682543955
4	92.9114342366%	13.81745706825
5	94.74003110785%	17.2001502029

FIG. 4: Table of corresponding recovery success rate and average SNR when the template was multiplied by different factors with S6 datasets

In conclusion, both S5 and S6 would not be able to discover signals with a magnitude similar to GW150914. If the signal is twice as strong, which means the event happens twice as close, the detection may be possible for both S5 and S6; and the detection can almost be promised if the signal is four or more times louder.

IV. CONCLUSION

In this research, we applied software injection with 195 datasets from LIGO's 5th science run and 191 from is 6th run using the event GW150914 template; we then attempted to recover the injection with the same template through matched filtering. Due to the high failure rate of recovery in both S5 and S6 data, we conclude that neither the Initial LIGO nor the Enhanced LIGO would have been able to detect events with magnitude similar to GW150914 because such signal is not distinguishable from the overall background noise levels in S5 and S6.

[1] B. P. Abbott et al. Observation of gravitational waves from a binary black hole merger. *Physical Review Letters*, 116:061102, Feb 2016.

[2] LIGO Caltech. Compact binary inspiral gravitational waves. https://www.ligo.caltech.edu/page/gw-sources.

[3] B.S. Sathyaprakash and Bernard F. Schutz. Physics, astrophysics and cosmology with gravitational waves. *Living Reviews in Relativity*, 12(2), 2009.

[4] Albert Einstein. Relativity: the special and general theory. *Thought*, 12 1916.

[5] J. Weber. Evidence for discovery of gravitational radiation. *Physical Review Letters*, 22:1320–1324, Jun 1969.

[6] R. A. Hulse and J. H. Taylor. Discovery of a pulsar in a binary system. *Astrophysical Journal*, 195:L51–L53, January 1975.

[7] LIGO Caltech. What is an interferometer. https://www.ligo.caltech.edu/page/what-is-interferometer.

[8] R. Adhikari, P. Fritschel, and S. Waldman. Enhanced ligo. Technical Note, LIGO-T060156-01-I, July 2006.

[9] LIGO Caltech. About aligo. https://www.ligo.caltech.edu/page/about-aligo.

[10] LIGO Open Science Center. Ligo data release. https://losc.ligo.org/data/.

[11] LIGO Open Science Center. Find a hardware injection. https://losc.ligo.org/inj/step1/.

[12] https://losc.ligo.org/s/sample_code/hwinj/find_inj.py.

[13] https://app.box.com/s/27jv137zfiiuic4f5xpmbdzhvpr2ftq2.