Comparison of Scalar and Tensor Analyses

Jacob Grant

July 21 2017

1 Background

Ever since their initial hypothesis in Albert Einstein's 1916 general theory of relativity (GR),[1] gravitational waves have been the subject of intense study. Now, 100 years and countless tests of proof later, the Laser Interferometer Gravitational-Wave Observatory (LIGO) has seemingly proven GR correct yet again by detecting tensor polarization gravitational waves.[2] These waves, emitted from a rapidly rotating binary black hole merger 410^{+160}_{-180} Mpc[3] away, were the first direct evidence that gravitational waves do in fact exist. Two others, since the first detection, have been confirmed but all have been produced by the same type of event: binary black hole mergers. As the black holes spiral closer and closer, they strongly emit tensor gravitational wave polarization while other possible polarizations, such as scalar, are covered up and thus, if they exist, have not been detected. Tensor polarization, the only predicted by general relativity, assumes that gravitational waves can have either a plus (+) or cross (×) polarization while scalar polarization, predicted by competing theories of gravity like the Brans-Dicke Theory, can have more of a breathing form. Scalar polarization is theorized to be emitted most strongly from spherical collapse events which mimic the polarization. Some possible examples include the collapse of a supermassive star/neutron star to form a black hole or certain types of core collapse supernovae.

A central question in the search for scalar polarization gravitational waves is if there is a need for a separate search, apart from the current tensor search, for such waves using a scalar specific analysis or if the usual tensor analysis already is sensitive enough to detect such a polarization. The focus of this paper will be on answering this question.

2 Methods

To determine which analysis has the better efficiency, we used the Coherent WaveBurst (CWB) program and the Atlas supercomputer. CWB gives us the ability to analyze

---

[1] B. P. Abbott et al. "Observation of Gravitational Waves from a Binary Black Hole Merger". In: vol. 116. American Physical Society, 2016, p. 061102. DOI: `10.1103/PhysRevLett.116.061102`. URL: `https://link.aps.org/doi/10.1103/PhysRevLett.116.061102`, p. 1.

[2] Ibid., p. 1.

[3] Ibid., p. 1.

hundreds or even thousands of possible events and create interpretable graphs, such as Detection Efficiency graphs for different injections. We then run this data on the Atlas supercomputer, located in Hannover Germany. In our quest to determine which analysis is more efficient, we decided to simulate a third detector, in addition to the existing detectors at Hanford, WA and Livingston, LA, to give us more accurate results and a better estimate at where the signal came from. We called this 'third detector' Virgo and it is created by time-shifting past LIGO Hanford data to match the observing period of the other two detectors. After adding the Virgo detector, we were ready to run the background and simulated analyses.

2.1 Background Analysis

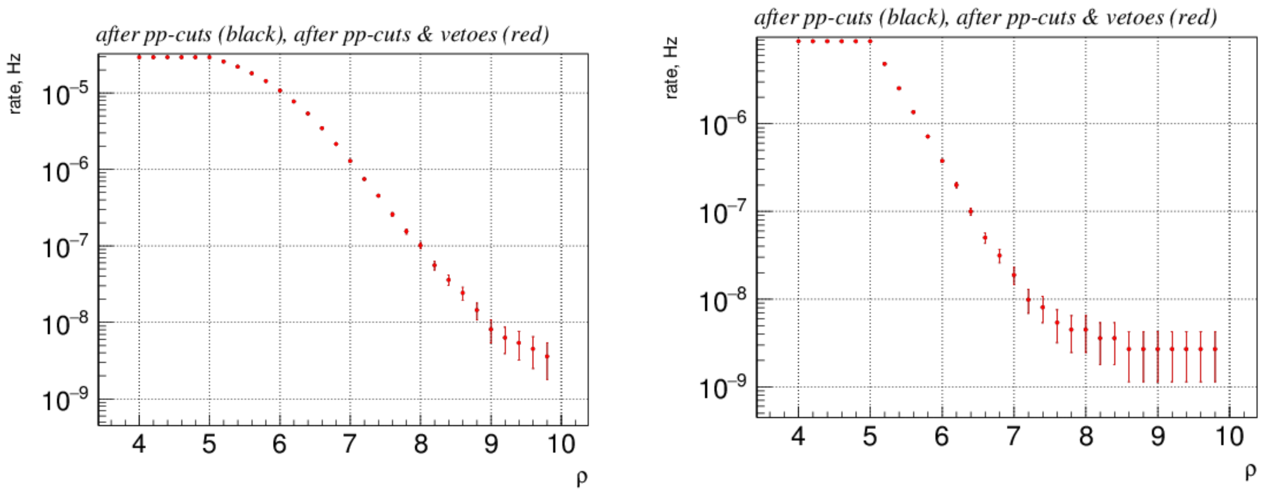
The background analysis is used to figure out the probability of the signal being noise versus an actual signal. By analyzing specific graphs, such as rate versus ρ, we can determine the false alarm rate (FAR) and the inverse false alarm rate (IFAR) of interfering noise. By determining the IFAR value, we can predict how often noise creates a signal that is strong enough to be confused with a normal signal. Only simulated signals with an IFAR of greater than 8 years contributed to our determination of the efficiency of the analysis. This means that only signals that should occur from noise once every 8 years or more, not very likely to occur, were included in the study as legitimate signals. In our study, we ran a scalar signal background analysis to compare it to the false alarm rate of the tensor signal background analysis.

2.2 Simulation Analysis

The simulated analysis uses either simulated scalar or tensor signals and adds them to real signals to create efficiency curves. These curves, created from all the signals that had an IFAR of greater than 8 years, tell us how efficient the analysis is at detecting various amplitudes of gravitational waves. The analysis runs over sine-gaussian and normal gaussian wave forms and records the efficiency of each. We ran two different types of simulated analyses: a scalar signal-scalar analysis (SGW) and a scalar signal-tensor analysis (TSGW). Our goal was to determine if the SGW analysis did a better job at detecting scalar signals or if the TSGW search already did an efficient enough job at detecting scalar signals.

3 Comparison and Conclusions

After all the analyses were complete, we first analyzed the scalar versus tensor background. Looking at the rate versus ρ graph, it was clear that the tensor analysis had a steeper drop in frequency as ρ increased than the scalar analysis (Figure 1). Thus, for the scalar analysis to reach an IFAR of 8 years (a FAR value of roughly $3.96 * 10^{-9}$ Hz) or greater, a ρ value of roughly 9.5 is needed compared to only a ρ of roughly 8.4 for the tensor analysis. Because fewer signals reach the 9.5 ρ qualification and thus cannot be



(a) Scalar Background Rate Vs. ρ

(b) Tensor Background Rate Vs. ρ

Figure 1

used for the scalar analysis, the efficiency of the scalar analysis would start at a disadvantage when compared to the tensor analysis. Another interesting finding was an apparent contradiction to previous studies that have compared rate versus ρ. For example, a study[4] which also used three detectors found the rate versus ρ graphs of tensor and scalar background analyses to be extremely similar. The reason for this contradiction is currently unknown.

Before we began comparing the TSGW and the SGW efficiencies, we noticed something surprising. The SGW analysis did not ever reach 90 percent efficiency or greater but instead leveled off at 70 percent efficiency for the GA (gaussian) injection and similarly for the other injections. We discovered that this leveling off of efficiency is due to the fact that for SGW analyses we use a gamma factor of -1.0, unlike TGW which uses gamma of -0.5, which helps efficiency at low hrss but reduces the sky coverage for high hrss.[5] However, this finding is again in contradiction to the previous study[6] where the SGW analysis efficiency reached close to 100 percent efficiency as the amplitude increased instead of leveling off at around 70 percent efficiency as in our study. The reason for this contradiction is currently unknown.

We then compared the SGW Detection Efficiencies, Figure 2(a), with the TSGW Detection Efficiency, Figure 2(b). It was clear that the SGW analysis did a more efficient job. For example, at an efficiency of 50 percent the signal named GA4d0 (Gaussian waveform with a width of 4 ms) had an hrss of 4.02E-22 for the SGW analysis while the same signal for the TSGW analysis had only 4.40E-22 hrss. This means that the SGW

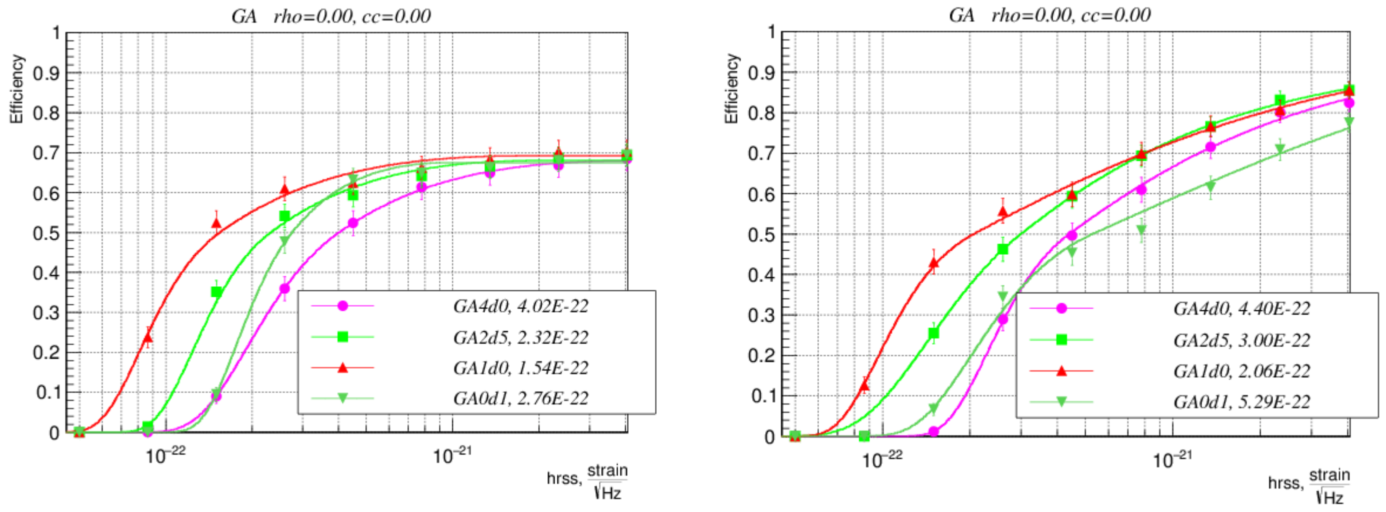
---

[4] Peter Shawhan et al. "Detectability of Scalar GW Bursts with LIGO and Virgo". In: 2013. URL: `https://dcc.ligo.org/DocDB/0103/G1300505/002/Shawhan_GR20-v2.pdf`, p. 2.

[5] Gabriele Vedovato. "The cWB 2G regulators". In: LIGO Scientific Collaboration. URL: `https://www.atlas.aei.uni-hannover.de/~waveburst/doc/cwb/man/The-cWB-2G-regulators-_0028svn_003e_003d4446_0029.html#The-cWB-2G-regulators-_0028svn_003e_003d4446_0029`, p. 3.

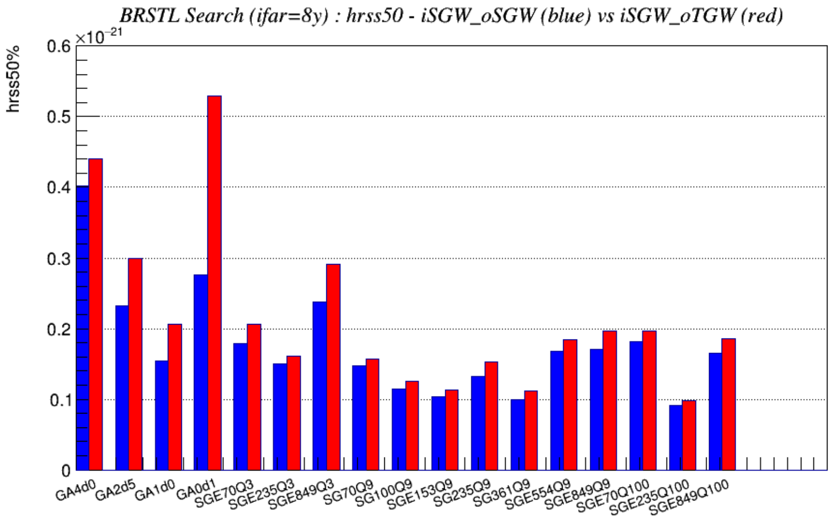
[6] Shawhan et al., "Detectability of Scalar GW Bursts with LIGO and Virgo", op. cit., p. 2.

Figure 2


(a) Scalar Signal-Scalar Analysis Detection Efficiency for Injections GA with 50 percent hrss included

(b) Scalar Signal-Tensor Analysis Detection Efficiency for Injections GA with 50 percent hrss included

(c) Comparing the SGW and TSGW efficiencies at 50 percent hrss



analysis has the ability to detect smaller amplitudes and is thus more sensitive. This conclusion continues to the other waveforms beyond the gaussian (GA) as can be seen in Figure 2(c). For all waveforms, the SGW analysis, blue region, is able to detect smaller hrss values than the TSGW analysis, red regions. This finding, that SGW is more efficient than TSGW, is in agreement with the previous study's conclusion.[7]

Even with a considerably higher ρ value, the SGW analysis still does a better job at

---

[7] Ibid., p. 2.

detecting potential scalar signals than the TSGW analysis does. Thus we have tentatively concluded that it is worth doing a separate search for scalar waves with a three detector network. The normal tensor analysis does a slightly worse job at detecting smaller scalar amplitudes and thus a scalar analysis search should be used in the search for scalar polarization gravitational waves.

4 Future

There are a few important questions which should be explored in future studies. Why do different studies have contradictions between the rate versus ρ graphs of the scalar and tensor background analyses? Why do the efficiency curves of one study's scalar signal analysis reach 100 percent while the other only reach 70 percent? Would our conclusions be the same or different if a fourth detector was added by time shifting LIGO Livingston data? These questions are integral to solve if a comprehensive scalar search is to be done.