

Recovering hardware injections in LIGO S5 data

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Introduction

The Laser Interferometer Gravitational Wave Observatory (LIGO) is using ground-breaking technology to directly detect gravitational wave signals from astronomical sources. Thus far, gravitational waves have never been directly detected, but as detector sensitivities increase, we expect to be able to detect gravitational wave signals from distant galaxies.

One particular signal we look for in the detector is generated by **compact binary coalescence**. Compact binary coalescence occurs when two compact massive objects, such as black holes or neutron stars, orbit one another and spiral in toward one another until they collide. The gravitational wave signal, one type of many which theory predicts LIGO may detect, has a recognizable waveform.

The LIGO Scientific Collaboration is preparing to release the data collected during Science Run 5 (**S5**) to the public. S5 contains data taken at the three LIGO observatories from 2005-2007.

Periodically throughout the S5 data collection, **hardware injections** were added to the data at planned times, for testing and calibration, by actuating the mirrors in the arms of the interferometers. In preparation for the release, the original documentation detailing interferometer conditions and the success or failure of hardware injections needs to be updated.



Figure 1: The LIGO detector in Hanford, WA. Each arm stretches on for 4 km.

Aim

- Search for compact binary coalescence injections in LIGO S5 data
- Compare results with expected values given in the original documentation
- Update the documentation with precise and accurate descriptions of the injections found in the data



Method

- Create compact binary coalescence waveform templates

Our templates model the strain/Hz $\tilde{h}(f)$ in the detector as a compact binary coalescence signal is detected. Strain is a measurement of how space-time is distorted by passing gravitational waves. It is related to the amplitude, A , frequency, f , and phase, Ψ , of the source according to equation 1.

$$\tilde{h}(f) = \left(\frac{1 \text{ Mpc}}{D_{\text{eff}}} \right) A_1 \text{ Mpc} (M, \mu) f^{-\frac{7}{6}} e^{-i\Psi(f; M, \mu)} \quad (1)$$

- Find the injections using a matched filter search

Figure 2 shows a spectrogram of the injected signal from a neutron star – neutron star binary coalescence.

We take a segment of data where we expect to see an injection, like that in figure 2, and Fourier transform it into the frequency domain. We then cross correlate the template with the data to find the time of highest correlation. This is our hardware injection. From this correlation and the parameters of the model, we now know the time of the injection and the mass parameters of the coalescing objects.

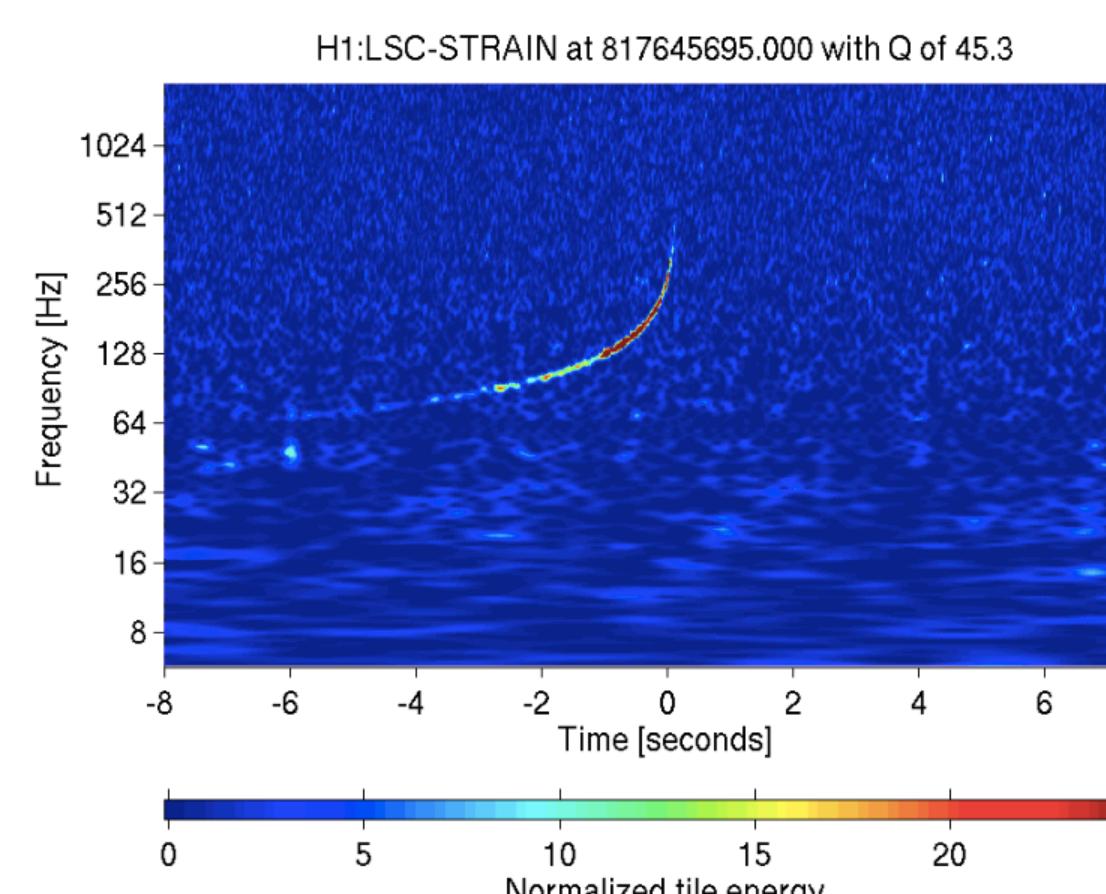


Figure 2: Spectrogram of a simulated 1.4 – 1.4 solar mass neutron star binary undergoing compact binary coalescence at a distance of 0.1 Mpc. Notice the increase in orbital frequency as the stars spiral inward toward one another. This is called a “chirp” because the frequency is audible when played with speakers.

- Determine the **recovered** signal to noise ratio (**SNR**) of the injection

The amplitude signal to noise ratio of the search output, $\rho_m(t)$, is related to the time domain search output, $z_m(t)$, and σ_m , a measure of the instrument sensitivity according to equation 2.

$$\rho_m(t) = \frac{|z_m(t)|}{\sigma_m} \quad (2)$$

- Determine the **predicted** signal to noise ratio of the injection

To determine the predicted signal to noise ratio, we look at the S5 injection documentation and find what effective distance, D_{eff} , was used to model the injection signal. Equation 3 gives predicted signal to noise ratio, with the same σ_m sensitivity measurement.

$$\rho_{\text{predicted}} = \frac{\sigma_m}{D_{\text{eff}}} \quad (3)$$

Results

Figure 3: This plot contains all injections marked as successful in the original S5 documentation from the 2km detector in Hanford, WA. The SNR our search recovers is plotted vs. the SNR predicted by the old documentation’s distance parameters. The blue line represents equal recovered and predicted SNR.

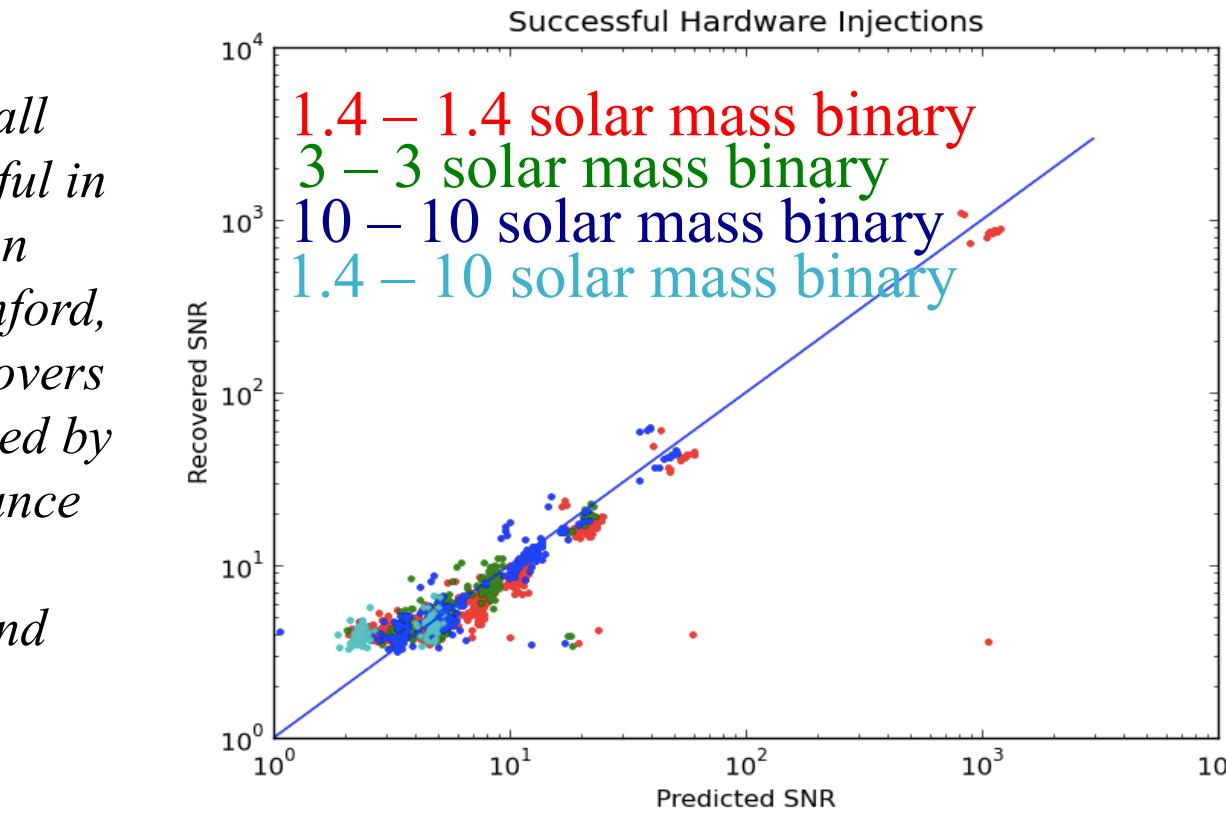


Figure 3 above plots all hardware injections marked as successful in the original documentation. The recovered signal to noise ratio is plotted versus the predicted signal to noise ratio. A few injections are not recovered due to a failure during the hardware injection process. This is an important result and we have now updated the documentation to reflect these findings.

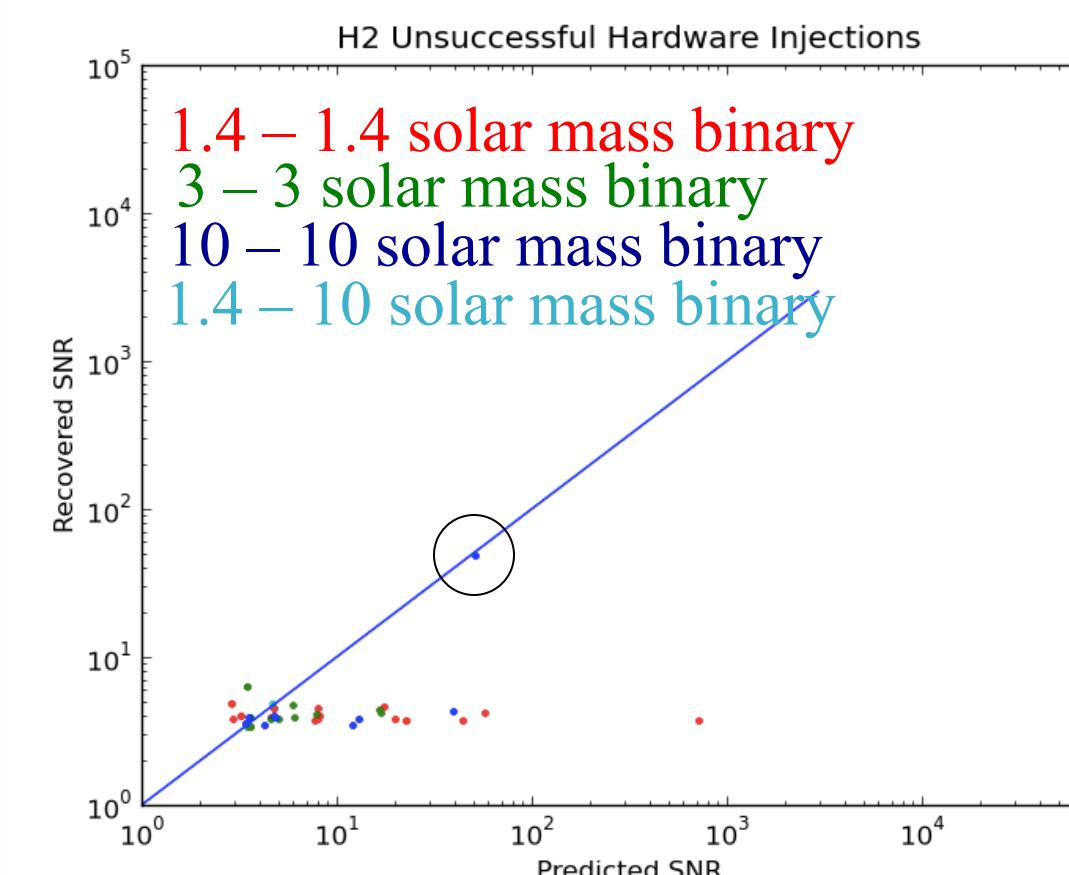


Figure 4: This plot contains all injections marked as unsuccessful in the original S5 documentation from the 2km detector in Hanford, WA. The SNR our search recovers is plotted vs. the SNR predicted by the old documentation’s distance parameters. The blue line represents equal recovered and predicted SNR.

Figure 4 plots all hardware injections recorded as unsuccessful. All of these are low recovered signal to noise ratio, as expected because they failed to inject into the data correctly, except for one. We have successfully recovered an injection that we did not expect to see according its unsuccessful label.

Upon closer inspection of the time surrounding this injection, we find that the injection was successful, though the interferometer went out of “science mode” shortly after the injection finished. (“**Science mode**” data is considered good, and all other data is not used.) Figure 5 shows a spectrogram of this mislabelled injection. It is a 10 solar mass – 10 solar mass binary coalescence that occurs at a 10 Mpc distance from the detector.

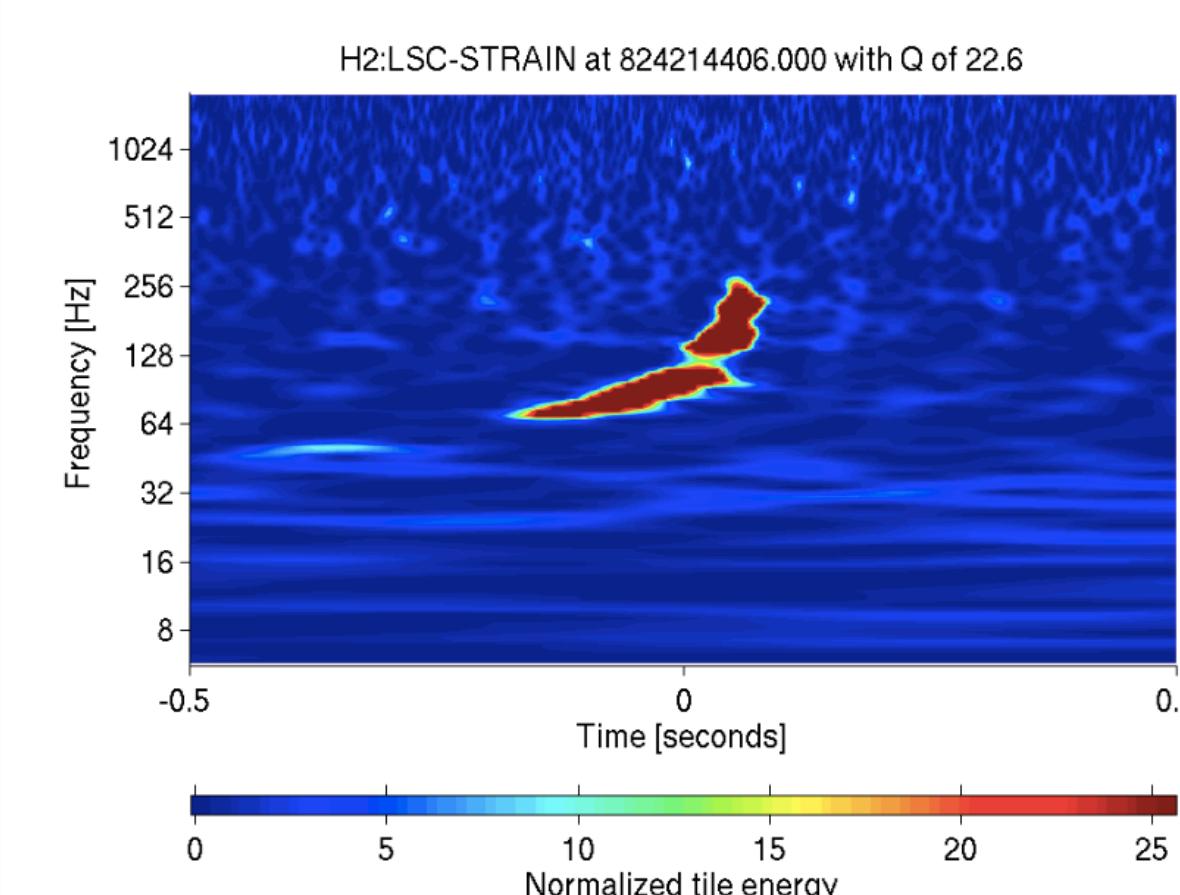


Figure 5: Spectrogram of a 10 – 10 solar mass compact binary coalescence hardware injection at a 10 Mpc distance. The detector went out of science mode shortly after the injection completed.

Conclusion

Detector	H1	H2	L1
Total # Injections	1200	1282	1271
Successful Injections, Data Available	870	929	770
Expected to be Recovered	614	333	545
Recovered	608	322	538
Successful Injections, Data Unavailable	21	19	14
Unsuccessful Injections, Data Available	46	45	51
Recovered	1	3	2
Unsuccessful Injections, Data Unavailable	263	289	436

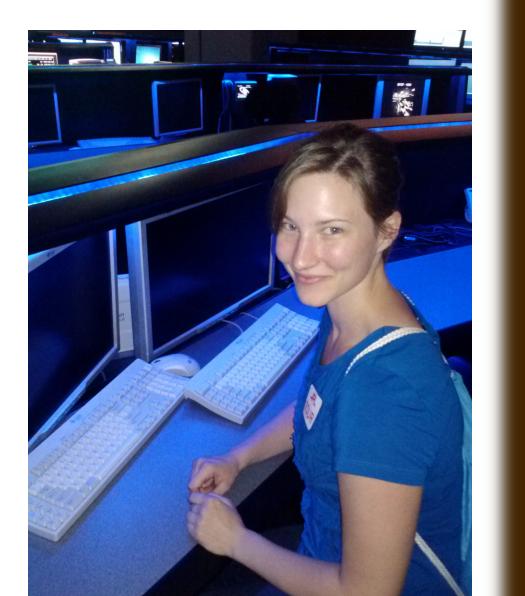
Table 1: The total number of scheduled injections at each detector is broken down into categories here. We expect to recover injections with an SNR > 8. We consider injections with an SNR > 6 to be successfully recovered.

Table 1 summarizes our findings for all injections in each of the three LIGO detectors. In each detector, we recover most of the successful injections, with the exception of a few. We also recover a couple injection that we do not expect to find. We have updated the hardware injection documentation to reflect these findings in preparation for the public data release.

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