

# Testing the LIGO inspiral analysis with hardware injections

**Duncan A Brown (for the LIGO Scientific Collaboration)**

Department of Physics, University of Wisconsin–Milwaukee, Milwaukee, WI 53211, USA

E-mail: [duncan@gravity.phys.uwm.edu](mailto:duncan@gravity.phys.uwm.edu)

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## Abstract

Injection of simulated binary inspiral signals into detector hardware provides an excellent test of the inspiral detection pipeline. By recovering the physical parameters of an injected signal, we test our understanding of both instrumental calibration and the data analysis pipeline. We describe an inspiral search code and results from hardware injection tests and demonstrate that injected signals can be recovered by the data analysis pipeline. The parameters of the recovered signals match those of the injected signals.

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(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

Gravitational radiation incident on the LIGO interferometers from an inspiralling binary will cause the test masses to move relative to each other. This produces a differential change in length of the arms [1]. *Injection* is the process of adding a waveform to interferometer data to simulate the presence of a signal in the noise. We use injections to measure the performance of the binary inspiral analysis pipeline [2]. *Software injections*, which add a simulated signal to the data after it has been recorded, are used for efficiency measurements. Since they performed this *a posteriori*, the interferometer is not affected while it is recording data. Alternatively, a simulated signal can be added to the interferometer control system to make the instrument behave as if an inspiral signal is present. We call this *hardware injection*; the data recorded from the instrument contain the simulated signal.

Analysis of hardware injections ensures that the analysis pipeline is sensitive to real inspiral signals and validates the software injections used to test the pipeline efficiency. In order to perform an accurate upper limit analysis for binary neutron stars, we must measure the efficiency of our pipeline [2]. That is, we inject a known number of signals into the pipeline and determine the fraction of those detected. Injecting signals into the interferometer for the duration of a run is not practical, so we use the analysis software to inject inspiral signals in

software. By comparing software and hardware injections we confirm that software injections are adequate to measure the efficiency of the upper limit pipeline.

Hardware injections provide a very complete method of testing the inspiral detection pipeline. By recovering the physical parameters of an injected signal, we test our understanding of all aspects of the pipeline, including the instrument calibration, filtering algorithm and veto safety. We injected inspiral signals immediately after the first LIGO science run (S1) in August—September 2002. The data taken during this time were analysed by using the software tools used to search for real signals. This paper describes the results from hardware injection tests performed by the Inspirational Working Group of the LIGO Scientific Collaboration (LSC).

## 2. Injection of the inspiral signals

To inject the signals, we generate the interferometer strain,  $h(t)$ , produced by an inspiralling binary using the restricted second-order post-Newtonian approximation in the time domain [3]. The LSC calibration group supplies a transfer function,  $T(f)$ , which allows us to construct a signal,  $v(t)$ , that produces the desired strain when it is injected into the interferometer. The transfer function,  $T(f)$ , is given by

$$T(f) = \frac{L}{C} \frac{f^2}{f_0^2} \quad (1)$$

where  $L$  is the length of the interferometer,  $C$  is the calibration of the excitation point in nm/count and  $f_0$  is the pendulum frequency of the test mass. Damping is neglected as it is unimportant in the LIGO frequency band. Codes are available in the LIGO Algorithm Library (LAL) [4] for simulating inspiral waveforms for hardware injection.

The interferometer *length sensing and control* system [5] has excitation points which allow arbitrary signals to be added into the servo control loops or to the drives that control the motion of the mirrors [6]. During S1, we injected signals corresponding to an optimally oriented binary. Injections of two  $1.4M_\odot$  neutron stars at distances from 10 kpc to 80 kpc were used to test the neutron star analysis. We also injected signals from a  $1.4, 4.0M_\odot$  binary and several  $1.4, 1.4M_\odot$  binaries at closer distances. These signals were injected into the differential mode servo and directly into an end test mass drive.

## 3. The S1 inspiral analysis pipeline

The data analysis pipeline used in the neutron star inspiral search is described in [2]. In brief, we use matched filtering with a bank of templates between  $1.0$  and  $3.0M_\odot$  for each element of the binary. This generates a list of triggers which exceed a signal-to-noise threshold and pass a waveform quality test, known as the  $\chi^2$  test, which has proved effective at excluding triggers that are due to glitches in the data. Auxiliary interferometer channels are filtered for glitches and those inspiral triggers that are coincident with a glitch are vetoed. We test for coincident triggers, subject to the less sensitive interferometer being able to see the trigger. Triggers that pass all cuts are considered events. The efficiency of the pipeline is measured by a Monte Carlo simulation which uses software injections into interferometer data.

## 4. Results

### 4.1. Detection of the injected signals

Table 1 shows the events generated by processing 4000 s of data from the Livingston 4 km interferometer (L1) on 10 September 2002 during the post-run hardware injections. It can be

**Table 1.** Hardware injection events found by the inspiral analysis pipeline. End time of injection is the known end time of the injected signal and end time of detection is the end time of the signal as reported by the analysis pipeline. Times are universal time (UTC) on 10 September 2002. The values of signal-to-noise ratio  $\rho$  and  $\chi^2$  veto are given for each event.

End time of injection	End time of detection	$\rho$	$\chi^2$
04 : 35 : 12.424928	04 : 35 : 12.424927	11.623 546	1.653 222
04 : 36 : 42.424928	04 : 36 : 42.425 171	20.230 101	1.671 016
04 : 38 : 12.424928	04 : 38 : 12.424927	37.488 770	0.443 966
04 : 39 : 42.424928	04 : 39 : 42.424927	69.815 262	1.375 486

seen that all of the hardware injections are identified as candidate events since they have high signal-to-noise ratios and values of the  $\chi^2$  test lower than 5, which was the threshold used in the S1 analysis pipeline [2].

Since we know the exact end times of the injected signals, we can compare them with the value reported by the search code and ensure that the pipeline is reporting the correct time. The raw data are resampled to 4096 Hz before being filtered. For each of the signals injected, we were able to detect the coalescence time of the injection to within one sample point of the correct value at 4096 Hz, which is consistent with the expected statistical error and confirms that the pipeline has not introduced any distortion of the signals.

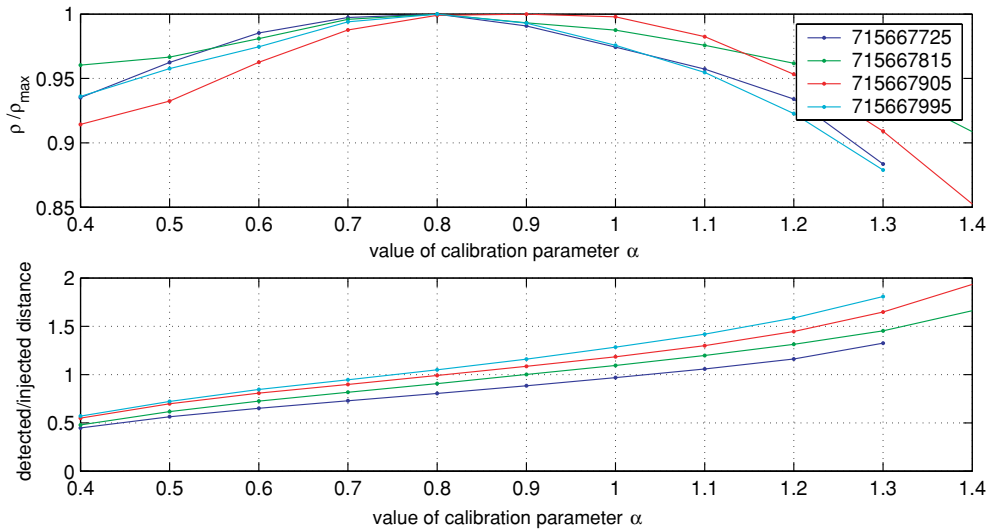
#### 4.2. Checking the instrumental calibration

Calibration measurements of the interferometers were performed before and after the run; these are the reference calibrations. In general, the calibration changes due to changes in the alignment on timescales of minutes. This variation can be encoded in a single parameter  $\alpha$  which is monitored using a sinusoidal signal injected into the detector (the calibration line) [7].  $\alpha$  is used as input to the data analysis pipeline and varied between 0.4 and 1.4 during S1. Data are analysed in 256 s segments. For each 256 s of data starting at time  $t_0$ , we construct the calibration,  $R(f; t_0)$  by using  $\alpha(t_0)$  and a reference calibration.  $R(f; t_0)$  is then used to calibrate 256 s of data.

Figure 1 shows a set of injections into the Livingston interferometer analysed with different calibrations generated by varying the value of  $\alpha$ . We expect that the signal-to-noise varies quadratically and the effective distance varies linearly with changes in  $\alpha$  [8]. This is confirmed by the injections. There is no single value of  $\alpha$  that gives the correct effective distance for all the injections; this is consistent with the estimated systematic errors in the calibration. Unfortunately the calibration line was not present during the time the hardware injections were performed, so we cannot directly compare a measured calibration with the result of the injections.

## 5. Conclusions and future work

The analysis of the hardware injections in S1 was very productive. It allowed us to test the software injections and check that the correct parameters are recovered for injected signals. We recovered all the injections for the signals between 10 and 80 kpc with a timing accuracy of  $1/4096$  s. The detected distance of the signals was correct to within the calibration uncertainty of approximately 30%. We confirmed that the variation of signal-to-noise ratio with calibration scaled as we expected. In addition, hardware injections were used to ensure that our pipeline did not veto real signals due to the use of unsafe auxiliary channels as vetoes [2].



**Figure 1.** Each curve corresponds to a hardware injection at the given GPS time. We re-analyse each injection with different calibrations to show how the detected quantities vary with  $\alpha$ . The upper plot shows the ratio of signal-to-noise ratio,  $\rho$ , to its maximum value,  $\rho_{\max}$ . The lower plot shows the ratio of the detected distance to the known distance of the hardware injection.

The first science run lasted two weeks, so our hardware injections were limited. The second LIGO science run (S2) took place on 14 February–14 April 2003 and a more comprehensive set of hardware injections was performed with the calibration line present. We are currently analysing the data taken during S2. The injection of inspiral signals into the interferometer will again form an important part of our analysis.

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