TESTING THE LIGO INSPIRAL ANALYSIS WITH HARDWARE INJECTIONS

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Introduction

Injection of simulated binary inspiral signals into the LIGO gravitational wave detectors is the most complete method of testing 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 performed injection of inspiral signals at the end of the first LIGO science run in August - September 2002 (S1). The data taken during this time was analyzed using the same pipeline used to search for real signals.

In this poster we describe the inspiral search code and results from hardware injection tests performed by the LSC Inspiral Working Group

Goals of Hardware Signal Injections

1. To test our data analysis pipeline from the interferometer to the result of the search algorithms.

Gravitational radiation from an inspiraling binary incident on the interferometer will cause the test masses to move relative to each other. This produces a differential change in length of the arms.

We feed known inspiral waveforms directly into the interferometer, causing it to behave as if a real signal was present.

Since we know the signal is present, we can analyze the output of the interferometer and ensure that the analysis pipeline is sensitive to real inspiral signals.

2. To validate the software injections used to test the pipeline efficiency.

In order to perform an accurate upper limit analysis for binary neutron stars, we have to measure the efficiency of our pipeline. That is, we must inject a known number of signals into the pipeline and determine the fraction of these 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 are able to ensure that software injections are sufficient to measure the efficiency of the upper limit pipeline.

Injecting the Signals

We generate the interferometer strain, h(t), produced by a pair of inspiralling binary using the restricted second order post-Newtonian approximation in the time domain.

The calibration team 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

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

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.
Since the signals to be injected have well defined frequency content f(t), we take advantage of the adiabatic limit to determine the excitation as

$$v(t) = h[t; f(t)]\, T[f(t)]$$

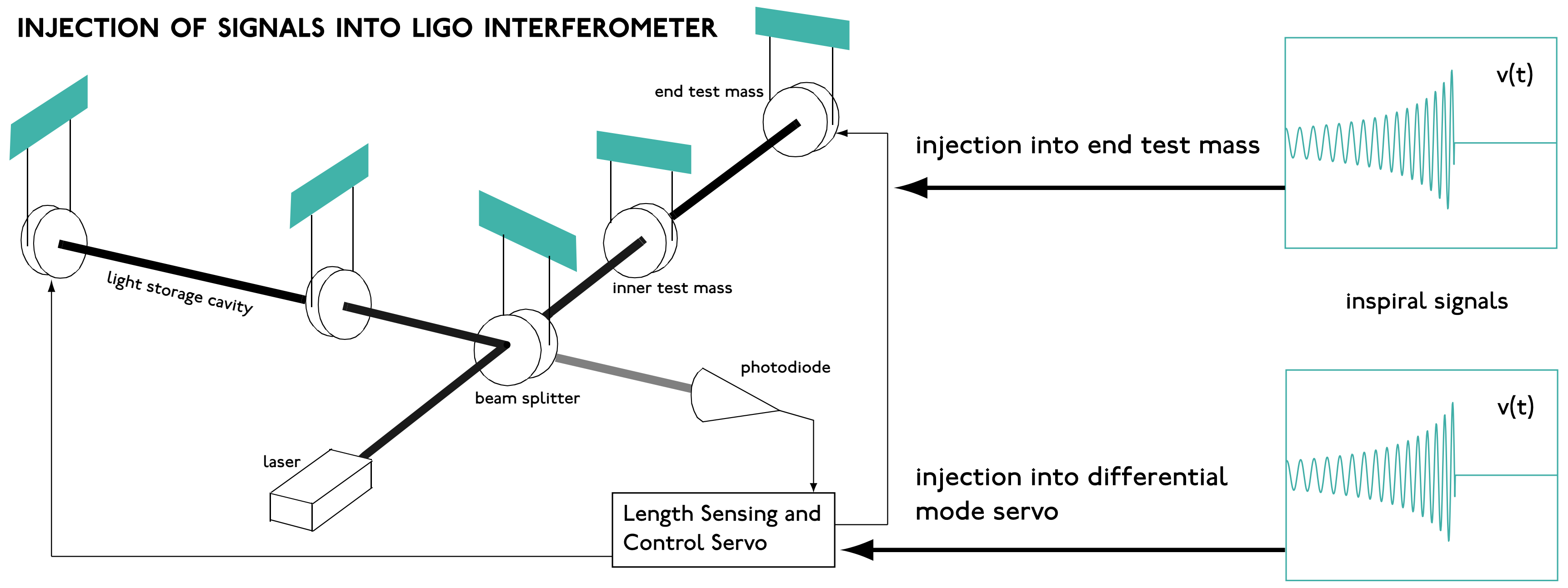
where h[t; f(t)] is the strain gravitational wave signal to be injected.

The interferometer Length Sensing and Control system has several excitation points. These allow arbitrary signals to be added into the servo control loops or sent directly to the drives that control the motion of the mirrors.

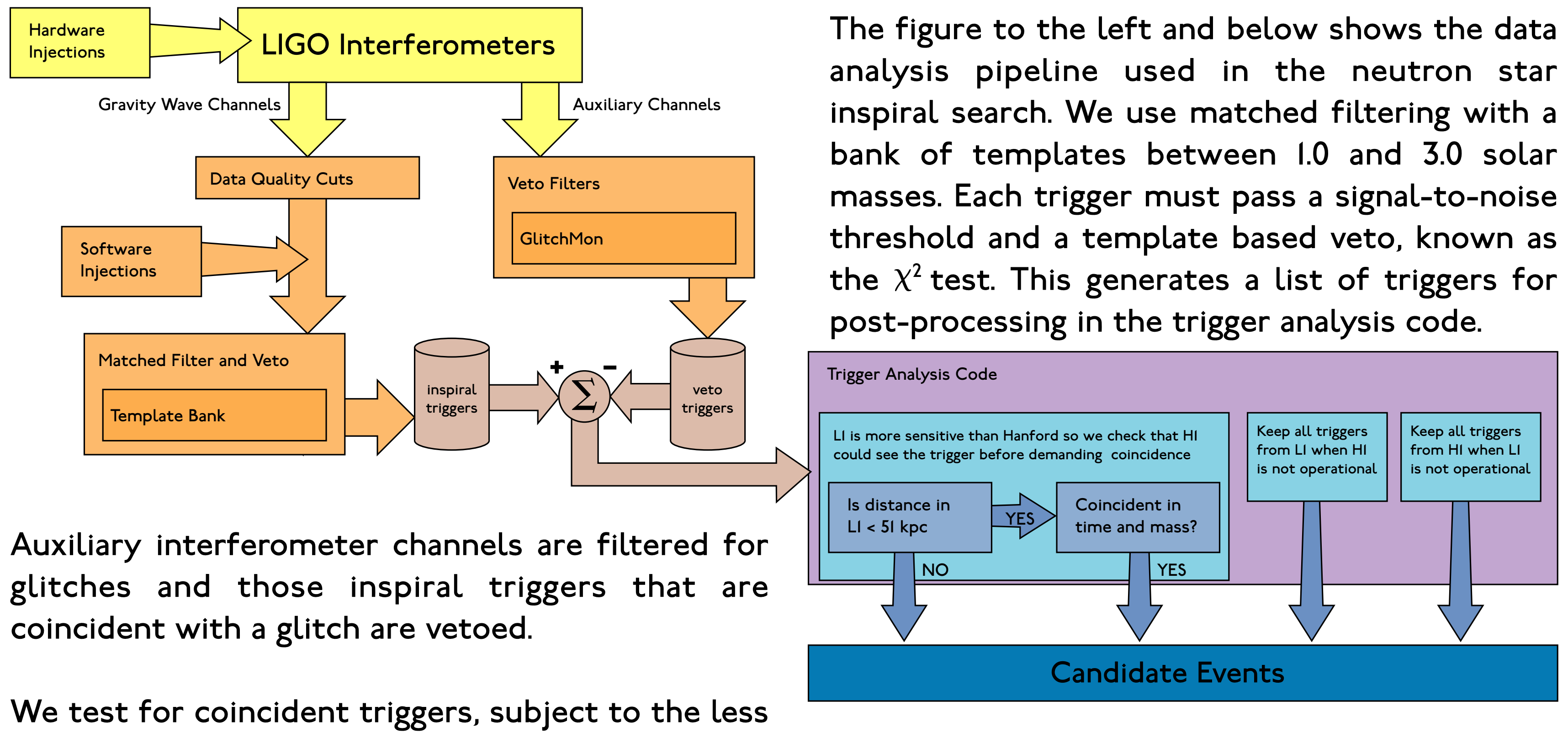
The waveforms are provided to the hardware injection team and are injected into the interferometer during the science run.

During S1, we injected signals corresponding to an optimally oriented binary containing two 1.4 solar mass neutron stars at several distances. These signals were injected into the differential mode servo and directly into an end test mass drive. However, all the binaries we injected during S1 were of the same orientation with respect to the detector.

INJECTION OF SIGNALS INTO LIGO INTERFEROMETER



The S1 Inspiral Analysis Pipeline



L1 is more sensitive than Hanford so we check that H1 could see the trigger before demanding coincidence

Is distance in L1 < 51 kpc

Coincident in time and mass?

Keep all triggers from L1 when H1 is not operational

Keep all triggers from H1 when L1 is not operational

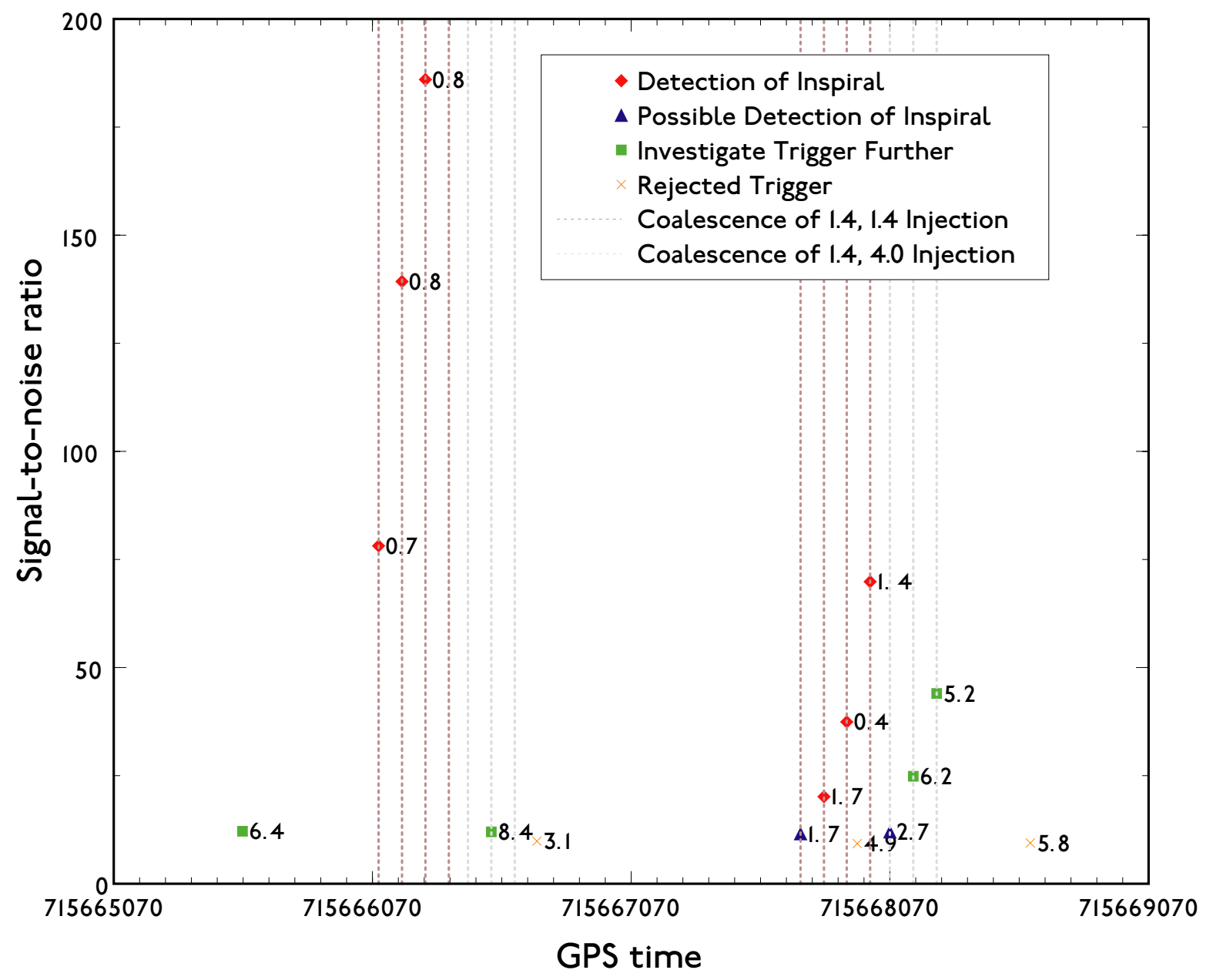
The figure to the left and below shows the data analysis pipeline used in the neutron star inspiral search. We use matched filtering with a bank of templates between 1.0 and 3.0 solar masses. Each trigger must pass a signal-to-noise threshold and a template based veto, known as the χ^2 test. This generates a list of triggers for post-processing in the trigger analysis code.

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 using a Monte-Carlo simulation with software injections.

Detection of the Injected Signals



The figure to the right shows the candidate events generated by processing 4000 seconds of data from the Livingston 4 km interferometer through the analysis pipeline described above.

This data included two sets of injections; the known coalescence times are indicated by the dashed vertical lines. The signal-to-noise ratio is plotted and the value of the χ^2 veto is shown next to the candidate event.

The first set of injections were large amplitude signals used to verify the inspirals were being correctly injected. We ignore these and concentrate on the second set, which were at more appropriate distances. We only consider the two 1.4 solar mass inspiral injection, as the 1.4,4.0 injection lies outside the template bank space.

It can be seen that all of the injections in the second group are identified as candidates. The largest ones were flagged as detected, the lower signal-to-noise ratio candidates were flagged for further investigation. Some of the 1.4,4.0 injections are also flagged for further investigation as they cause templates inside the bank to ring, but have high χ^2 values as they are not exactly matched.

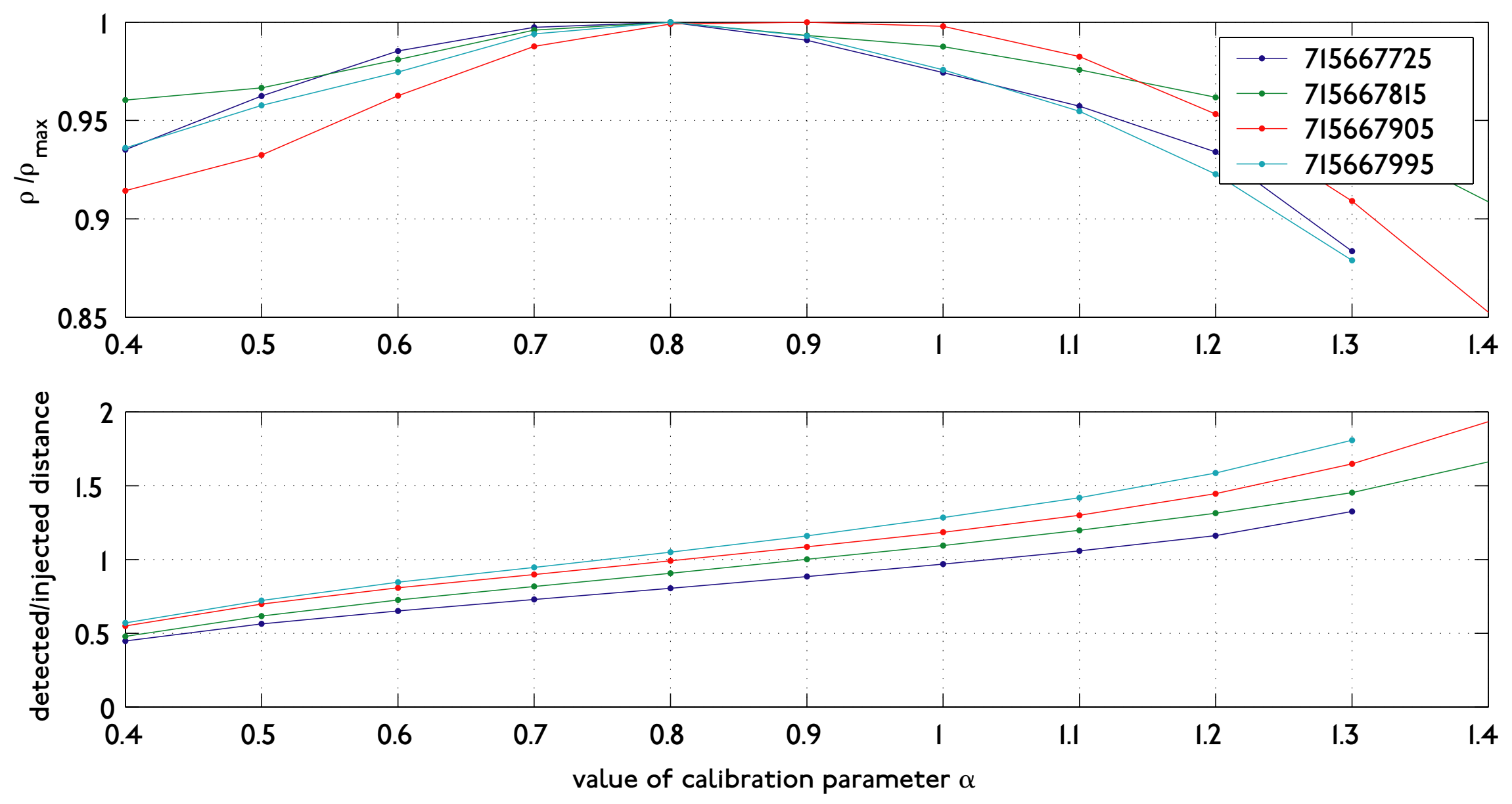
Since we know the exact coalescence time of the injected waveform, we can compare this with the value reported by the search code and ensure that the pipeline is reporting the correct time.

For each of signals injected, we were able to detect the coalescence time of the injection to within one sample point of the correct value, which is consistent with the expected statistical error.

Checking the Calibration for Inspiral Signals

Calibration measurements of the interferometers were performed before and after the run. Over the course of the run the calibration changes, due to changes in the alignment. This variation is encoded in a single parameter, α, which is computed from a sine wave injected into the detector. α can vary between 0.4 and 1.4. We construct the calibration at any time by using α and the point calibration.

The figure below right shows a set of injections into the Livingston interferometer analyzed with different calibrations generated by varying the value of α. We expect that the signal-to-noise varies quadratically and the effective distance varies linearly with changes in α. This is confirmed by the injections.



It can be seen that there is no single value of α that gives the correct effective distance for all the injections.

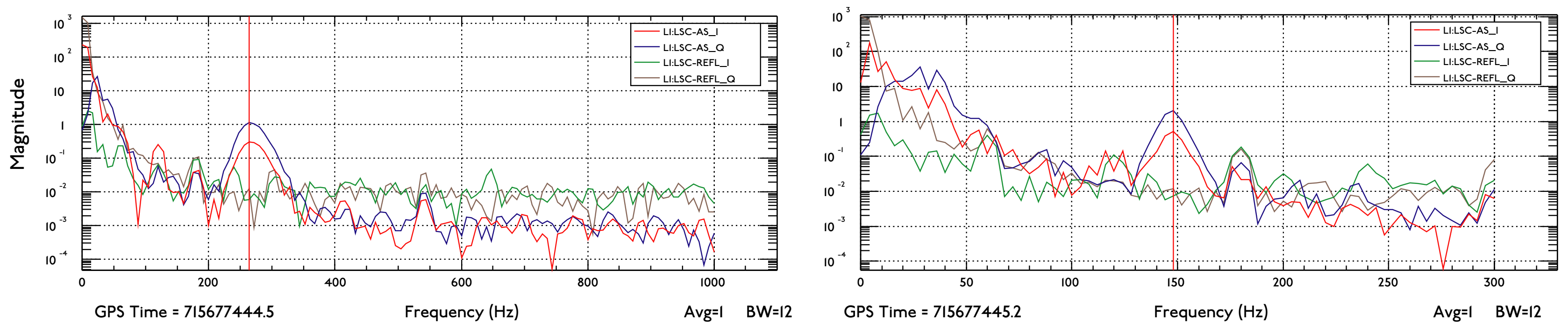
This is consistent with the expected systematic errors in the calibration.

Safety of Vetoes

During construction of the pipeline we considered using inspiral triggers found in auxiliary interferometer channels as vetoes on triggers in the gravitational wave channel. Concern was raised that a real inspiral signal may couple between these channels and a real signal may be inadvertently vetoed.

To check this, we examined coupling between the channels at the time of an injection. The figures below show the power spectra of the gravity wave channel, called AS_Q, and the auxiliary channels that we considered using as vetoes during an injection. The broad peak in the spectrum is the inspiral signal and the two power spectra show it sweeping across the band.

We determined that there was coupling between some of the proposed auxiliary channels and the gravity wave channel, so we did not use these channels in our final pipeline.



Conclusions and Future Work

The analysis of the hardware injections in S1 was very productive. It allowed us to:

1. Test our software injections and check that the correct parameters are recovered for injected signals.
2. Confirm that the variation of signal-to-noise ratio with calibration scaled as we expected.
3. Ensure that our pipeline did not veto real signals due to using unsafe auxiliary channels as vetoes.

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

Credits

Poster designed by: Duncan Brown, University of Wisconsin-Milwaukee. LIGO-G030666-00-Z.
Analysis performed by LSC Inspiral Working Group, LSC Calibration Team and Science Run Injection Team.
Calibration analysis courtesy of Gabriela Gonzalez.
Power spectra of auxiliary channels courtesy of Peter Shawhan.