

# Vetoos for inspiral triggers in LIGO data

Nelson Christensen<sup>1</sup>, Peter Shawhan<sup>2</sup> and Gabriela González<sup>3</sup>  
(for the LIGO scientific collaboration)

<sup>1</sup> Physics and Astronomy, Carleton College, Northfield, MN 55057, USA

<sup>2</sup> LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

<sup>3</sup> Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803, USA

E-mail: nchriste@carleton.edu, shawhan\_p@ligo.caltech.edu and gonzalez@lsu.edu

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## Abstract

Presented is a summary of studies by the LIGO Scientific Collaboration's Inspirational Analysis Group on the development of possible vetoos to be used in the evaluation of data from the first two LIGO science data runs. Numerous environmental monitor signals and interferometer control channels have been analysed in order to characterize the interferometers' performance. The results of studies on selected data segments are provided in this paper. The vetoos used in the compact binary inspiral analyses of LIGO's S1 and S2 science data runs are presented and discussed.

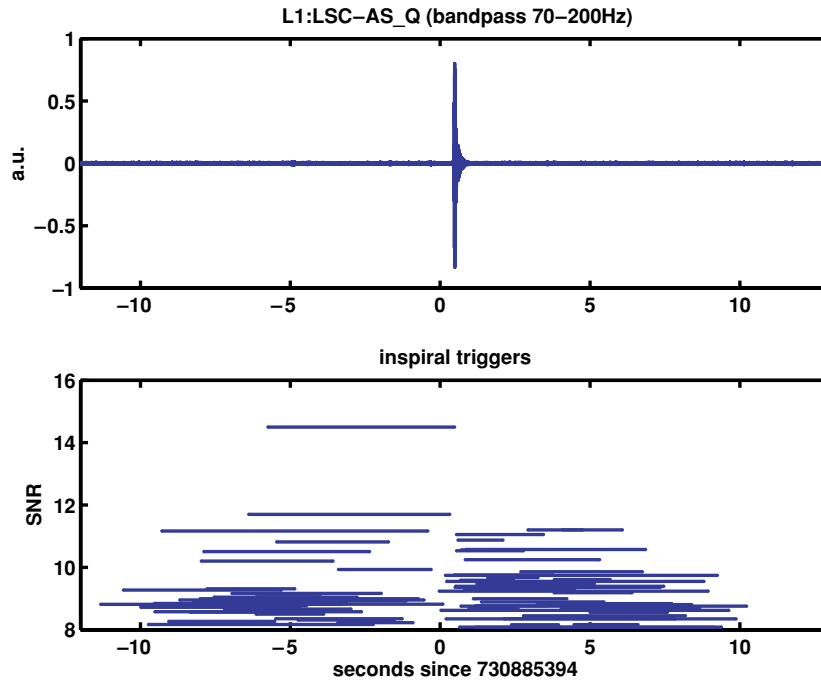
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(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

The Laser Interferometer Gravitational Wave Observatory (LIGO) is now operating, and collecting meaningful scientific data [1]. The LIGO Scientific Collaboration (LSC) is conducting searches for several types of gravitational wave signals. To date, analysis of data from LIGO's first science data run has led to the publication of searches for continuous waves from pulsars [2], the 'inspiral' (orbital decay) of compact binary systems [3], short bursts [4] and an isotropic stochastic background [5].

The waveform emitted by an inspiralling compact binary system can be modelled accurately (at least if the component masses are fairly low), allowing the use of matched filtering techniques when searching for this class of signals. The data are filtered using a large number of 'template' waveforms in order to search for signals with a range of physical parameters. For any given template, the search algorithm generates a 'trigger' each time the output of the matched filter exceeds a pre-determined threshold in signal-to-noise ratio (SNR),

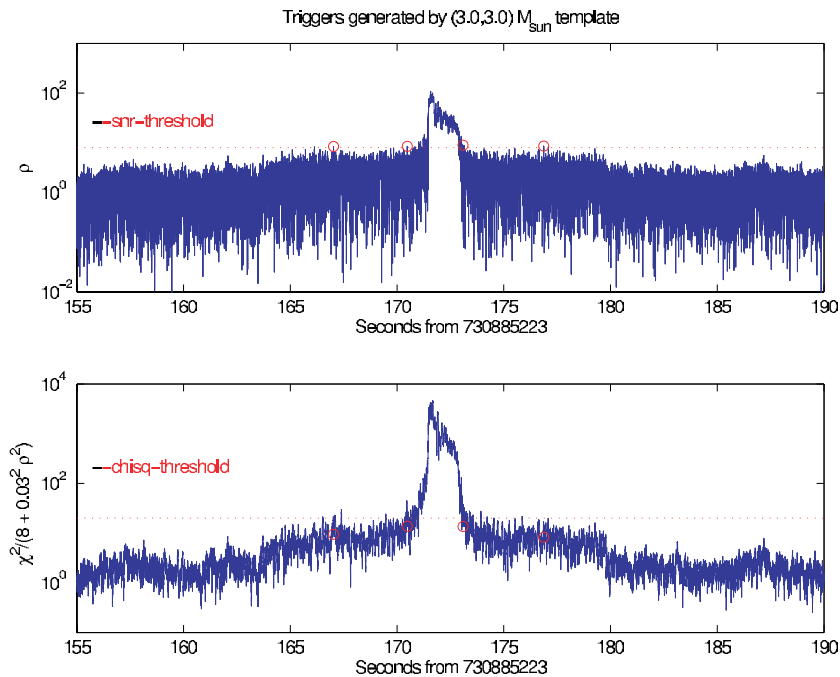


**Figure 1.** An example of how a large amplitude *glitch* can cause numerous templates to report significant SNR triggers. The top trace shows a glitch observed in the time series of the LIGO Livingston gravitational wave channel, denoted by L1:LSC-AS\_Q. The bottom plot shows the inspiral triggers with SNR > 8 which were reported (based on filtering with many template waveforms) in the vicinity of this glitch. Each trigger is represented by a horizontal bar which extends from the time at which the template waveform passes 100 Hz to the inferred coalescence time. The vertical position of the bar indicates the maximum SNR observed in that template. The inferred coalescence times extend over a span of  $\sim 16$  s.

provided that the frequency distribution of the signal power is consistent with the expected waveform, checked quantitatively using a  $\chi^2$  test.

While this search algorithm is optimal in the case of stationary Gaussian noise, the actual noise in the LIGO interferometers is strongly influenced by optical alignment, servo control settings and environmental conditions. Large amplitude *glitch* events, or short stretches of increased broadband noise, will excite the inspiral filter for many templates, thereby leading to false triggers in the search. An example of this can be seen in figure 1, where a large-amplitude glitch causes numerous inspiral templates to respond over a time span as long as  $\sim 16$  s. This time scale is related to the treatment of sharp features in the power spectral density of the detector noise, which is used as an inverse weighting factor in the matched filter. Figure 2 shows the output of the matched filter in the vicinity of this glitch, illustrating how these inaccurate inspiral coalescence times can arise from the ringing of the template filter: although the main SNR peak is easily rejected by the  $\chi^2$  test, there are a few nearby times for which the SNR exceeds the trigger threshold while  $\chi^2$  is below the rejection threshold.

The goal of the studies described in this paper is to eliminate demonstrably bad stretches of data and to identify environmental or instrumental causes of glitches when possible, allowing us to ‘veto’ (reject) any inspiral triggers occurring at nearby times. In addition to the main data channel in which a gravitational wave signal would appear (called ‘LSC-AS\_Q’ because it is the length sensing and control signal extracted from the ‘anti-symmetric port’ photodiode



**Figure 2.** Time series displays of the output of the matched filter, for one particular template, in the vicinity of the large glitch shown in figure 1. The top plot shows the SNR and the threshold used to identify triggers, while the bottom plot shows the  $\chi^2$  variable which is required to be below a threshold. The circles note the times when the signal exceeded the SNR threshold (top), yet passed the  $\chi^2$  test (bottom).

using quadrature demodulation phase), numerous additional channels are recorded to monitor auxiliary optical signals and servo control points in the interferometer, as well as environmental conditions. In some cases, we are able to significantly reduce the rate of false triggers by using these additional channels as indicators of instrumental or environmental disturbances.

LIGO's first science data run, called S1, spanned 17 days from 23 August to 9 September, 2002. The second science data run, called S2, spanned two months from 14 February to 14 April 2003. The average noise in the LIGO interferometers was roughly an order of magnitude better during S2 than during S1. Building on the analysis of the S1 data [3], a search for binary neutron star (BNS) inspiral events is being conducted with the S2 data; an upper limit will be placed on the coalescence rate in the Milky Way and nearby galaxies [6]. The specifics determining the vetoes are presented in the remainder of the paper. Section 2 outlines the concepts used in veto studies and summarizes the S1 veto analysis; a more complete description can be found in [3]. A comprehensive description of the S2 inspiral veto analysis is presented in section 3. A summary of our conclusion, and thoughts on possible future analysis plans, is contained in section 4. In the course of this paper we refer to the 4 km interferometer at Livingston, LA, as L1, and the 4 km and 2 km interferometers at Hanford, Washington, as H1 and H2 respectively.

## 2. Vetoes for LIGO science data run S1

A description of the vetoes implemented for the BNS inspiral analysis of data from LIGO science data run S1 [3] is presented here. In order to avoid the possibility of statistical

bias, potential veto conditions were studied using only a ‘playground’ data set comprising about 10% of the collected data, selected by hand to give a sampling of different degrees of non-stationarity observed in the detector noise at different times. These playground data were not used in the calculation of the inspiral rate limit.

Only the L1 and H1 interferometers were used for the S1 inspiral analysis. For either interferometer, sections of data were excluded from examination if there were problems with calibration signals. This resulted in the exclusion of 5% of the L1 data and 7% of the H1 data. In addition, periods of time when the noise level of an interferometer was abnormally large were excluded from analysis. This determination was made through the monitoring of the band-limited root-mean-square noise that occurred in four frequency bands [3, 4]. This veto eliminated 8% of the L1 data and 18% of the H1 data.

Numerous interferometer control and environmental monitoring channels were examined at times when the inspiral templates reported triggers during the playground section, in order to look for correlations. The subset of channels, which showed a possible correlation, were processed using a glitch-finding program which generated ‘veto triggers’. These veto triggers were compared to the list of inspiral triggers, with an adjustable time window to account for instrumental delays as well as the different trigger generation algorithms. The effectiveness of a channel as a veto, using a given time window, was measured by calculating the veto efficiency (fraction of inspiral triggers rejected by veto triggers), usage fraction (fraction of veto triggers coincident with at least one inspiral trigger) and deadtime (fraction of total run time during which inspiral triggers would be rejected according to the set of veto triggers and the time window).

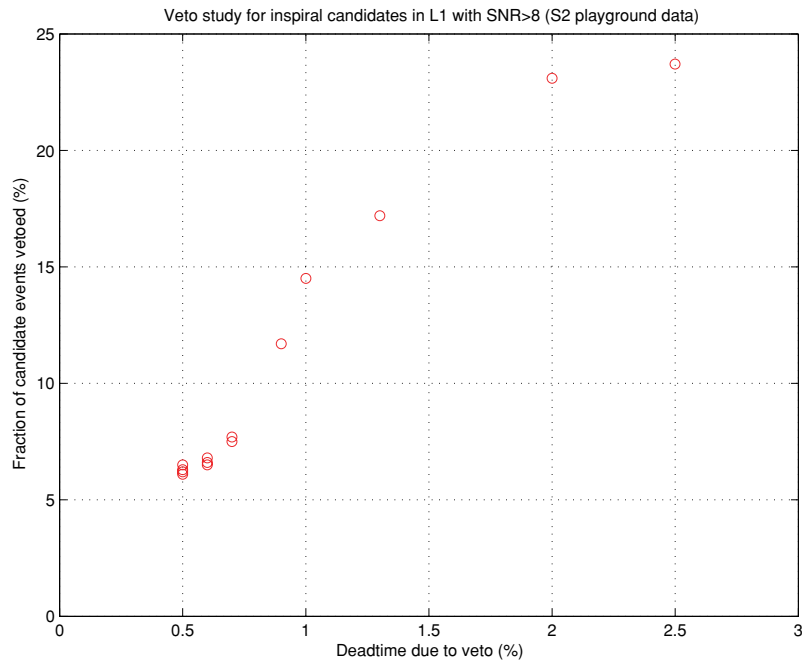
The H1 channel H1:LSC-REFL\_I, a photodiode signal at the interferometer’s reflected port, was found to contain large glitches which correlated well with large glitches seen in the gravitational wave channel. A program called *glitchMon*<sup>4</sup> was used to filter the H1:LSC-REFL\_I channel and record large excursions as veto triggers. A time window of  $\pm 1$  s around these veto trigger times yielded a veto efficiency of over 60% for inspiral triggers with SNR > 10, with a deadtime of only 0.2%. A prospective veto condition for the L1 interferometer, using a channel called L1:LSC-AS\_I which is derived from the same photodiode as the gravitational wave channel, was abandoned due to concerns that a gravitational wave could appear in this channel with non-negligible amplitude.

Once these data quality and veto conditions had been developed using the playground data, they were subsequently implemented as part of the S1 analysis pipeline [3]. Inspirational triggers that passed the SNR threshold,  $\chi^2$  test and veto condition were reported as event candidates and were used to calculate an upper limit on the rate of binary inspirals in the Galaxy. A ‘*post-mortem*’ examination of these events provided illuminating information. For example, the ‘loudest’ event detected in the L1 data was the result of a saturation of the interferometer’s antisymmetric port photodiode, probably caused by a misalignment in the optical system. These results and the experience from the S1 veto analysis served as a starting point for the examination of the S2 data.

### 3. Vetoes for LIGO science data run S2

The character of the S2 data was very different from that of S1. The stability of all of the LIGO interferometers had improved significantly, and the quality of the data was dramatically improved. The interferometer sensitivities had also improved, and consequently new noise

<sup>4</sup> *glitchMon*, written by M Ito (University of Oregon), is a program which looks for transient signals in selected LIGO data channels. It is based on the LIGO Data Monitoring Tool (DMT) library.

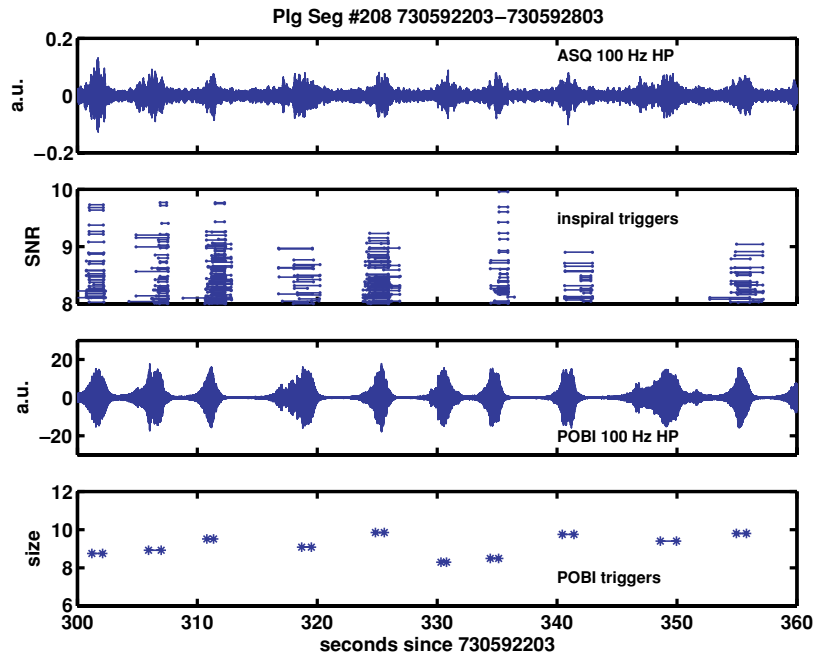


**Figure 3.** An example of the veto efficiency (for BNS inspiral triggers in L1) versus deadtime for the veto channel L1:LSC-POB\_I, using symmetric windows of 0.0,  $\pm 0.05$ ,  $\pm 0.1$ ,  $\pm 0.15$ ,  $\pm 0.2$ ,  $\pm 0.25$ ,  $\pm 0.3$ ,  $\pm 0.4$ ,  $\pm 0.5$ ,  $\pm 0.75$ ,  $\pm 1.0$ ,  $\pm 2.0$ ,  $\pm 4.0$  and  $\pm 6.0$  s. The data from L1:LSC-POB\_I were filtered with a fourth-order Chebyshev 70 Hz high-pass filter, and excursions found by *glitchMon* with significance of  $7\sigma$  or greater were taken to be veto triggers. These results are from the S2 playground data.

sources became visible. The experience derived from the S1 analysis was brought forward, but due to the different behaviour of the interferometers it was necessary to reinspect all of the interferometer control and environmental monitoring channels in detail again. Numerous tools were used for the task. What was initially helpful was to use the inspiral template triggers, found in playground data, and to inspect candidate channels at these times.

Data quality examinations (more comprehensive than those done for the S1 analysis) provided the means to exclude sections of data where there were obvious problems. A number of problems caused data to be excluded: data outside the official S2 run times, missing data, missing or unreliable calibration, non-standard servo control settings (in a few L1 segments) and input/output controller timing problems at L1. The playground data were then used to judge the relevance of other potential data quality flags, leading to two additional data quality vetoes. One concerned the H1 interferometer, which suffered from occasional episodes of elevated non-stationary broadband noise. We eliminated data in which the noise level in the upper part of the sensitive frequency band was high for consecutive periods of at least 3 min; this requirement ensured that a real gravitational wave inspiral signal would not invoke this veto condition, even if it had an exceptionally large amplitude. The other data quality veto used pertained to the saturation of the photodiode at the antisymmetric port at any of the LIGO interferometers, as was observed during S1. This effect correlated with a small, but significant number of the L1 inspiral triggers.

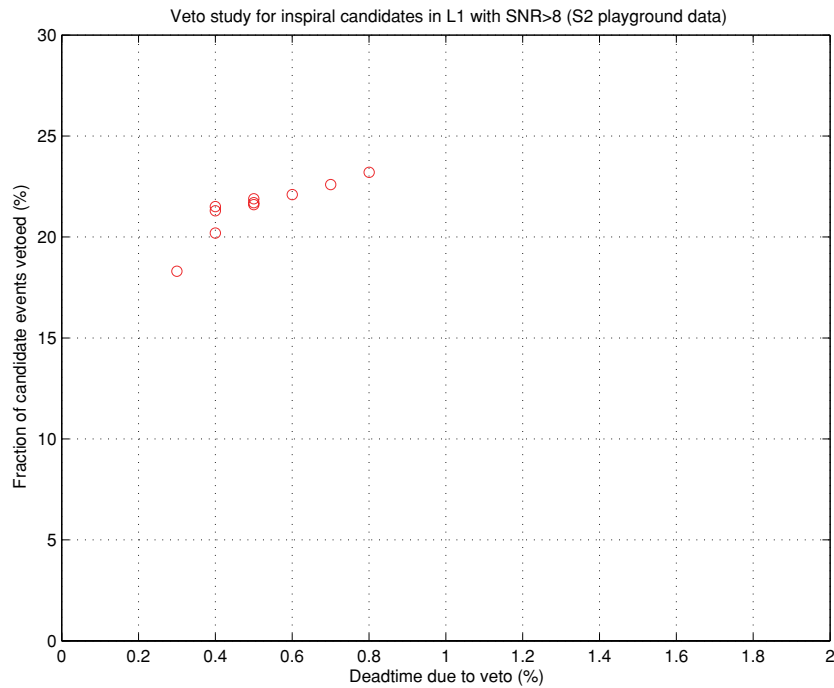
As in the S1 veto study, numerous channels, with various filters and thresholds, were processed with *glitchMon* to produce veto triggers. The efficiency and deadtime for each possible veto condition were evaluated using a playground data set, which for the S2 run



**Figure 4.** Correlation between glitches in the gravitational wave channel L1:LSC-AS\_Q (abbreviated as ‘ASQ’ in the figure) and the prospective veto channel L1:LSC-POB\_I (‘POBI’). The first and third plots show the time series of these channels after filtering with a fourth-order Chebyshev 100 Hz high-pass filter. The second and fourth plots show the time intervals of the triggers reported by the software, represented as horizontal bars. In the case of L1:LSC-AS\_Q, the data were filtered using many template waveforms, and the SNR for various templates is indicated by the vertical positions of the bars. In the case of L1:LSC-POB\_I, the vertical position of the bar indicates the glitch ‘size’ reported by *glitchMon*. The data shown here are from a time in the S2 playground data for which L1:LSC-AS\_Q is especially glitchy and the efficiency of the L1:LSC-POB\_I veto is especially good, and is not typical of the entire S2 run.

consisted of 600 s out of every 6370 s of data. This definition of the playground ensured that it was representative of the entire run; for instance, it included some data from all times of the day. The ‘safety’ of several potential veto channels was evaluated by injecting simulated gravitational wave signals into the interferometer arm lengths and checking for the signals to appear in various auxiliary channels. The signals were found to appear in just one tested channel, L1:LSC-AS\_I, with measurable amplitude, so that channel was deemed to be unsafe for use as a veto.

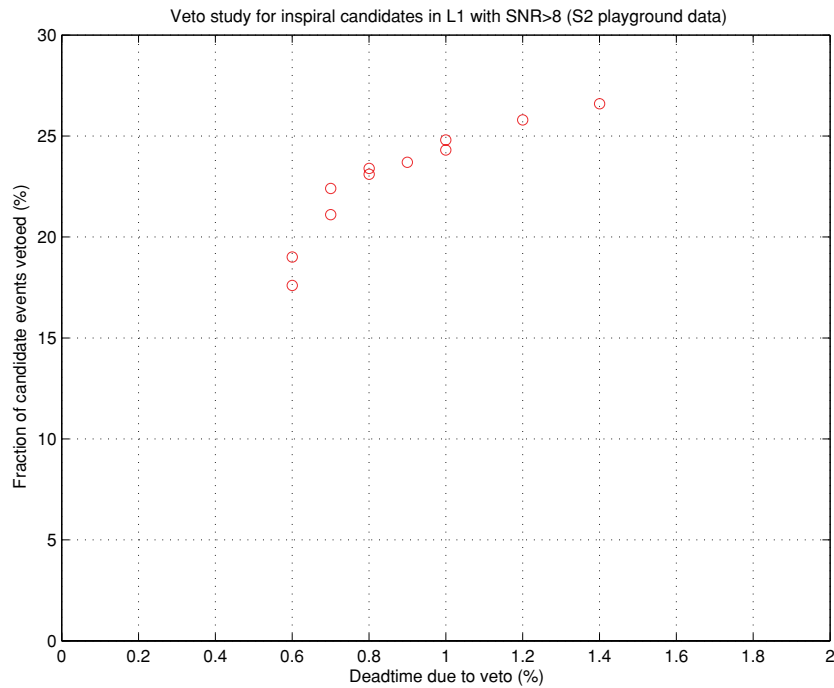
No good candidate veto channels were identified for H1 and H2; however, there were a few candidates for L1. Non-stationary noise in the low frequency part of the sensitivity range used for inspiral search, initially 50–2048 Hz, appeared to be a dominant cause of deleterious glitches in the data. In particular, the non-stationary noise in L1 had dominant frequency content around 70 Hz. A key auxiliary channel, L1:LSC-POB\_I, also had highly variable noise at 70 Hz. There are understandable physical mechanisms for this: the power recycling servo loop (for which L1:LSC-POB\_I is the error signal) has a known instability around 70 Hz when the gain is too high; independently, when the gain of the differential arm length servo loop goes too low (due to low optical gain), glitches around 70 Hz tend to appear. Sometimes these glitches in L1:LSC-POB\_I couple into the differential arm length signal sufficiently strongly to produce inspiral triggers. To avoid these excess triggers, we decided to increase the lower bound of the frequency band used for the BNS inspiral search to 100 Hz. This



**Figure 5.** An example of the veto efficiency (for BBH inspiral triggers in L1) versus deadtime for the channel L1:LSC-AS\_Q, using symmetric windows of  $0.0, \pm 0.05, \pm 0.1, \pm 0.15, \pm 0.2, \pm 0.25, \pm 0.3, \pm 0.4, \pm 0.5, \pm 0.75$  and  $\pm 1.0$  s. The data from L1:LSC-MICH\_CTRL were filtered with a fourth-order Chebyshev 100 Hz high-pass filter, and resulting transients with amplitudes exceeding  $16\sigma$  were declared veto triggers. These results are from the S2 playground data.

reduced the number of inspiral triggers, and simulations indicated that the loss of sensitivity for the target population of binary neutron star systems was acceptably small.

The lists of veto triggers produced by *glitchMon* were compared to the output of the inspiral template search using data in the S2 playground. Figure 3 shows an example of the veto efficiency versus deadtime for the channel L1:LSC-POB\_I, using symmetric time windows of  $0.0, \pm 0.05, \pm 0.1, \pm 0.15, \pm 0.2, \pm 0.25, \pm 0.3, \pm 0.4, \pm 0.5, \pm 0.75, \pm 1.0, \pm 2.0, \pm 4.0$  and  $\pm 6.0$  s. In this case, the L1:LSC-POB\_I data were filtered with a fourth-order Chebyshev highpass filter with a corner frequency of 70 Hz, and *glitchMon* triggers with a significance of more than  $7\sigma$  were taken to be veto triggers. Note that the veto efficiency rises significantly as the time window is increased. As was illustrated in figure 1, a large-amplitude glitch can cause the inspiral search algorithm to generate triggers with inferred coalescence times rather far from the time of glitch. For this reason, we found that we had to use rather long veto time windows to achieve good veto efficiency. After a long series of studies, we settled on using the L1:LSC-POB\_I channel, with the filtering and threshold given above, with a very wide and asymmetric window,  $-4$  s to  $+8$  s. In the playground data, this veto condition vetoed 27% of the BNS inspiral triggers with  $\text{SNR} > 8$  and 35% of the inspiral triggers with  $\text{SNR} > 10$ , with a deadtime of 2.5%. The usage fraction of the veto was 25% for  $\text{SNR} > 8$  and 7% for  $\text{SNR} > 10$ , while the expected random use would be 4.6% and 0.5%, respectively. The final analysis of the full S2 data set (excluding the playground) was done using a more stringent  $\chi^2$  threshold to reduce the number of false triggers, so the final veto efficiencies and usage fractions are somewhat lower than the numbers given above: the efficiency is 13% for inspiral triggers with  $\text{SNR} > 8$  and  $30 \pm 10\%$  for inspiral triggers with  $\text{SNR} > 10$ , with a deadtime of 3.0%.



**Figure 6.** An example of the veto efficiency (for BBH inspiral triggers in L1) versus deadtime for the channel L1:LSC-AS\_Q, using symmetric windows of 0.0,  $\pm 0.05$ ,  $\pm 0.1$ ,  $\pm 0.15$ ,  $\pm 0.2$ ,  $\pm 0.25$ ,  $\pm 0.3$ ,  $\pm 0.4$ ,  $\pm 0.5$ ,  $\pm 0.75$  and  $\pm 1.0$  s. The data from L1:LSC-POB\_I were filtered with a fourth-order Chebyshev 70 Hz high-pass filter, and resulting transients with amplitudes exceeding  $7\sigma$  were declared veto triggers. These results are from the S2 playground data.

Figure 4 demonstrates the appropriateness of this veto channel in a different way, using data from an epoch in the S2 run during which the L1 detector noise was extremely non-stationary. Presented is a sample time-trace (from the S2 playground data) of the interferometer’s gravitational wave signal channel, L1:LSC-AS\_Q, after high-pass filtering, along with the signal from L1:LSC-POB\_I. Also displayed in figure 4 are the template waveform starting/ending times and the SNR for the BNS inspiral triggers and the time intervals of the L1:LSC-POB\_I veto triggers as reported by *glitchMon*.

In addition to the S2 search for binary neutron star inspiral signals, a search is underway for binary black-hole (BBH) signals. These signals have shorter duration and are restricted to a lower frequency range than in the BNS case, so it is possible that different channels could provide the best veto conditions. We have repeated the veto study using a preliminary list of BBH inspiral triggers in the S2 playground data. L1:LSC-POB\_I again appears as a good candidate for veto, with efficiency roughly comparable to what was measured for the BNS case. However, the channel L1:LSC-MICH\_CTRL (the control signal for the servo loop which controls the differential distance between the beamsplitter and the input mirrors of the long Fabry–Perot arm cavities) appears to yield comparable veto efficiency with slightly less deadtime. Figures 5 and 6 show the veto efficiency versus deadtime for L1:LSC-MICH\_CTRL and L1:LSC-POB\_I, respectively, using veto time windows up to  $\pm 1$  s. Combining the two channels only increases the veto efficiency by 1%, indicating that the two channels appear to be glitching concurrently. The final choice of veto condition for the BBH inspiral search will be made after refinement of the inspiral search algorithm and parameters.



#### 4. Discussion and conclusions

LIGO is now acquiring data, and astrophysically interesting analyses are being conducted [2–5]. From the S1 and S2 data it has been seen that spurious events, or glitches, can exceed the SNR threshold and occasionally pass the  $\chi^2$  test in the BNS inspiral search. As the interferometers' sensitivities continue to improve, the character of the data changes. The investigations into possible vetoes for the inspiral analyses will continue to evolve as the interferometers' performance changes.

For the S2 inspiral trigger studies we have eliminated problematic data using data quality checks and a coincident glitch veto. Data quality cuts eliminate high-noise data in H1 as well as photodiode saturations in all three LIGO interferometers. Based on preliminary investigations, the low-frequency cutoff for the BNS inspiral search was elevated to 100 Hz in order to avoid problematic non-stationary noise around 70 Hz. The L1:LSC-POB\_I channel provided a moderately efficient veto for the L1 interferometer, with a deadtime of 3%. No suitable veto conditions were identified for the H1 or H2 interferometers.

The BBH inspiral search is still being developed and tuned. Based on preliminary studies, either L1:LSC-POB\_I or L1:LSC-MICH\_CTRL appears to provide a useful veto, comparable in efficiency to the BNS case.

For future LIGO science runs we hope to gain a better understanding of the root causes of glitches. As the interferometers' noise decreases it is hoped that environmental causes of triggers will be clearly identified. It is likely that low-frequency environmental noise can cause higher frequency noise in the interferometer output through nonlinear coupling. We intend to use higher-order statistical measures, such as the *bicoherence*, as a means of monitoring the nonlinear up-conversion. Also, we hope to implement further inspiral waveform consistency tests [7] in order to eliminate false triggers that manage to pass the SNR threshold and current  $\chi^2$  test.

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