Gravitational wave burst vetoes in the LIGO S2 and S3 data analyses

Alessandra Di Credico†(for the LIGO Scientific Collaboration)
Physics Department, Syracuse University, Syracuse NY 13244, USA

Abstract.
The LIGO detectors collected about 4 months of data in 2003–2004 during two science runs, S2 and S3. Several environmental and auxiliary channels that monitor the instruments’ physical environment and overall interferometric operation were analyzed in order to establish the quality of the data as well as the presence of transients of non-astrophysical origin. This analysis allowed better understanding of the noise character of the instruments and the establishment of correlations between transients in these channels and the one recording the gravitational wave strain. In this way vetoes for spurious burst events were identified. We present the methodology we followed in this analysis and the results from the S2 and S3 veto analysis within the context of the search for gravitational wave bursts.

PACS numbers: 04.80.Nn, 07.05.Kf

1. Introduction

The Laser Interferometer Gravitational wave Observatory (LIGO) collected data during the years 2003 and 2004 in two distinct science runs: S2 (February 14, 2003 - April 14, 2003) and S3 (October 31, 2003 - January 9, 2004). Using this data a search for gravitational wave bursts was conducted and, for the S2 run, results are to be published soon 1. The search for gravitational wave bursts represents a great challenge for the data analysis, since it looks for signals that are very poorly (if at all) modelled and of unknown (although very short) duration. For most of the LIGO searches for bursts so far, the frequency range has covered the best sensitivity range for the LIGO detectors (100–1100Hz).

Several methods exist for the identification of candidate burst events in LIGO. In S2 and S3 the search result was obtained by using a wavelet-based algorithm called WaveBurst 2 3. WaveBurst identifies clusters of excess power in the time-frequency plane once the signal is decomposed in the wavelet domain. This Event Trigger Generator (ETG) processes gravitational wave data from two interferometers at a time. Following this event selection by WaveBurst we checked the consistency of the waveforms of the candidate events. This was done using the r-statistic 4, a

† on leave from Laboratori Nazionali del Gran Sasso (INFN, Italy)
time-domain cross-correlation method sensitive to the coherent part of the candidate signals.

2. Data Quality

A key first step in the search for gravitational wave bursts is establishing the overall quality of the data produced by the interferometers.

In both the S2 and S3 searches for bursts with LIGO, and given the sensitivity of the instruments, we limited our search in the 100–1100 Hz frequency regime. Within this frequency range there are still sources of non-gaussian noise, which especially affect the quality of the data when it is to be searched for burst signals.

Several algorithms running in real-time with the data acquisition (“monitors”) keep track of the statistical properties of the noise in the detectors. One such algorithm is the band-limited root-mean-square, BLRMS, monitor of a channel’s amplitude power within a frequency band. Several frequency bands are monitored and trends of the in-band power are continuously recorded. Data quality flags based on the BLRMS monitors executed on the gravitational wave channel as well as many other channels have been traditionally used to signal noisy or overall problematic data taking [5]. During S2, excursions of the BLRMS monitor running on the gravitational wave channel in the 4km Hanford interferometer (H1) were seen to be resulting from instabilities in the servo loops. A data quality cut based on this was derived and implemented in the S2 search for bursts. The cut selected instances when the BLRMS exceeded a threshold of 0.0002 ct$^2$/Hz in power over a five minute interval in H1 in the 200–400 Hz band. This cut resulted in a loss of live-time of $\sim$0.4%. No similar BLRMS excursions of the gravitational wave channels persisting over five minutes (or more) were seen during S3.

Calibration lines (fixed amplitude harmonic excitations) are continuously injected into the end test masses of the LIGO instruments during the science runs. This is in order to enable us to monitor the detector’s sensitivity and frequency response throughout a run. We require the calibration lines to be always present and their amplitudes strong enough so that the calibration of a gravitational wave strain measurement is reliable. During S2, this requirement reduced the triple coincidence live-time by about 2% and 2.4% in S3.

There are occasional losses of synchronization, timing issues, or overall data acquisition related problems that may result in loss of data. These affected overall small fractions of the instruments’ triple coincidence live-time, at the level of 0.3% in S2 and about 5% in S3.

The reduction of the noise floor of the LIGO instruments in the last two years has revealed previously invisible couplings with their physical environment. For this reason our veto search requires ongoing investigation.

One such coupling is of seismic origin: seismic activity is present in all detector locations but its effects on the gravitational wave channel were mostly noticed in the Hanford site. Its origin has been connected to human activity like gravel trucks
driving by the Hanford Observatory or natural phenomena like strong winds or local earthquakes. During S3 we observed elevated interferometer noise during long stretches of high seismic activity as identified by the BLRMS monitor. Looking at the output of a seismometer located in the corner building of the Hanford site, we set a flag when the seismic noise was too high. A cut derived from this flag reduced the S3 data by 1.3%.

Acoustic coupling of the LIGO instruments to their environment has been observed since the early engineering runs through the manifestation in the interferometric data of overflying airplanes or strong winds. Several microphones are located in the vicinity of the test masses, laser and output photodyodes. Elevated acoustic ambient noise is identified via a BLRMS excursion of power in these microphonic channels. In the case of overflying airplanes, the microphones record an additional typical Doppler shifted acoustic signature in the 50–100 Hz frequency range, with a duration of tens of seconds. A typical example of the signal recorded by one of the microphones in the vicinity of the Hanford instruments when an airplane is flying over the site is displayed in figure 1.

![Figure 1](image.png)

**Figure 1.** Spectrogram of the acoustic noise observed with a microphone located in the proximity of the Hanford detector, at the time an airplane was flying over the site.

The use of the ambient acoustic noise as a data quality cut was introduced in our S3 burst analysis. This is after the S2 search for bursts yielded a single candidate event that was found to be of acoustic origin in the Hanford detectors and was found to correlate perfectly and as expected from direct measurements with elevated acoustic power in the microphones. Between S2 and S3 significant work took place in order to reduce the acoustic coupling of the instruments. Although this resulted to 2 or 3 orders
of magnitude reduction of such coupling, it is still non-zero and for this the acoustic data quality cut is envisioned to be used in the search for bursts in S3 and beyond. For the S3 analysis a flag of acoustic noise was set whenever the band limited RMS, for the frequency band 62–100 Hz, exceeded a threshold value set independently at the Hanford and Livingston sites. This resulted in a live-time loss of less than 1%.

3. Event-by-event vetoes

After excising the data that fail the data quality cuts described above we analyze the remaining gravitational wave burst data with the burst-finding algorithms. The outcome of this search is candidate events that reflect the time-frequency and waveform consistency among signals in the three LIGO instruments. Since our first search for gravitational wave bursts [5], we have allowed in our search pipeline the incorporation of event-by-event vetoes. These vetoes are derived from environmental and auxiliary channels and indicate disturbances of non-astrophysical origin that couple to the gravitational wave strain channel.

Our analysis starts with a subset of the data, about 10% of the total, that is called “playground”. The concept of playground was introduced in the first LIGO analyses in order to look at a representative fraction of the data, define the analysis parameters there and then apply them to the rest of the data without introducing a bias.

Most of the results that we will show here are derived from triggers generated by the glitchMon and KleineWelle methods. glitchMon [6] is a time-domain transient-finding algorithm developed within the Data Monitoring Tool (DMT) environment. It allows the selection of times when a channel’s amplitude exceeds a user-defined threshold, either in absolute ADC counts or in units of amplitude rms. KleineWelle [7] is also developed within the Data Monitoring Tool (DMT) environment. It is a time-frequency method offering the multi-resolution approach of the wavelet decomposition. Within KleineWelle the time series is first whitened using a linear predictor error filter. Then the time-frequency decomposition is obtained through the Haar wavelet transform. The squared wavelet coefficients, normalized to the scale’s rms, provide an estimate of the energy associated with a certain time-frequency pixel. A clustering mechanism is then invoked, in order to increase the sensitivity to signals with less than optimal shapes in the time-frequency plane, and a total normalized cluster energy, $E_C$, is computed. This quantity, like the previous single pixel normalized energy, is $\chi^2$ distributed (for gaussian white noise). The significance $S$ of this cluster of pixels is then defined using the standard definition for a $\chi^2$ distribution with $N$ degrees of freedom:

$$S = -\ln \int_{E_C}^{\infty} \chi^2_N(E) dE$$

(1)

The significance is a function of the cluster energy and the number of pixels in the cluster, $N$, and is the parameter used in the threshold choice for the KleineWelle transient production.
The ultimate goal of the veto data analysis is to establish a correlation between spurious triggers in the gravitational wave channel and triggers in auxiliary channels, above the rate of accidental coincidences. For our purposes the coincidence is defined by the overlap of the gravitational wave trigger (thought of as a window of a given start time and stop time) with a trigger (thought of in the same way) from an auxiliary channel.

The central notions in analysing an auxiliary channel as a potential veto are the following:

- **efficiency**: this is the percentage of gravitational wave events which are vetoed by the auxiliary channel triggers,

- **use percentage**: this is the percentage of auxiliary channel trigger that veto a gravitational wave event,

- **dead-time**: this is the percentage of the instruments’ live-time reflecting the total duration of the auxiliary channel triggers,

- **accidental coincidences**: this is the number of overlaps between the gravitational wave and auxiliary channel triggers that may occur from pure chance,

- **safety**: this is the assurance that the coupling of the auxiliary channel to a genuine gravitational wave signal is null, or below a threshold of detectability.

Our search for vetoes includes the calculation of the above quantities for multiple auxiliary channels as well as for varying thresholds for both the auxiliary channel and the gravitational wave channel. Several plots and derived quantities starting with the above can guide us in making veto choices in a search. A channel with high efficiency and low dead-time is clearly desirable. In figure 2 we show a typical such plot for H2:LSC-PRC_CTRL (see below in subsection 3.2 for a description of this channel). The curve traces a total of 9 different thresholds of the auxiliary channel.

Another consideration in choosing a veto channel is the use percentage of its triggers: the higher being the better. The accidental coincidences between the gravitational wave and auxiliary channel triggers are evaluated by introducing artificial time shifts between the two trigger lists. This is shown in figure 3 for the case of H2:LSC-PRC_CTRL.

The above quantities are generally interconnected and a decision on the choice of a veto can not be readily automated. So far we have taken a conservative approach requiring potential vetoes to result in minimal dead-time (of order of few percent) with an efficiency of 10% or more. While this procedure is reasonable for an upper-limit search, a more inclusive approach in accepting vetoes is being examined in a detection-oriented search. Part of this direction includes the study of the efficiency of vetoes to reject outliers of single-interferometer gravitational wave triggers as well as basing choices and thresholds of vetoes on direct measurements of their coupling to the gravitational wave channel.

In order to assess the safety of potential veto channels, we have used a set of signals injected directly into the LIGO interferometers. This allows us to measure the coupling
Figure 2. Efficiency versus dead-time study for H2:LSC-PRC_CTRL. The empty diamonds refer to different choices of threshold for the transient significance: from right to left: 20,30,40,50,80,100,300, 400,500. The full circle refers to the threshold chosen in the S3 veto analysis.

Figure 3. Real coincidences appear at lag (time-shift) = 0 sec in this plot for H2:LSC-PRC_CTRL. Random coincidences are seen when the lag is either positive or negative of a veto channel to the gravitational wave channel or to establish an upper-limit to the coupling. This is essential for making sure that such veto does not reject an astrophysical event.

3.1. Vetoes in S2

The veto analysis for the S2 data considered several auxiliary channels, including those which track possible environmental signals. Most of these channels did not make good
Gravitational wave burst vetoes in the LIGO S2 and S3 data analyses

veto candidates as they showed efficiencies typically below 10%, accompanied by dead-times of around 5%. The most interesting candidate veto channel was found in the Livingston interferometer, L1:LSC-AS\_DC. This channel reads the DC level of the light output in the antisymmetric port of the instrument, and was observed to correlate with the gravitational wave channel through a non-linear coupling with interferometer alignment fluctuations. The efficiency level for this channel reached 15% with a dead-time of 5%, both of marginal interest for accepting it as a veto. In a conservative approach we decided not to use it in the S2 search.

3.2. Vetoes in S3

The study of vetoes in the S3 playground yielded a few auxiliary channels which presented an interesting correlation with the gravitational wave triggers. Among these were LSC-AS\_I for the 4km Hanford interferometer (H1) and LSC-PRC\_CTRL for the 2km Hanford one (H2). Both these channels show a veto efficiency above 10% and a dead-time of less than 1%.

The LSC-AS\_I channel is tightly connected to the gravitational wave channel (LSC-AS\_Q) as both of these signals are extracted from the antisymmetric port signal. LSC-AS\_I records the “In phase” part of the signal while LSC-AS\_Q records the “Quadrature phase”, the part of the signal directly related to the gravitational wave strain. Given the common source, small mixing between the two channels is possible, and the safety of the LSC-AS\_I channel must be established with special care.

The safety study on LSC-AS\_I has been conducted also by the inspiral search working group and has brought similar results: this auxiliary channel can be considered safe only when a threshold is imposed on the significance of the triggers and the ratio between the LSC-AS\_I and the gravitational wave trigger significances is above 0.5 [8].

In the burst veto search, when these safety conditions are applied, the efficiency of LSC-AS\_I reaches levels too low to be acceptable.

Another auxiliary channel that has shown interesting efficiency in vetoing the gravitational wave channel is H2:LSC-PRC\_CTRL. This channel is related to the power recycling cavity and monitors the feedback loop that keeps it in resonance. When a high-pass filter at 70Hz is applied to the signal, a good correlation between the transients observed in this channel and those seen in the gravitational wave channel has been observed. The highest veto efficiency reached with this auxiliary channel is of about 40%.

In Figure 2, values of efficiency versus dead-time for different significance thresholds are shown. The dead-time, computed considering only the duration of the lowest threshold transients, is about 2.4%.

The choice of the threshold for the veto channel is determined mainly by the dead-time and by the safety of the veto. Figure 4 shows the result of the safety study for H2:LSC-PRC\_CTRL. A few burst hardware injections signals were found in coincidence with low significance auxiliary channels transients. A conservative threshold of 200 has
Gravitational wave burst vetoes in the LIGO S2 and S3 data analyses

thus been chosen to guarantee the safety of the veto channel.

Figure 4. Veto safety study for H2:LSC-PRC_CTRL. Coincidences with reconstructed hardware injection signals are plotted as full triangles. Coincidences between the same auxiliary channel transients and the gravitational wave channel triggers are plotted as empty triangles.

The final choice for a veto to be applied to the S3 burst analysis is H2:LSC-PRC_CTRL with a significance threshold 200. This yields an efficiency of 12% and a dead-time of less than 0.5%.

4. Summary

During the S2 and S3 runs of the LIGO gravitational wave burst data analyses, an important effort has been made in order to find efficient ways to clean the data from known noise sources. Several methods to isolate poor quality data or select effective vetoes have been studied and applied in both analyses. In the S2 analysis case, no good veto was found. For the S3 analysis a veto has been proposed, based on the channel LSC-PRC_CTRL high-pass filtered at 70Hz, for the Hanford 2km detector.

Acknowledgments

The authors gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory and the Particle Physics and Astronomy Research Council of the United Kingdom, the Max-Planck-Society and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector. The authors also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the Natural Sciences and Engineering Research Council of Canada, the Council of
Scientific and Industrial Research of India, the Department of Science and Technology of India, the Spanish Ministerio de Educacion y Ciencia, the John Simon Guggenheim Foundation, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

References
[1] Abbott B et al 2005 Upper Limits on Gravitational Wave Bursts in LIGO’s Second Science Run. In preparation.
[2] Klimenko S, Yakushin I, Rakhmanov M and Mitselmakher G 2004 Class. Quantum Grav. 21 S1685
[3] Klimenko S and Mitselmakher G 2004 Class. Quantum Grav. 21 S1819
[4] Cadonati L 2004 Class. Quantum Grav. 21 S1095
[5] Abbott B et al (LIGO Scientific Collaboration) 2004 Phys. Rev. D 69 102001
[6] A code written by M. Ito - University of Oregon
[7] Chatterji S, Blackburn L, Martin G and Katsavounidis E 2004 Class. Quantum Grav. 21 S1809
[8] Christensen N (for the LIGO Scientific Collaboration) 2005 Veto Studies for LIGO Inspiral Triggers These Proceedings.