A powerful veto for gravitational wave searches using data from Virgo's first scientific run

T Ballinger for the LIGO Scientific Collaboration and the Virgo Collaboration

Physics and Astronomy, Carleton College, Northfield MN 55057, USA

E-mail: `mabizoua@lal.in2p3.fr`

Abstract. The use of vetoes generated from auxiliary channels suppresses most of the high amplitude noise triggers that impair gravitational wave (GW) burst and binary inspiral searches. During Virgo's first scientific run (VSR1), many of the remaining loud burst and inspiral Virgo triggers were observed with nearly equal significance in both the in-phase (ACp) and quadrature (ACq) interferometer output channels, while we expect the ACq channel to be insensitive to a GW signal. We describe a veto based on the ratio of the amplitude of the ACp and ACq signals. From studying hardware signal injections, we demonstrate that the ratio of the amplitude of coincident ACp and ACq triggers can be safely used to define a veto; we show its efficiency for the burst and binary inspiral analyses of the VRS1 data.

1. Introduction

The search for gravitational waves (GW) with a network of interferometric detectors (three LIGO detectors located in the United States and Virgo in Italy) has been carried out using the data acquired from October 2005 up to October 2007 by LIGO (run S5) and from May 2007 up to October 2007 by Virgo (run VSR1). Burst and compact binary coalescence (CBC) GW searches are very sensitive to short time noise disturbances, referred to as *glitches*, that can mimic genuine GW events. It is necessary to suppress these triggers by developing a veto strategy based on an understanding of the detectors' noise. The origin of a significant fraction of these glitches occurring in S5 and VSR1 has been determined. Periods of data of poor quality are marked by some data quality flags, and are then subsequently turned into vetoes. Some other vetoes are generated from auxiliary channels after checking the coincidence between glitches in the auxiliary channels and the GW channel. These two main sources of vetoes suppress most of the high amplitude noise triggers that impair gravitational wave burst and CBC analyses in VSR1 data [1].

However, many of the remaining loud burst and CBC Virgo triggers were observed with nearly equal size in both the in-phase (ACp) and quadrature (ACq) Virgo interferometer output channels, while we expect the ACq channel to be much less sensitive to a GW signal, provided that the demodulation phase is well tuned. A phase modulation on the laser light is applied before it enters the interferometer by an electro-optical modulator, generating sidebands on the carrier. As a consequence the signal associated with a relative arm length change will be detected as an event at the modulation frequency that is high enough (6.3 MHz) such that it will prevent the GW signal from being spoiled by laser power and electronic noises that dominate at low frequency. The photodiode currents are then subsequently demodulated in phase and in quadrature, and the signal from an arm length change is observed at its correct frequency in the recorded data. An error in the demodulation phase induces a small coupling of the GW signal with the quadrature channel. However, the ratio of the GW energy coupled into the two phases is expected to remain high. In other words, a real GW event will be seen with a SNR in ACp much higher than in ACq. On the contrary, ACq will be sensitive to glitches in signals which are related to interferometer common mode noise. It may happen that some source of noise can affect both quadrature signals with similar strength. This is especially the case for a dust particle crossing the laser beam before the output dark port photodiode where the beam is especially small in width.

The ratio between the two amplitude channels is expected to be proportional to $\frac{1}{sin(\delta\phi)}$, where $\delta\phi$ is the error on the demodulation phase [3]. Usually, the ratio of signal amplitudes ACp/ACq, which can be estimated using calibration signal at a fixed frequency, is in between 10 and a few hundreds. It has been previously proposed in GEO [2] and LIGO [3, 4] to use the ratio of energy seen in the two quadrature channels to reject false alarm events. Here, we examine such a veto. A critical point is to assure

that no real GW events would be suppressed; therefore one should develop a veto with a rather good security factor. To do so, we used the hardware signal injections to verify safety and develop the characteristics of this veto. The hardware injections are signals (simulating a GW waveform) that are artificially injected into the GW strain channel by applying a force on the input mirror of one of the interferometer arms' Fabry-Perot cavity. We report in this article the development and results for this veto obtained using VSR1 data.

2. Veto definition

A burst search wavelet algorithm, KleineWelle (KW) [5], has been used to generate triggers on both the ACp and ACq channels. Each trigger list contains the peak time and the significance of the trigger. The KW significance is defined through the assumption that the energy in a cluster composed of N wavelet coefficients follows a χ^2 distribution with N degrees of freedom. The threshold on KW significance has been chosen rather low in order to be able to detect the residual component of GW in the ACq channel when looking at high SNR hardware injections. Data quality vetoes [1] have been applied such that we do not consider in this study periods of time where known and identified problems occurred. Coincidence between ACp and ACq triggers within some time window, Δt, is required. A sharp coincidence between noise triggers in ACp and ACq is expected. However a 10 ms time window has been used in order to take into account the KW timing accuracy (a few ms). Furthermore, $\Delta t = 10$ ms maintains the coincidence of rather long (in time) and large (in SNR) triggers in ACp and/or ACq; for a long glitch the peak time might not be well defined. The ratio between the KW significance in the two demodulation phase channels, measured in coincidence, is

$$\kappa = \frac{SNR_{ACq}}{SNR_{ACp}} \tag{1}$$

For a real GW signal we expect to have $\kappa << 1$. On the contrary, coincident triggers with κ higher than a given threshold Σ should be considered as noise glitches. A veto is then defined by considering the time around coincident KW triggers whose κ is higher than Σ. Yet, since this *PQ veto* is designed to suppress high SNR events in the ACq channel that induce a transient in the GW channel, it is reasonable to consider only high significance ACq triggers. A threshold $\Theta > 10$ is applied on the ACq significance of the coincident triggers.

3. Validation using injected signals in the data

In order to both validate the safety hypothesis and decide which thresholds to apply on κ, data segments containing hardware signal injections are studied. The hardware injections that have been used were Sine Gaussian waveforms; seven different frequencies associated with the Sine Gaussians have been used (70, 105, 235, 393, 554, 850, 914 and 1304 Hz). The SNR of the injected waveform was 7.5, 15, 75 and 150. In total,

2561 hardware injections have been performed and used in this analysis. The low SNR injections (7.5) were not expected to produce a signal in the ACq channel detectable by KW despite the very low threshold applied on the KW triggers' significance. 76% of the hardware injections have been detected by KW in the ACp channel, but only 6% are seen in coincidence in the ACp and ACq channels.

We first look for hardware injection signals in the coincident ACp-ACq KW triggers by requesting that the time difference between the injected signal and the ACp trigger be smaller than 20 ms. Given the coincident ACp-ACq triggers rate, the number of accidental coincidence events due to the size of the coincidence time window is about 15 for the entire VSR1. Figure 1 shows the KW significance in ACp versus ACq of coincident triggers. On the same plot, triggers associated with a hardware injection are displayed. None of the hardware injection triggers have a KW significance higher in ACq than in ACp. The hardware injections whose reconstructed ACp significance is higher than 100 correspond to signals injected with a SNR of 75 and 150. Below a ACp significance of 100, some hardware injections of rather low SNR (15) are associated with a trigger in ACq. Those 19 triggers corresponds to accidental association due to the high ACp-ACq coincident trigger rate, and should not be considered in this study. Only the loudest hardware injections, with a SNR of 75 or 150, are strong enough to generate a signal in the quadrature ACq signal. The highest value of the ratio κ is 0.45, as shown in Figure 2. This is higher than what is expected (8%) if one assumes an error on the demodulation phase of 5 degres. We noticed that the highest κ values correspond to some of the loudest hardware injections (SNR = 150) whose ACp KW significance is $\sim$ 5 times smaller than the average value. We do not have a satisfactory explanation for these observations. However, we noticed that the ACp KW significance distribution is rather wide for the loudest hardware injections. Given that result, we determined that vetoing periods of time during which an excess of energy is seen in coincidence in the ACp and ACq channels with a ratio κ higher than 1 is safe and would not suppress a genuine GW event.

4. Veto construction

For the definition of the PQ veto, we considered all coincident ACp-ACq KW triggers whose ratio κ is higher than 1. Furthermore, only coincident triggers with an ACq significance higher than a given threshold (10) have been considered. This selection allows us to focus only on the periods of data where significant glitches in the ACq channel are observed (we are not interested in suppressing periods with low energetic glitches). The third parameter that has been considered is the veto time window size about the ACp-ACq coincidence time. The size of this window has to be large enough such that all glitches connected to a PQ event are really suppressed. Indeed, we have noticed that some of the glitches are so long (several hundreds of ms) that a large veto window is needed; a fixed 800 ms veto window has been applied in the definition of the PQ veto. It turns out that this veto window was large enough so that it could be adapted
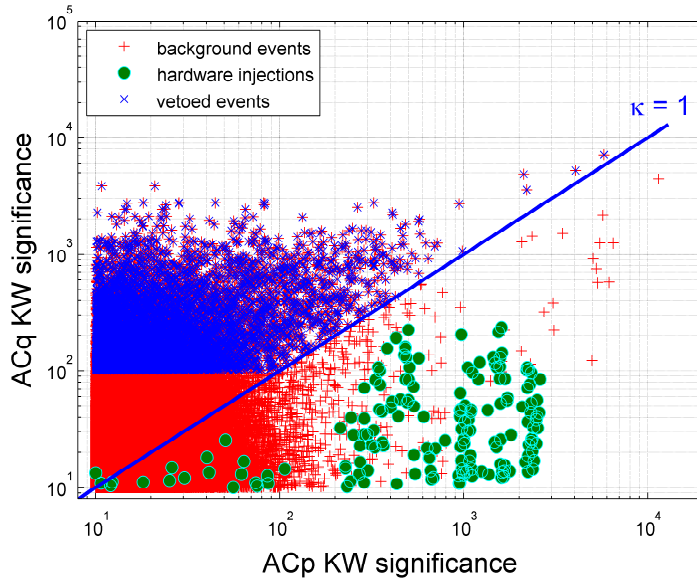
Figure 1. SNR of the coincident KW triggers in the two quadrature demodulated channels of the output dark port signal: ACp (in phase) and ACq (in quadrature). The time coincidence window of the triggers seen in the two channels is 10 ms. All other data quality flags have already been applied. The hardware injection signals, which were seen in both of the two demodulation phase channels, are indicated by the circles.
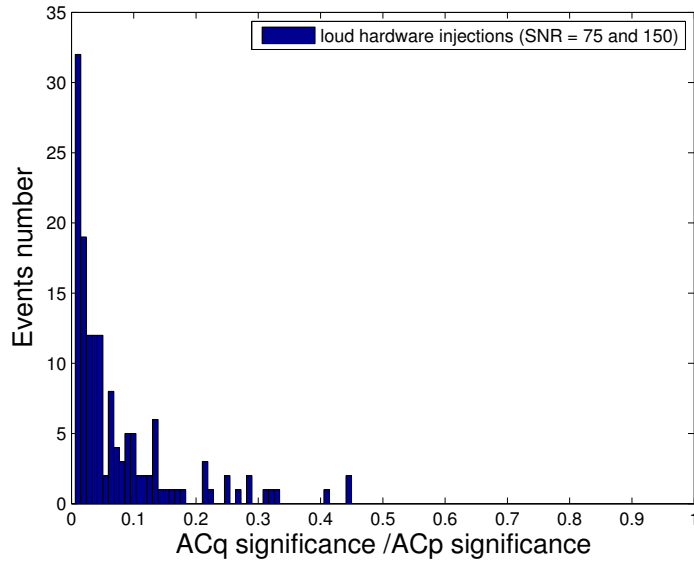

Figure 2. Ratio of the KW significance of coincident triggers seen in the in-phase GW channel ACp and the quadrature channel ACq. These KW triggers have been associated to the high SNR (75 & 150) hardware injections.

Burst	h(t) significance higher than	50	100	200
	PQ veto efficiency (%)	13	25	40

Table 1. Fraction of KW burst triggers suppressed by the PQ veto. The deadtime is 0.036 %, much smaller than the efficiency.

CBC	h(t) SNR higher than	8	9	10	11	12	13
	PQ veto efficiency (%)	9	21	33	38	43	45

Table 2. Fraction of MBTA triggers suppressed by the PQ veto. The deadtime is 0.036 %, much smaller than the efficiency.

both for the burst and CBC searches. We considered several values of the threshold on the KW significance of the ACq triggers, and decided to choose 100 and $\kappa = 1$. $\kappa = 1$ is the minimal value that we could consider given the safety results obtained in Section 3. The threshold on ACq has been chosen considering the ratio efficiency/deadtime. It should be noted, that keeping a high threshold on the KW significance of the ACq triggers allows one to concentrate the application of this veto on the loudest events, and thereby keeping the deadtime (and accidental coincidences) relatively low. This corresponds to a veto dead time of 0.036%, which is sufficiently small.

5. Application to burst and CBC analyses

Once defined, the PQ veto has been applied to triggers of several burst and CBC pipelines. We estimate the fraction of triggers louder than a given SNR that are effectively vetoed. In Tables 1 and 2, we report the PQ veto efficiency for KW [5] Virgo triggers (burst analysis) and MBTA (Multi-band Template Analysis) [6] Virgo triggers (CBC analysis)

For large SNR triggers, this veto has a very high efficiency. Furthermore, the deadtime is much smaller than the efficiency, demonstrating the significance of the veto. Despite the fact that the PQ veto only corresponds to a relatively small number of triggers, almost half of the loudest remaining triggers after all other data quality flags and vetoes have been applied can be suppressed by this veto. This demonstrates its usefulness for the burst and CBC analyses. Figure 3 shows the SNR distribution of the MBTA triggers before and after the application of the PQ veto.

6. Conclusions

We have developed for the VSR1 data a veto to suppress glitches that show up with more energy in the quadrature than in the in-phase interferometer output channel. We demonstrated using hardware injections that the veto is safe with respect to a real GW event. Furthermore, the deadtime of the veto is very small and it suppresses half of the
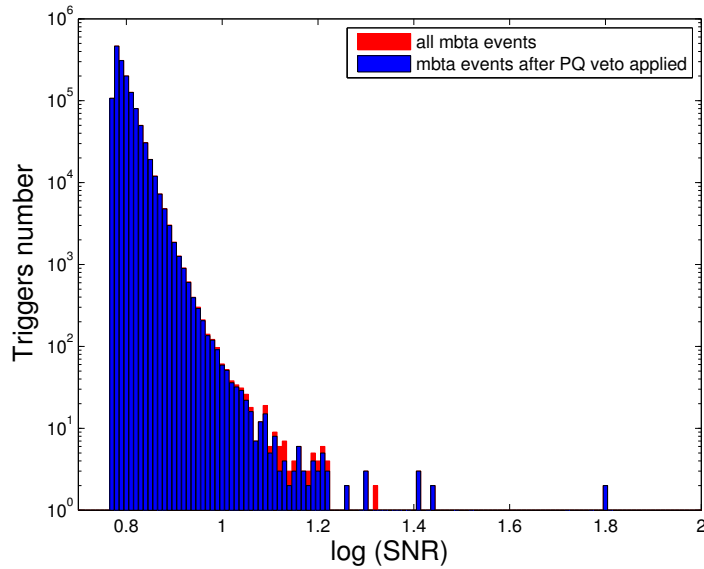
Figure 3. Distribution of the SNR of the MBTA Virgo triggers before the application of the PQ veto (red) and after the veto is applied (blue). All other data quality flags and vetoes have been applied.

remaining loudest Virgo triggers in the burst and CBC pipelines after all the other data quality flags and vetoes have been applied. This veto is being considered as a powerful way to reduce loud glitches in Virgo and thus the rate of the LIGO-Virgo accidental coincidences.

References

[1] N Leroy for the LIGO Scientific Collaboration and Virgo Collaboration, these proceedings.
[2] K Koetter, I Heng, M Hewitson, K Strain, G Woan and H Ward, Class. Quantum Grav. **20** S895-S902 (2003).
[3] C R Hanna (for the LSC Collaboration), Class. Quantum Grav. **23** S17-S22 (2006).
[4] N Christensen (for the LSC Collaboration), Class. Quantum Grav. **22** S1059-S1068 (2005).
[5] S Chatterji et al, Class Quantum Grav. 21, S1809 (2004).
[6] F Marion et al, Proceedings of Les Rencontres de Moriond 2003, Ed. Frontiers (2004).