Data Quality Studies of Enhanced Interferometric Gravitational Wave Detectors

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Abstract. Data quality assessment plays an essential role in the quest to detect gravitational wave signals in data from the LIGO and Virgo interferometric gravitational wave detectors. Interferometer data contains a high rate of noise transients from the environment, the detector hardware, and the detector control systems. These transients severely limit the statistical significance of gravitational wave candidates of short duration and/or poorly modeled waveforms. This paper describes the data quality studies that have been performed in recent LIGO and Virgo observing runs to mitigate the impact of transient detector artifacts on the gravitational wave searches.

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1. Laser Interferometers and Data Quality

Laser interferometer gravitational wave detectors are designed to measure small variations in the relative separation of mirrors at the ends of two perpendicular arms, corresponding to gravitational wave strain [1]. In the course of these studies, a global network of *enhanced* gravitational wave detectors, Enhanced LIGO and Virgo+, were jointly taking data. The enhanced era science runs provided an opportunity to test ground-breaking detector technology and improve the detectors' sensitivity in preparation for the *advanced* detector era [2]. The network was composed of two Laser Interferometer Gravitational wave Observatory (LIGO) detectors in Hanford, WA and Livingston, LA each with 4 km arms, and the Virgo detector, with 3 km arms, in Cascina, Italy. During LIGO science run 6 and Virgo science runs 2 and 3, the detectors were capable of measuring differences in length up to one part in 10^{21} [3, 4], which is roughly the strain expected from transient gravitational wave sources such as binary black hole inspirals.

Such gravitational wave signals can be easily masked or mimicked by transient noise, and a wide variety of transient noise sources have been observed in LIGO and Virgo data. *Auxiliary channels*, with data from sensors monitoring environmental and instrumental variables that are not sensitive to gravitational waves, are useful in identifying non-astrophysical noise sources. For example, environmental auxiliary channels monitor variables such as seismic motion, changes in local magnetic field, and acoustics at key locations that house the most sensitive equipment within the detectors. Similarly, instrumental auxiliary channels monitor systems such as laser beam alignment, laser stabilization, and mirror suspension and control.

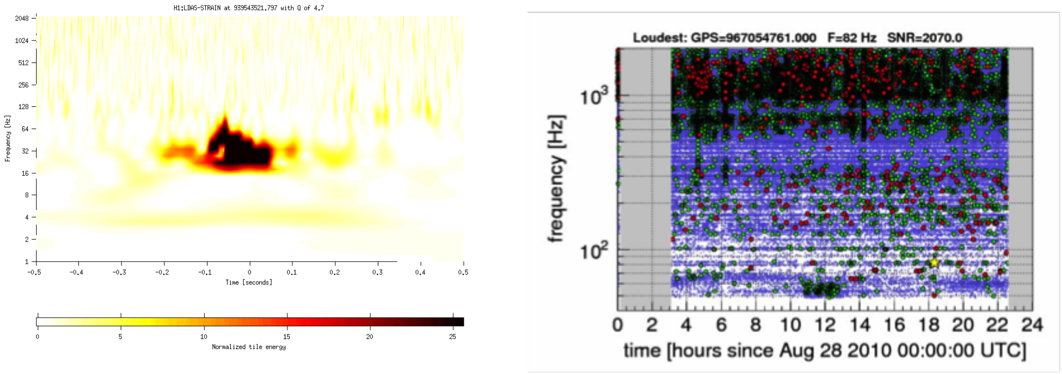
Data quality studies, which often make use of auxiliary channels, are necessary to mitigate noise transients in the gravitational wave channel, allowing for searches to probe deeper into space and in the case of non-detection, to set more stringent upper limits. Noise transients are especially troublesome in searches for gravitational waves produced by short duration compact binary coalescence (CBC) and burst sources. CBC searches use a templated matched-filter analysis, which requires candidate events to match a template of known waveforms in addition to coincidence [5]. The search for bursts is an unmodeled and largely unconstrained analysis, and the multi-detector burst analysis pipelines look for excess power in the signal that is coincident and coherent between detectors [6, 7] .

2. Introduction to Noise Transients: Characteristics and Impact

Noise transients in the gravitational wave data channel are characterized by their signal-to-noise ratio (SNR), central frequency, and spectrogram morphology. These characteristics are used to identify *populations* of noise transients that share similar traits.

Figure 1a illustrates a spectrogram of a noise transient as seen by a low-latency single interferometer search algorithm, Omega, which interprets excess transient noise as a set of triggers, each with an assigned central time, frequency, and signal to noise ratio (SNR) [8]. The transient from figure 1a would be seen as a single red dot in the time series plot in figure 1b, which shows the time frequency distribution of triggers over one day of data. Transients of this type would occur roughly once every few minutes, depending on the conditions of the day shown.

The panels in figure 2 provide some context for the loudness of noise transients and how often they occur. Column a shows what is considered a "good" day, when there was a low-to-normal rate of noise transients, and a "bad" day, when there was a high number of noise transients. There is a factor of 15 difference in the rate of loud (SNR >10) noise transients from the "good" day to the "bad" day. When the interferometers are performing optimally, one could expect to see roughly one noise transient with an SNR >10 every couple of minutes, which is still significantly higher than the predicted Gaussian noise curve shown in blue in the rate histograms of figure 2. How often "bad" days occur depends largely on external factors - there are a large number of potential sources of loud or frequent noise transients in the detectors, including (but not limited to) bad weather, nearby train, truck, or air traffic, fluctuating magnetic fields



(a) Spectrogram of a noise transient

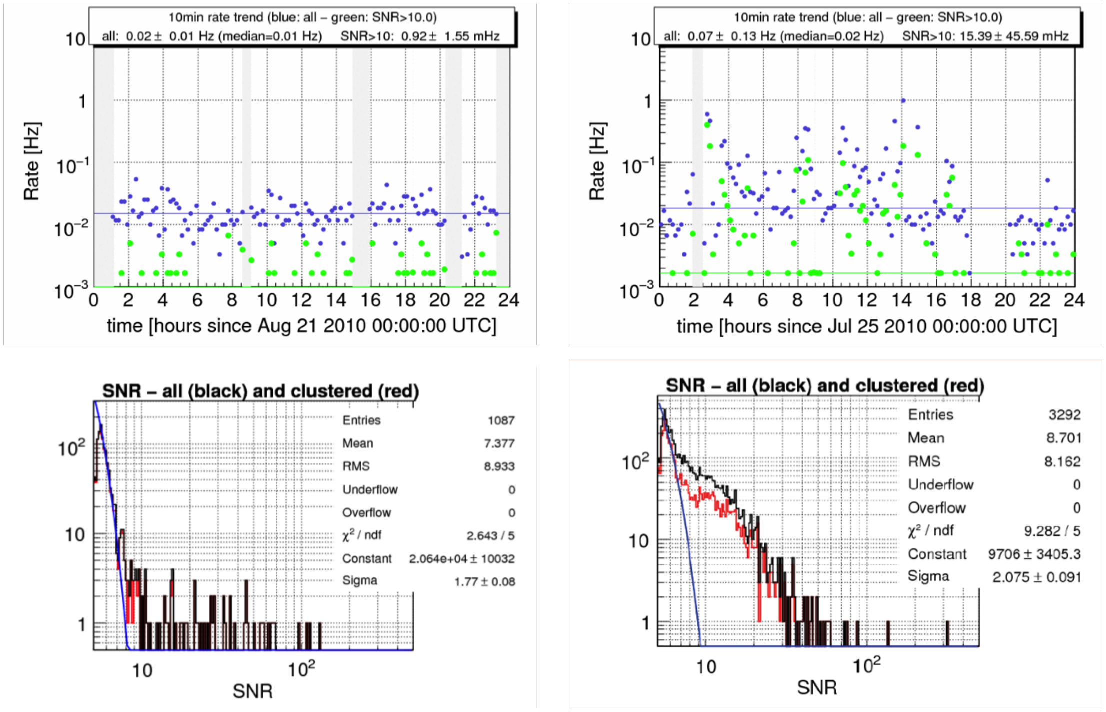
(b) Noise transient time series

Figure 1. *(a) An example spectrogram depicting a noise transient in the gravitational wave data channel of the Hanford LIGO detector during the 6th LIGO science run, as seen through one of the single detector search algorithms, Omega [9, 8]. Here color represents energy (with white being the lowest and red the highest. (b) An example time-frequency plot of noise transients in the Virgo gravitational wave data channel as seen by Omega. The smaller blue points represent lower SNR transients (>5), and green and red represent progressively higher ranges of SNRs (>10, >20).*

around equipment, seismic noise, digital signal processing artifacts, or malfunctioning equipment.

The first line of defense against a noise transient masquerading as a potential gravitational wave signal is requiring coincidence or coherence between interferometers in the global network. However, noise transients do occur frequently and loudly enough to affect the searches, even when coherence is required. In figure 3, a histogram of triggers (transient noise events) as seen by a Coherent WaveBurst, an unmodeled search algorithm requiring coincidence and coherence between detectors [10], is overlaid on a histogram of triggers seen by the single interferometer unmodeled search algorithm Omega. This illustrates the reduction in sensitivity to noise transients that requiring coincidence and coherence can achieve, and also which SNR range of single detector triggers has the most impact on coherent unmodeled searches; in this case, a solid population of triggers with an SNR <20 and a few triggers with an SNR up to 200.

Each search is affected differently by noise transients. For example, the templated match-filter based search is primarily affected by loud noise transients or noise transients that mimic the template forms, while the unmodeled search requiring coincidence is more affected by very frequent noise transients, which are more likely to be coincident. It is the responsibility of the LIGO and Virgo detector characterization groups to limit the impact of these noise transients as much as possible, using methods outlined below.



(a) “good day” (b) “bad” day

Figure 2. *Rate time series (above) and histograms (below) of triggers produced by a single detector algorithm that identifies excess power in the time frequency domain, Omega. Blue dots represent triggers of all SNRs and green dots represent triggers of SNR >10. The histograms compare the daily trigger rate for triggers of all SNR (the black mean line) and ”clustered” triggers of SNR >10 (the red mean line) to the expected Gaussian distribution, in blue. On a “good” day, the trigger distribution is much closer to Gaussian. The “good” and “bad” days were each taken from different periods of the S6 run in the LIGO Hanford detector, but have comparable detector livetime.*

3. Methods Used to Abate Noise Transients

Noise transients are generally dealt with in one of two ways. Ideally the data quality team tracks down the source of the noise and/or the coupling mechanism to the gravitational wave data channel, and the collaboration uses this input to fix the problem. Failing that, the second option is to cut the “bad” parts out of the data, which also reduces the overall data duration time available for the analysis.

3.1. Identification of noise transient sources

The detector characterization group focuses on populations of noise transients that are troublesome for astrophysical searches, generally far outside Gaussian noise behavior. Sources of noise transients can vary wildly from external/environmental factors such as ocean waves, to equipment malfunction such as loose wire contacts. We can use the characteristics of the noise transients as clues to help track down the corresponding

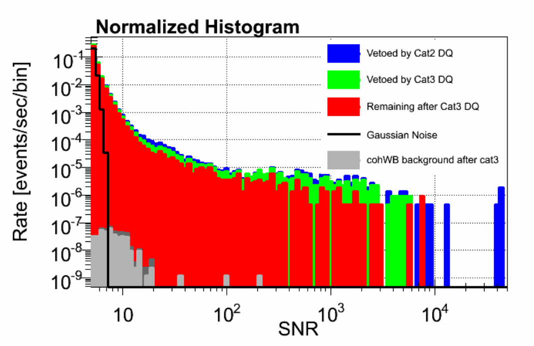


Figure 3. *The topmost group of red, green, and blue triggers are seen by the Omega pipeline and are pictured after various levels of data quality flags have been applied. The bottom set of grey triggers represent the search background of an unmodeled search requiring coincidence and coherence between detectors, produced using time slides [10]. These plots are used to determine which trigger SNR populations most impact the astrophysical searches. This figure also illustrates a great reduction in the rate of noise transients by constraining the search to require coincidence. Further improvement can be obtained by requiring candidate triggers to match a modeled waveform [5, 6, 7].*

noise source. There are also many examples of environmental noise sources coupling to the gravitational wave data channel via instrumental imperfection or malfunctioning. For example, scattered light due to flaws in optical components is a mechanism through which seismic noise couples into the data.

The data quality teams routinely check noise transients for coincidence with the detector's auxiliary channels. Algorithms such as Hierarchical Veto [11] and Used Percentage Veto [12], produce statistical results ranking the coupling of auxiliary channels with the gravitational wave data channel on a daily or weekly basis. These suggest which channels or families of channels are the most closely associated with noise transients during that time - a helpful tool in noise mitigation.

3.2. Data Quality Vetoes

While ideally all sources of noise transients would be identified and corrected in hardware, in practice this is not possible and we deal with them as we analyze the data by vetoing bad times. *Data quality flags* mark second integer periods of time when a detector is suffering from a known problem or a period of questionable data quality. Searches assign flags to categories that dictate how the flag is to be used [13].

- Category 1 flags veto instances when a serious problem with the detector occurred, or the detectors were not taking data in the design configuration. This data is removed prior to running the analysis.
- Category 2 flags veto times when a well understood problem with demonstrated coupling into the gravitational wave data channel occurred. These events are

removed before the analysis searches for statistical significance.

- Category 3 flags veto intervals when an incompletely understood or defined problem occurred. This data is not used when setting astrophysical limits.

Automatically produced, or *online*, data quality flags are generated in near real-time (within a few minutes) when some condition on a measured environmental variable or auxiliary channel is met. Some example conditions are wind at the detector site being over 30mph, or data occurring a certain amount of time (10, 30, 60, or 120 seconds) before a loss of interferometer lock. A goal of the data quality groups is to produce as much of the data quality flag information as possible online, but so far the LIGO low latency online data quality flags remove only a small fraction of noise transients.

There are also flags automatically produced with a week latency by the aforementioned statistical ranking algorithms (hierarchical veto and UPV). These flags produce vetoes of sub-second time intervals that target individual noise transients.

The most effective flags are generated offline to target troublesome populations of noise transients. These are usually finalized after a noise transient population has been studied, and some external condition or auxiliary channel is identified as being able to "predict" these noise transients. If the feature is recurring, these flags are eventually made into online data quality flags. Figure 7 illustrates the improvement in noise transient reduction seen for the S6 LIGO Hanford after applying targeted offline data quality flags.

3.2.1. What makes a suitable flag Data quality flag performance is estimated by applying the flags, which correspond to segments of time, to the output of a search algorithm run on a single detector, such as Omega, which produces triggers with a central time, frequency, and SNR. The standard quantity used to determine data quality flag performance is the ratio:

$$\kappa = \varepsilon / \tau$$

where ε, or efficiency, is the percentage of total triggers the flag removes during the analyzed time period, and τ, or deadtime, is the percentage of analyzed total time the flag removes. For example, in an analyzed data segment containing 500 triggers in 1000 seconds, we might find a flag catches 200 of the triggers, or has 40% efficiency, and removes 50 seconds, or has 5% deadtime. Then this flag's efficiency over deadtime ratio would be 8, and this flag would probably be used as a category 2 or 3. By the same standard, if a data quality flag was selecting triggers at random, we would expect its efficiency over deadtime ratio to be around 1.

Different searches might set different thresholds on this ratio for a suitable data quality flag considering not only the efficiency over deadtime ratio, but also the total deadtime. In the previous example, even though the flag had a high efficiency over deadtime ratio, a search team might choose not to use it as a category 2 because the flag's deadtime (search livetime lost) exceeds what is considered an acceptable threshold.

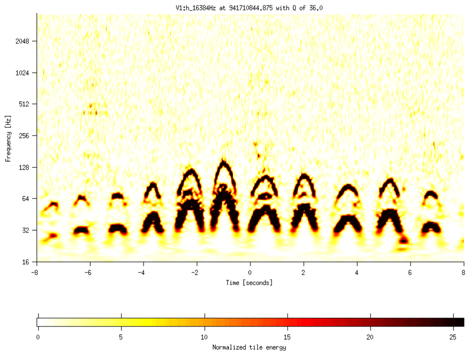


Figure 4. *Time-frequency plot of the strain signal over a 16 second period around the time of the micro-seismic glitch*

3.2.2. Testing for safety A data quality flag is considered *safe* if it does not veto gravitational wave signals based on the conditions of the flag. To test the safety of a veto we use *hardware injections* that are injected into the data by applying forces on the interferometer mirrors to induce a differential arm motion that mimics the effect expected from gravitational wave signals [14] over a wide range of waveforms and SNRs.
As the flags are analyzed for their κ ratio, they are also tested for safety. If a data quality flag is coincident with injected signals with less frequency than random chance, it is considered safe [12]. If a flag fails this test then the team will do a follow-up. Because injections during the most recent science runs have only been done for roughly ten injections per day, the safety evaluations are made with small statistics. For example, a flag with very small deadtime that catches 1 injection when Poisson statistics predicted it would catch 0.5 would not necessarily be deemed "unsafe". Follow-ups are performed for these marginal cases and take other factors into consideration, e.g. if the flag is catching lower or higher SNR injection signals.

4. Results and Examples

This section provides examples of data quality flags used for the analysis of data from Virgo+ and Enhanced LIGO, and presents the overall data quality flag performance results for the three interferometers.

4.1. Virgo+

A problematic glitch population during VSR2 was *micro-seismic* noise transients caused by light back-scattering from optical components in contact with the ground, making their dominant low frequency motion micro-seismic. Such noise is clearly identified in spectrograms as arches with peak frequency proportional to the velocity of the scatterer motion (see figure 4) [15]. Virgo implemented an efficient seismic data quality flag to

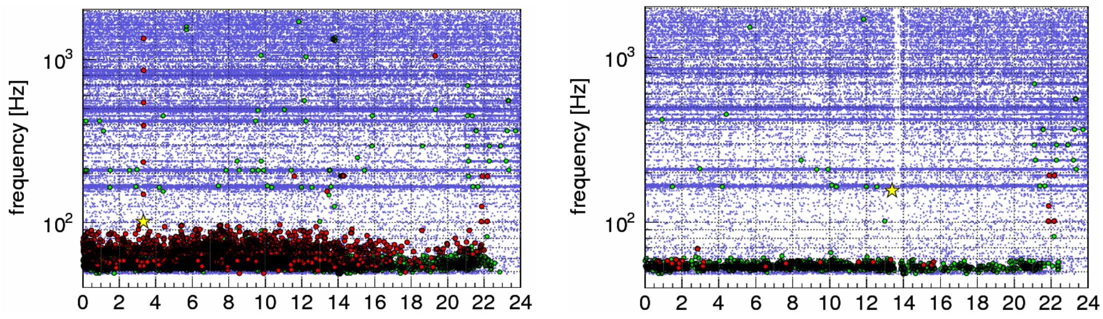


Figure 5. *Omega triggers in time-frequency before and after the event based micro-seismic data quality flag has been applied*

Categories:	cat1+2	cat1+2+3
Efficiencies:	54.2%	80.8%
Deadtimes:	6.2%	11.6%

Table 1. VSR2 data quality flag performance for trigger SNR >8

Categories:	cat1+2	cat1+2+3
Efficiencies:	19.3%	27.2%
Deadtimes:	4.2%	8.8%

Table 2. VSR3 data quality flag performance for trigger SNR>8

veto such noise transients (see figure 5), but its performance is weather dependent and the flag introduces a large dead-time in bad weather conditions. Its overall performance over the VSR2 run, on Omega triggers with SNR > 8, was an efficiency of 26.6% with a deadtime of 1.7%. The efficiency increased to 29.5% for noise transients with central frequency below 100 Hz, which is the population containing most of the micro-seismic glitches [16].

The Virgo data quality flags' performance was estimated using the percentage of Omega triggers vetoed by category 1 and 2 or category 1, 2, and 3 data quality flags (see table 1). The results for VSR2 were good - most of the loudest glitches in VSR2 were vetoed. Figure 6 shows the VSR2 Omega trigger SNR distribution before and after cat1, 2,and 3 data quality flags have been applied. The moderately worse VSR3 performance (table 2) is mainly due to a high rate of noise transients in the first weeks of the run, caused by a high level of diffused light at the output of the Virgo interferometer.

4.2. Enhanced LIGO

One of the more successful flags during Enhanced LIGO was the *Seisveto* flag applied to Hanford science run 6 (S6) data [17] . This flag targeted seismic noise that increased the tails of the background distribution in the transient astrophysical searches.

The Seisveto flag produced the highest efficiencies during enhanced LIGO, with a 4.5% deadtime, 28% efficiency, and a κ of 6.2 on LIGO Hanford data triggers with an SNR >20 during the last epoch in S6 (known as "S6D" and lasting about 4 months). However, it was only applied as category 3 to the unmodeled search due to its high deadtime.

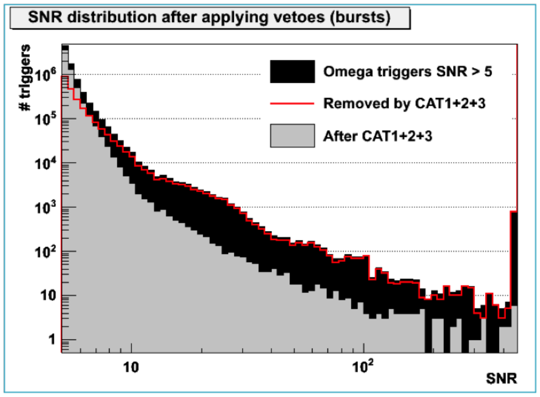


Figure 6. *VSR2 Omega trigger SNR distribution before and after data quality flags have been applied.*

Categories:	cat1+2	cat1+2+3
Efficiencies:	3.8%	39.8%
Deadtimes:	0.3%	16%

Table 3. LHO S6D data quality flag performance for trigger SNR >8 as defined by the burst (unmodeled) analysis

Categories:	cat1+2	cat1+2+3
Efficiencies:	1.7%	29.4%
Deadtimes:	0.7%	14.3%

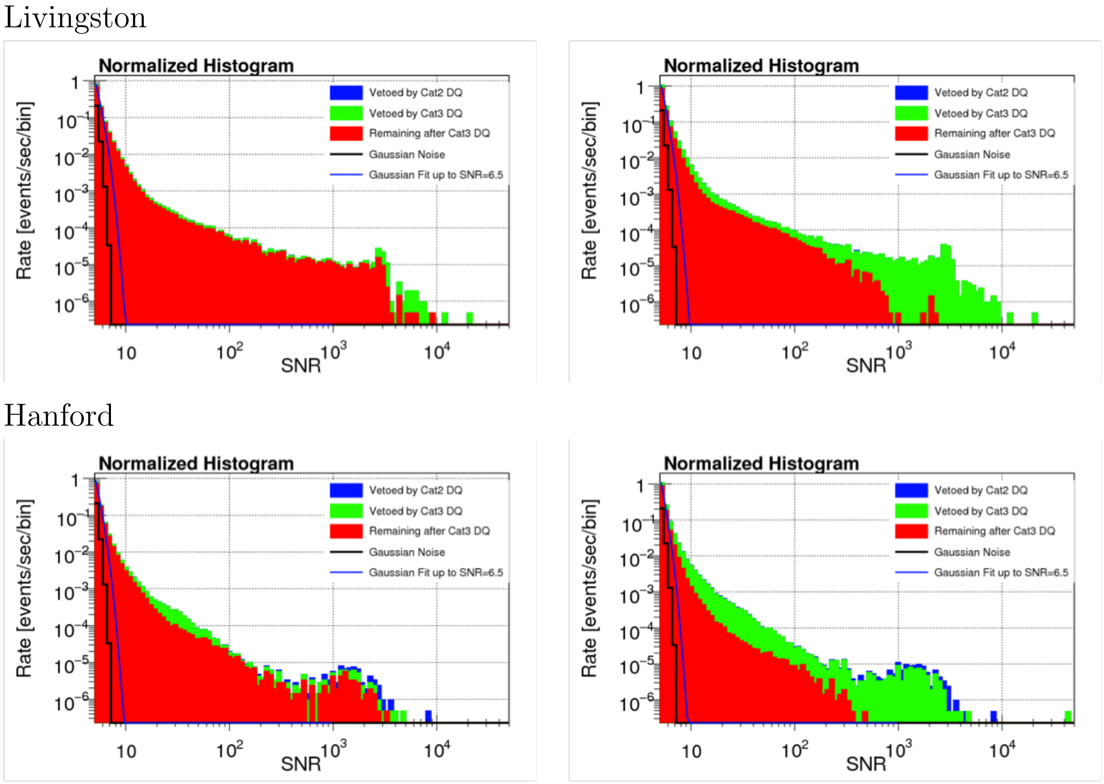
Table 4. LLO S6D data quality flag performance for trigger SNR >8 as defined by the burst (unmodeled) analysis

The enhanced LIGO detectors performed with the least frequent and quietest noise transients during S6D [18]. Comparing these to the first S6 epoch (S6A) plot in figure 3, not only has the data quality flags' impact drastically improved, but the rate of noise transients have also improved over the course of S6 (see figure 7). The overall efficiency over deadtime ratios were not optimal during this period (see tables 3 and 4), however the S6 data quality flags performed far better on high SNR triggers. Category 3 efficiencies approached 100% for triggers of SNR >1000 for both of the LIGO detectors. The category 2 and 3 flags also removed most of the high SNR trigger population, which was problematic for the searches (see column b of figure 7).

5. Data Quality in the Advanced Detector Era

The LIGO and Virgo collaborations have made progress in noise transient abatement during the recent science runs. LIGO and Virgo's online veto production provided fairly good results in the latest science runs, but the majority of glitch populations remained unexplained and/or unvetoed, motivating the development of new vetoing tools in preparation for the next era of detectors.

LIGO is currently being upgraded to Advanced LIGO, and Virgo is just starting its Advanced configuration installation. The Advanced detectors will be quantum-noise-limited interferometers, with a large improvement in strain sensitivity. Studies predict



(a) Online data quality vetoes applied (b) Online and targeted data quality vetoes applied

Figure 7. *LIGO Omega trigger SNR distribution during S6D. The difference between columns (a) and (b) illustrates the effectiveness of targeted data quality vetoes vs. online vetoes. Both columns (a) and (b) exclude event based vetoes.*

that Advanced LIGO and Advanced Virgo should routinely detect gravitational waves from astrophysical sources [19].

Advanced era data quality studies will aim to provide low-latency and reliable information. This means to optimize the efficiency over deadtime ratios of data quality flags, develop new vetoing tools, and continue to explore and implement new techniques for targeting noise transients.

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