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LIGO S6 detector characterization studies

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Abstract
LIGO recently commenced its sixth science run (S6) simultaneously with Virgo starting its second science run (VSR2). Because of differing interferometer configurations with respect to S5, much effort has been invested understanding new sources of noise in the LIGO S6 interferometers. The LIGO Scientific Collaboration's detector characterization working group is actively investigating the origin of noise in the LIGO interferometers and determining the periods of good, bad or questionable data quality. We describe the instrumental issues found to affect the data quality in S6 and the vetoes developed for burst and inspiral searches. The methods used to search for and identify periodic noise lines are also presented. A summary of other noise search efforts in S6 is also given.

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

1. Introduction

The LIGO [1] and Virgo [2] gravitational wave interferometric detectors are presently operating at or near their initial design sensitivities. LIGO's sixth scientific run, S6, and Virgo's second scientific run, VSR2, commenced on 7 July 2009. GEO 600 [3] is also participating in this run. The LIGO Scientific Collaboration (LSC) and the Virgo Collaboration are working together during S6/VSR2 in their effort to detect binary inspiral [4, 5], burst [6, 7], continuous wave (CW) [8, 9] and stochastic background [10, 11] signals, as well as gravitational waves associated with electromagnetic (such as gamma ray burst) events [12, 13]. We refer to the 4 km arm-length LIGO detector at Hanford, WA, as H1 and the 4 km detector at Livingston, LA, as L1. Note that the 2 km detector at Hanford, H2, did not operate during S6.

In addition to looking for gravitational wave signals, much effort must be expended in identifying and characterizing the numerous *events* that arise from mundane instrumentation

[1] A list of members of the LIGO Scientific Collaboration and the VIRGO Collaboration can be found at the end of this issue.

faults or environmental disturbances. Hundreds of interferometer control and auxiliary channels are recorded, and all of these signals are analyzed so that associations can be monitored between events in these channels and the gravitational wave strain signal $h(t)$. Channels that record interferometer signals (servos for interferometer and laser locking, suspension, alignment, etc) are particularly useful for observing the generation of noise from within the detector itself. Also, at each of the observatory sites, the interferometers are supplemented with a set of sensors to monitor the local environment. Seismometers and accelerometers measure vibrations of the ground and of various interferometer components; microphones monitor acoustic noise at critical locations; magnetometers monitor magnetic fields that could couple to the test masses via the coil drivers or electronics; radio receivers monitor radio frequency (RF) power around the laser modulation frequencies; voltage line monitors record fluctuations of the ac power. These physical environment monitoring (PEM) devices are used to detect environmental disturbances that can couple to the gravitational wave channel. The PEM devices are placed at strategic locations around the observatory, especially near the corner and ends of the L-shaped interferometer where important laser, optical and suspension systems reside. Careful analysis of data from the PEMs can help to identify noise that is originating from the environment around the detectors.

In this paper we describe the effort by which the quality of the LIGO S6 data is judged and how deleterious times are determined and then *flagged* as problematic. In addition, we describe the means by which periodic noise lines are searched for and identified. A similar data quality (DQ) examination effort has been conducted with respect to VSR2 data [14, 15]. Here we describe the means by which LIGO defines various DQ flags for the analysis of S6 data and how these DQ flags are ranked and applied. The method used in S6 to judge the quality of the data is similar to how LIGO conducted its DQ studies with S5 data [16, 17]. LIGO implemented a number of new systems in S6: a dc readout of the output of the interferometers, an output mode cleaner, in-vacuum seismic isolation systems, increased optical power (10 W to 35 W) and consequently a more substantial CO_2 laser system (8 W to 25 W) to correct for mirror thermal deformations [18]. With new systems there inevitably come new noise sources and hence the need for rigorous S6 detector characterization studies. It should be noted too that the results reported in this paper represent the output from dozens of researchers in the LSC who are hunting down noise sources at the sites and comprehensively examining the vast quantity of data originating from the interferometers, their control systems and the environment at the observatories.

The LSC and Virgo signal search groups *veto* data in different ways. CW signal detection is particularly susceptible to noise sources that produce a periodic signal with a constant (or relatively constant) frequency; these same noise lines can also affect the search for a stochastic gravitational wave background. The LIGO effort to find periodic noise lines, and locate their source through observations of PEM signals, is accomplished through the use of CW search codes applied on $h(t)$ and PEM channels, as well as the coherence between $h(t)$ and PEMs [19]. The coalescing binary and burst search groups find that short instantaneous *glitches* can complicate their data analysis tasks and produce a background of events that can potentially mask real signals. The development of vetoes based on interferometer control and PEM signals has been an important activity for the S1 through S5 search efforts [20–22] and continues to be so during S6/VSR2 [23].

The organization of the paper is as follows. In section 2 we describe the procedure for defining S6 DQ flags. The process by which vetoes are defined for the S6 coalescing binary and burst searches is presented in section 3. The method by which the source of S6 noise lines is found is summarized in section 4. Other examples of noise search efforts used during S6 are described in section 5. A summary is given in section 6.

2. Data quality flags

Defining DQ flags is an important activity performed by a number of researchers within the LSC's detector characterization group and the glitch working group [17]. DQ flags typically exclude sections of data with lengths of a second to many seconds when there is a reason to believe that the detector is behaving badly. As a comparison, vetoes (especially for the coalescing binary and burst searches) typically cut out hundreds of milliseconds to 1 s based on auxiliary channel *triggers*. The DQ flags are organized in various categories depending on the severity of the associated problems (category 1 being the most severe, down to category 3 being the least) and how well we can determine the origin of the problems; see [16] for a complete description of the classification of the different DQ categories. The category 4 flag refers to the periods of time containing artificial signals injected into the interferometers via so-called hardware injections.

DQ flags are created in a number of different ways. In S6 the scientific monitors (Scimons) in the interferometers' control rooms have been asked to be more active in flagging problematic times that they observe during their shifts. During S6 the LSC Scimons have been required to spend a minimum of a week at the observatory sites for their shifts so that they can become more closely tied to detector characterization efforts. Consequently, Scimons have defined numerous DQ flags based on their direct observations of events at the sites. These flags are reviewed by the detector characterization group and used like *online* DQ flags (i.e. those created automatically using computer programs searching for known problems) when indicated.

Many S6 flags are created in a very similar way to how they were defined in S5 [16, 17], and as a result the technology associated with creating similar DQ flags carried over to the current run. Some of these flags are then able to be defined online based on auxiliary channel monitoring. For example, there are flags defined to control channel overflows, calibration line dropouts and light dips (due to a brief misalignment) in the power in Fabry–Perot cavities of interferometer arms [16]. Signals from PEMs are critical in defining other DQ flags: microphones register airplanes flying overhead, seismometers and accelerometers detect seismic activity or loud human-made events (trucks, trains, logging) and magnetometers detect thunderstorms and large fluctuations in the mains power supply.

Further analysis of the data by the LSC's detector characterization group has then resulted in the definition of other flags. As an interesting example, consider the *Autoburt* flag. It was observed that early in S6 in H1 there were events (glitches) coinciding with the hourly back-up of computers at the observatory. A DQ flag was created with a fairly large deadtime (percentage of data excluded by the flag) of 9.5%. The problem was then subsequently corrected by only backing up the computers at Hanford when H1 was out of *science mode* (science mode is the time when the interferometer is locked, operating properly and collecting quality data).

As S6 progresses there continues to be active work to create DQ flags for various problems. For example, there are noise events that may (although a definitive association has yet to be made) be created in the output mode cleaners (OMC), which are a new addition in S6 to the interferometer design [18]. Glitches from OMC photodiode saturations were coincident with 20–30% of H1 events in early S6. The computer code mediating communications between the OMC and the length control of the interferometer suffered from timing slips that resulted in bad samples being fed into the length servo. The resulting glitches were detected by comparing the length readout to OMC auxiliary channels, and the code was updated first to automatically detect these slips and finally to fix them altogether. A class of glitches that are also observed in various OMC channels (although the cause is not necessarily located in the OMC) in L1 has been associated with some of the loudest events in the $h(t)$ strain channel. Noise in the

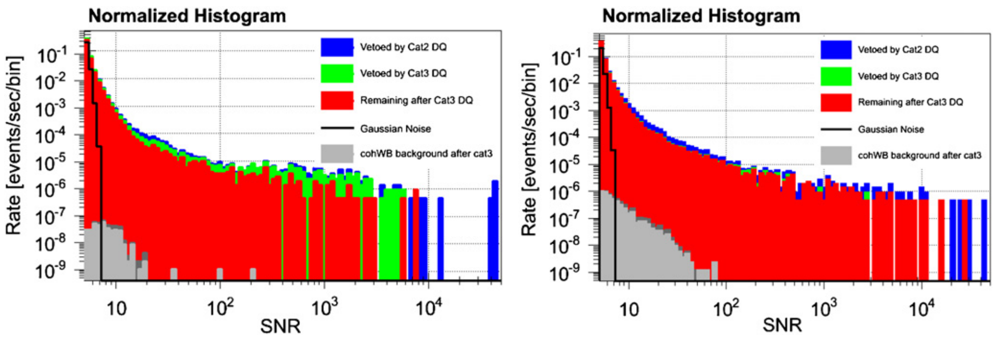

Figure 1. Single interferometer SNR plots from the coherent wave burst [25] pipeline overlaid with the single interferometer Omega [24] burst triggers; the Gaussian distribution is also given for comparison. Note that the SNR ∼10 events are the problem for the coherent analysis; the single interferometer rate of SNR ∼10 events is very large. The effect of the successive application of the DQ flag categories can be seen in the results for H1 (left) and L1 (right) from S6.

mirrors' thermal compensation system [1] is clearly associated with events seen in $h(t)$, but the construction of an effective DQ flag has proven difficult (but not impossible). This is an area of current research and investigation.

In figure 1 we can see the effect of successfully applying the DQ flags of category 1 through 3. The figure displays the number of single interferometer triggers (from the first 6 months of S6) observed by the Omega burst search pipeline [24] as a function of the signal to noise ratio (SNR). Also displayed are the triggers from a coherent wave burst [25], a search pipeline that demands both time coincidence and coherence in the events seen between multiple detectors; the figure shows the single interferometer coherent wave burst events for H1 and L1. It is interesting to note that the majority of these coherent triggers have SNRs with values around 10: the rate of SNR ∼10 events is substantial.

3. Vetoes for coalescing binary and burst searches

Both the coalescing binary and burst search efforts make use of vetoes to eliminate triggers that can be shown to be statistically attributed to events that are observed in interferometer control and PEM channels. These events are typically short in duration (milliseconds). Vetoes such as these have been used by LIGO in the analysis of data from all of its previous scientific runs [20–22]; Virgo has also applied similar vetoes in its previous searches [7, 13, 26, 27]. When a clear statistical association can be made between a measured interferometer control or PEM channel event and a coincident glitch in the output $h(t)$ strain channel of the interferometer, these events are excluded from the search for burst or coalescing binary gravitational wave signals. Through the use of vetoes it is possible to remove many events seen in the $h(t)$ channel that are due to problems with the functioning of the interferometer or noise in the environment that is coupling to the detector.

In S6, LIGO is using two veto pipelines: hveto (hierarchical veto) and UPV (used percentage veto) [23]. Results from both hveto and UPV are generated daily for use in data analysis studies by the LSC detector characterization and glitch groups. They are also examined by the Scimons at the sites. Results based on the observation of a week's worth of data are used to formally define the vetoes: the hveto results are applied to the burst search, while UPV is applied to the coalescing binary search. It should be noted that hveto and UPV are also being used to generate vetoes for the Virgo burst and coalescing binary searches [14, 23]. Both of the veto pipelines make use of the event triggers from a wavelet-based burst/glitch search program called *KleineWelle* (KW) [24]. KW registers events found in hundreds of the interferometer control and PEM channels.

The hveto pipeline has been found to be a good way to look for families of glitches. It searches lists of KW triggers made from all channels and finds the interferometer control or PEM channel most significantly correlated with the interferometer output (the *round 1 winner*); this is done by comparing the number of coincidences found with the number expected by chance. The program then deletes all interferometer output triggers vetoed by that channel (the round 1 winner) and hveto then looks again for significant correlations. The round 2 winner is treated in the same way as with round 1: all of the corresponding output triggers are deleted. This process repeats until no further significant correlations are found. When this process converges, the program sorts the triggers into groups, as measured, according to which interferometer control or PEM channels were correlated with them. The formal veto times for the burst search based on the hveto come from the events found in the *winning* channels; typically hundreds of milliseconds are excluded about each of the KW trigger times for these veto channels. Through the use of hveto on S6 data, several observations can be made. Glitches tend to group into distinctive families, and there are many such families. Rarely do we observe single-channel (or few-channel) families. Many channels have a high use percentage (the percentage of KW triggers for that channel that are successfully used as a veto divided by the total number of KW triggers for that channel over the period in question), but others have quite a poor (low) use percentage.

The UPV again uses the KW triggers from the interferometer control and PEM channels. The magnitude of KW triggers are ranked via their *significance* [24]. When the UPV examines the KW triggers, it raises the threshold of the KW significance until the use percentage of the veto reaches 50%. This means that at least half of the KW triggers from the potential veto channel are within ± 1 s of a trigger from the interferometer output channel. A more complete description of the UPV and its application on S6 data can be found in [23]. It should be noted that UPV and hveto typically find the same veto channels; this is especially true when there are a large number of triggers for the veto channel. hveto often identifies rare or intermittent problems, while the 50% used percentage criterion for UPV yields veto channels that have a large statistical correlation with $h(t)$ triggers over a weekly time period.

The safety of a veto is of paramount concern since we do not want to exclude a real gravitational wave event. Both hveto and UPV look carefully at the periods of times when artificial signals are injected into the interferometers by pushing on an end mirror. If this signal couples into an interferometer control channel, then that channel is not considered safe. All defined veto channels must not show a statistically significant correlation with these hardware injection times.

The vetoes are very successful in cleaning up the distribution of observed events. Figure 2 displays the number of coalescing binary inspiral triggers from H1 and L1 for the first 3 months of S6 as a function of the SNR (after DQ category 1 and 2 flags have been applied) before and after the application of the UPV. The veto is effective in cleaning up the distribution of these single interferometer coalescing binary triggers. Similar results are also seen with VSR2 data [14]. The total amount of data excluded by these vetoes varies; typically there is a 1–4% deadtime in H1 and L1 as a result of these vetoes, but in some rare weeks when severe problems exist it can grow as large as 20%.

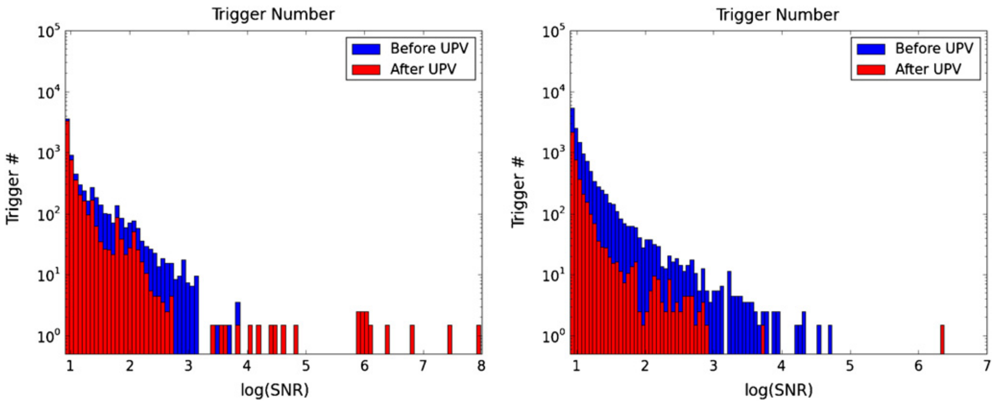

Figure 2. The number of coalescing binary triggers from H1 (left) and L1 (right) from the first 3 months of S6 versus SNR after application of category 1 and 2 flags, and then after applying the UPV results.

4. S6 noise line search and identification

The search for noise lines (noise appearing at a fixed frequency) in the data is another important activity of the LSC's detector characterization group. This type of noise affects the search for CWs [28] and a stochastic gravitational wave background [10], and consequently it has been of great importance to find the origin of this noise in the interferometers' environment. Virgo also conducts similar noise line searches [29, 30].

In S6 there was a concerted effort to locate the sources of noise lines via two different data analysis techniques; a comprehensive description of the effort can be found in [19]. The CW detection pipeline, *Fscan*, was run on the interferometers' output channels, $h(t)$, as well as a number of interferometer control and PEM channels. Fscan results were generated based on daily, weekly and monthly averages. The frequencies of the noise lines in $h(t)$ could then be searched for in the Fscan results for the interferometer control and PEM channels. The other technique used was the calculation of the *coherence* between the interferometers' output channels and interferometer control or PEM channels. The coherence was also calculated using daily, weekly and monthly averages. The coherence output was mined for statistically significant peaks. A web-based tool was also developed to allow one to search for significant lines in the Fscan and coherence database. The Fscan search reports channels as significant if the signal power per frequency bin exceeds three times a median power in that frequency region, while the coherence tool reports a line as significant if its coherence value is 15 times the theoretical standard deviation σ, where σ is the reciprocal of the number of time segments averaged in calculating the coherence [19].

In addition to data analysis techniques, investigations in the laboratory at the observatories provide the definitive evidence as to the origin of noise lines. The combination of results from Fscan and the coherence can provide clues as to the location of a noise source; subsequent hunting in the lab (with tools such as a portable magnetometer) can then definitively locate the offending device.

The effort to find the source of noise lines has been successful in S6. For example, a pair of particularly troublesome noise lines was seen in both L1 and H1 at the start of S6; 54.496 Hz and its harmonic 108.992 Hz showed up as significant noise lines at both sites. Scientists at the observatories tracked the cause of the noise to VME CPUs at both sites. Similarly, the

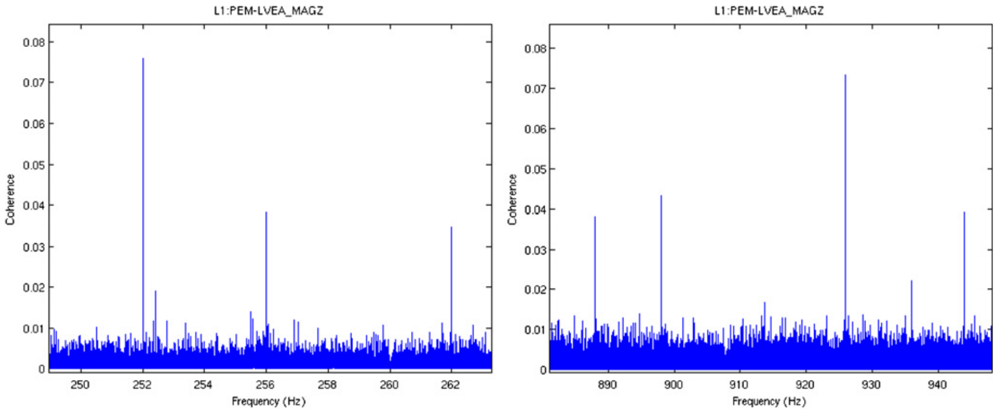

Figure 3. The coherence between L1's output signal and data from a magnetometer in the central building of the LIGO-Livingston Observatory. The coherence was averaged over a week in March 2010. 2 Hz and 16 Hz harmonics are seen in the coherence at numerous locations across the operating band of the interferometer. On the left, lines are observed at 252, 256 and 262 Hz, while on the right there are lines at 888, 898, 926, 936 and 944 Hz. All of these lines were found to be statistically significant, namely greater than 15 times the theoretical standard deviation (which was 2×10^{-3} for this example).

source of a 158 Hz line was a Foundry Ethernet switch seen in line with the gravitational wave channel and three rack magnetometer channels in one of the buildings at LIGO-Hanford, while a 340 Hz line in H1 was found to be originating mechanically from a periscope at the pre-stabilized laser. A total of nine lines (spanning the range from 140 to 568 Hz) in the H1 data have also been observed to be coherent with the ripple in a power supply. 2.0 Hz and 16.0 Hz harmonics have been observed in the data from both H1 and L1 and have greatly affected the CW searches; commissioning work at LIGO-Hanford in January 2010 on the OMC system had the result of eliminating the 2 Hz harmonic noise lines in H1, thereby leading to the belief that the source of the 2 Hz lines originated there. Figure 3 shows an example of using the coherence to try to find the source of the 2 Hz and 16 Hz harmonics; displayed is the coherence between the L1's output signal and the data from a magnetometer located in the central building. Numerous 2 Hz and 16 Hz harmonics are seen in the coherence across the operating band of the interferometer, and figure 3 shows two (of many) regions where these lines appear.

5. Other noise search efforts

Many problematic effects appear in interferometers, and often they can be difficult to diagnose and correct. Consequently there have been numerous investigations, both experimental and via data analysis, that have been conducted in order to decipher the origin of S6 noise. A direct way to measure the transfer function between environmental noise and interferometer output has been attempted via *PEM injections*. In these studies, seismic, acoustic, magnetic and RF noise is injected into the environment around the interferometer (this work has been done primarily at LIGO-Hanford). Areas around the interferometer that are vulnerable to noise infiltration have been identified via these tests. The injections have also provided a great deal of information on the nonlinear up-conversion of noise, namely how low-frequency environmental excitations can produce interferometer noise at higher frequencies. Other experiments have also helped to identify regions where light exiting the interferometer can scatter back in, thereby creating noise.

Another investigation has been conducted to find out if the interferometer output in the different frequency bands is Gaussian. Useful information can be derived from the interferometer noise spectra based on whether it is stationary. In S6 there has been a study of the distribution of the noise spectra as a function of frequency. Interferometer noise can have a distinct spectral shape while remaining Gaussian. The spectra are compared to the Rayleigh distribution, normalized by the median value for each frequency bin. Comparisons are then made with pure Gaussian noise. The results of this effort are important in identifying the frequency regions where the noise is the most non-Gaussian. The region around 100 Hz is the most non-Gaussian for both H1 and L1 in S6.

Many of these noise studies are dependent on PEM signals. With about 100 PEM signals per interferometer site, there is a good chance that a device will fail at some point during the run or its signal may somehow become corrupted. A *dead channel monitor* (DCM) was implemented during S6. The DCM continuously observes all of the PEM data from LIGO-Hanford and LIGO-Livingston and produces a warning when the channel flat-lines (zero, the maximum or minimum of ADC counts), the average value is too close to zero, or the root mean square or the standard deviation changes significantly from their recorded standard values. The DCM posts its results for web-access and also creates a log file. Dead channel information is also forwarded to scientists at the observatories so that the channels can be fixed.

6. Summary

The noise in LIGO science runs S5 and S6 is similar in some ways and different in others. The character of the environmental noise is the same in both runs. Some noise lines are similar between S5 and S6; for example, the 16 Hz harmonics are present in both runs, presumably due to the same data acquisition systems. Spurious noise events caused by, for example, light power dips in the interferometers' arms are also the same in S5 and S6, and the means by which these events are identified is the same. However there are some noticeable differences. The presence of the output mode cleaner and increased laser light power have definitely brought new noise, such as the 2 Hz harmonic noise lines or the very loud noise glitches that show themselves in the L1 data. The new systems in S6 have changed the character of the noise. This should serve as a warning for the advanced LIGO and Virgo detectors; the noise characteristics in those systems will definitely be different, and a large amount of time and effort will need to be devoted to examining the DQ when they come on-line.

The S6 noise search effort is a major endeavor for numerous LSC scientists. Many different approaches and tools are used to help identify noise and locate its sources, and in this paper we have attempted to give a summary of them. Noise studies will continue through to the end of S6, but the analysis of the S6 data will continue until all of the S6 search papers have been published. The LSC signal search groups (coalescing binary, burst, CW and stochastic background) work closely with the detector characterization group in order to try to eliminate or at least minimize the deleterious sources of noise that corrupt our attempts to detect gravitational waves.

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