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Identification and mitigation of Advanced LIGO noise sources

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Abstract. In order to increase the reach of the astrophysical searches, various sources of instrumental and environmental noise must be identified and ameliorated. Here we discuss efforts to understand the origin of noise manifested as short-duration bursts (glitches) and/or range-impacting features at LIGO Hanford. Several examples found at LIGO Hanford Observatory in O1 and O2 were identified including glitches due to an air compressor, ringing phone, airplanes, and an incorrect servo setting, and a decrease in detector sensitivity due to truck traffic.

1. Introduction

GW150914, the first direct detection of gravitational waves from a binary black hole merger was a milestone for physics and astronomy [1]. Making this detection required instruments of exquisite sensitivity that could measure a length change equivalent to the width of an atom in the distance from the earth to the sun. To achieve this sensitivity, the characteristics of the noise in the Advanced LIGO (aLIGO) instruments [2] must be studied, leading to improved sensitivity and improved ability to distinguish signal from noise. The motivation to study the noise is clear. Glitches are transient noise events that could mimic astrophysical events [3] or indicate badly behaving components of the detectors. Classes of glitches with similar properties offer a target for identification of their cause. Even if the cause of a class of glitches is unknown, glitches known to belong to a class can be identified and removed from any influence on the data analysis [4, 5]. So far, the aLIGO detectors have engaged in two observing runs, O1 and O2, taking data from 12 September 2015 to 19 January 2016 and from 30 November 2016 to 25 August 2017 respectively.

aLIGO noise is non-Gaussian and non-stationary.[1] This means that from day to day or even hour to hour both the overall level of noise and the character of that noise can change. For this reason, the LIGO Scientific Collaboration (LSC) initiated a program of data quality (DQ) shifts wherein a collaboration member is assigned to monitor remotely either the detector at Hanford (LHO) or at Livingston (LLO) for several days and then report back to the Detector Characterization (DetChar) group on any changes or issues noticed during the DQ shift that might affect the astrophysical searches. Urgent issues are reported directly to staff at the site as soon as possible. Most DQ shift reports are summarized in the public aLIGO logbooks [6, 7].

[1] Most of the time, the noise is sufficiently Gaussian and stationary for astrophysical events to be identified (see the discussion in, e.g., [8]) but care must be taken.

IOP Conf. Series: Journal of Physics: Conf. Series **957** (2018) 012004 doi:10.1088/1742-6596/957/1/012004

Tools developed by the DetChar group members make it possible to keep a close eye on the instruments. Key to the ability to perform remote DQ shifts are the Summary Pages[2] (SP) [9]. For those in the LSC, the SP provide information such as time series, spectrograms, spectra, and glitch activity of the gravitational wave channel $h(t)$ and many other channels of these complex instruments. They are available with about one-hour latency through any internet connection.

Three additional tools have played a role in the work described here. Omicron [11] is a software algorithm that identifies glitches in the data according to features such as peak frequency , signal-to-noise ratio (SNR), and bandwidth. The SP include glitchgrams, Omicron's output in terms of peak frequency vs time, color coded for SNR. Advanced LIGO monitors thousands of channels in addition to the gravitational wave channel $h(t)$. These auxiliary channels can be studied to find correlations between instrumental or environmental sensor signals and the gravitational wave channel. To make use of this information, a further analysis is carried out by hVeto [12] which identifies statistically significant correlations between glitches in $h(t)$ and glitches in auxiliary channels. hVeto is applied hierarchically to identify independent glitch families associated with different sets of auxiliary channels. Finally, a sophisticated plotting package, ligoDV-web (ldvw) [13], allows exploration of the data in all channels.

In the remainder of this paper, we will discuss several examples including the 50 Hz glitches traced to an air compressor, the 1083 Hz glitches traced to an incorrectly set servo gain, peculiar features in the $h(t)$ spectrogram found to be caused by a ringing phone, airplane glitches, and the 5 am Pacific-time truck-traffic range drop. The focus will be on discovery of the class of glitches and steps taken to understand their nature, and, if possible, fix their cause. We will only consider glitches found at LHO.

2. Examples

The 50 Hz glitches. The first example is a series of glitches seen early in O1 in the gravitational wave channel, $h(t)$, with peak frequency of 50 Hz visible in Fig. 1.

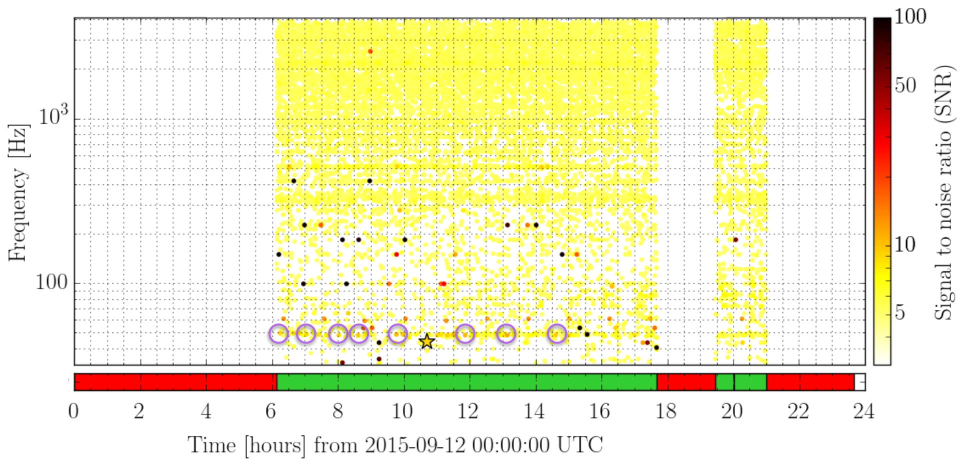

Figure 1. The 50 Hz glitches. A glitchgram is shown for the entire day of 12 September 2015 with time on the horizontal axis and frequency on the vertical axis. The glitches are color coded by SNR using yellow-to-black with yellow indicating lower SNR and black indicating higher SNR. The 50 Hz glitches, circled, are about 1 hour apart.

[2] Note that a version of the Summary Pages has recently become publicly available on the LIGO Open Science Center website [10].

When analyzed by hVeto, the most significant channel was a channel measuring the light incident on a photodiode used for alignment control of the X-arm of the LHO detector. This was not surprising. However, the display of all significant channels showed that environmental channels recording seismic vibrations at the end of the X-arm of the detector were also correlated with the glitches in $h(t)$. This meant that there was a relationship between the 50 Hz glitches and ground vibrations at the X end station. The DetChar group then suggested [14] that the glitching in $h(t)$ originated in the electric power mains but were coupling to the gravitational wave channel through a seismic connection. It was then speculated that the culprit was a chiller compressor cycling on and off in response to the temperature in its immediate environment. Sure enough [15], when LHO staff visited the end station on 30 September 2015 to look for the problem, they discovered that the vibration-isolation feet on the air compressor at the end station were ineffective and needed to be replaced. They were replaced and the 50 Hz glitches disappeared. While other glitch families were identified and mitigated in O1, the remaining examples presented here occurred in O2.

The 1083 Hz glitches. The first of these were noticed early in O2 as a line of glitches in the daily gltichgram centered on 1083 Hz. Detailed spectrograms showed continual glitching at frequencies around the line. This particular frequency corresponds to one of the LHO calibration (spectral) lines [16] used to determine the actual value of the observed strain. It was first supposed that the problem might arise from fluctuations in the calibration line. However, that was ruled out when the line was briefly turned off. The gltiching did not change. This is shown

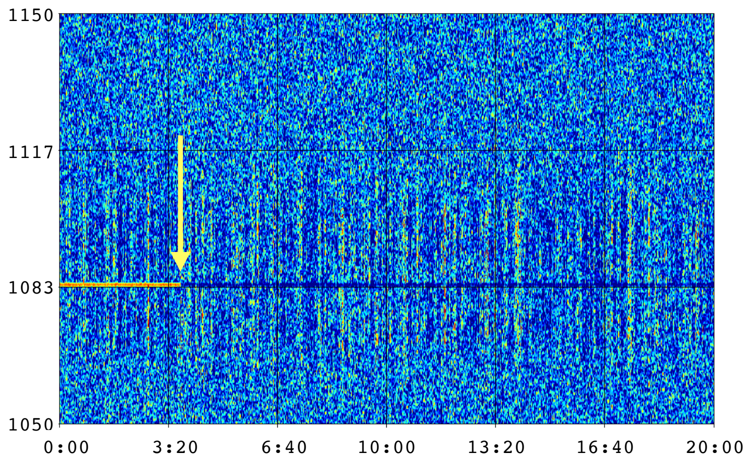

Figure 2. The glitching around the 1083 Hz calibration line. A 20-minute spectrogram of $h(t)$ starting at 21:30 UTC on 15 November 2016 is shown. The yellow arrow points to the time at which the calibration line is turned off. The vertical yellowish bands arise from nearly continual glitching and persist after the line is turned off. The horizontal axis shows the time in minutes after the start time while the vertical axis shows frequency in Hz.

in Fig. 2. For some weeks, these glitches remained a puzzle. hVeto often reported correlations with some channels but the alignment in time was not precise. Apparently, because $h(t)$ was glitching all the time, it accidentally correlated with other channels that were glitching all the time. Finally, a breakthrough occurred when the first appearance of the glitching was tracked down to the second lock stretch on 11 October 2016. What happened at that time? It turned out that output mode cleaner (OMC) length-dither-line amplitudes had been lowered on that day. There should have been an accompanying OMC servo gain to compensate for the change but that did not happen (although no one realized it at the time). On 9 January 2017, the servo gain was reset to the correct value and the gltiching disappeared [17].[3] In fact, the channel

[3] Initially, the correction was temporary to see if the problem had been identified. There was a concern that fixing the glitch problem might create other issues. When that did not to happen, the change was made permanent.

IOP Conf. Series: Journal of Physics: Conf. Series **957** (2018) 012004 doi:10.1088/1742-6596/957/1/012004

associated with the OMC length dither was glitching strongly at frequencies of 4 – 7 kHz and these glitches did align with those in $h(t)$ around 1083 Hz.

The phone rang. On 4 December 2016 at about 17:45 UTC, one of the LHO operators noticed a peculiar series of glitches. This was then independently noticed by offsite DQ experts. A spectrogram of the time interval of the peculiar glitching is shown in Fig. 3. After some head-scratching, someone thought to create a sound file of the spectrogram. Note that this is meaningful because the aLIGO frequencies are in the range of human hearing. The sound file revealed a loudly ringing phone, followed by a softer ring, followed by an answering machine and some talking before another loud ring was heard. Oops! During science runs, there are not supposed to be ringing phones near the vacuum enclosure of the instrument. Of course this problem was fixed by making sure all phones were either removed or turned off [18].

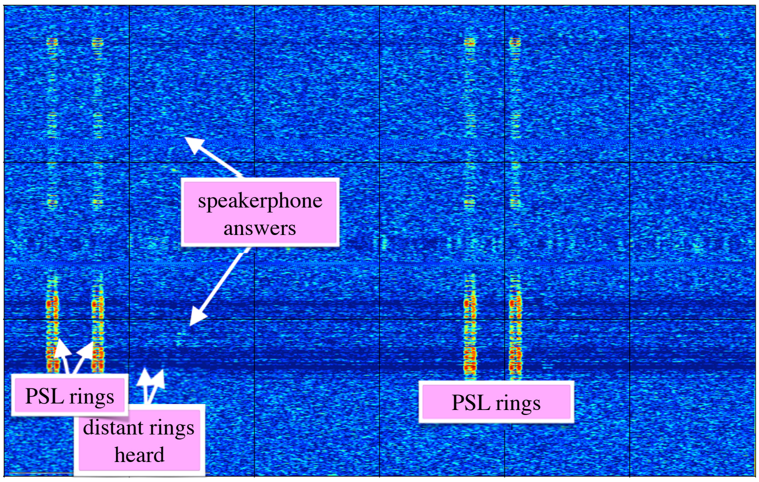

Figure 3. Spectrogram of strange glitching in $h(t)$. A pattern of regular broad-band glitches with some "scruff" in between is shown along with indicators of the eventual explanation. The phone creating the problem was located in the pre-stabilized laser (PSL) chamber.

Airplane overhead. One source of noise for LHO in initial LIGO was caused by airplane flyovers through acoustic coupling to the buildings housing the instruments. In fact, a software monitor had been developed to track plane flights over the site by tracking Doppler shifts picked up by microphones at the X- and Y-arm end stations and at the connecting corner station as the plane moves over the various parts of the instrument [19]. This was not expected to be an issue for aLIGO due to its greatly enhanced seismic isolation. However, on 1 March 2017 at about 1:51 UTC, a peculiar noise pattern was seen in the spectrogram of $h(t)$ with a duration of more than a minute with two parallel bands with frequencies decreasing in time from about 100 Hz to about 70 Hz. hVeto reported the involvement of microphone channels. Fig. 4 shows an overlay of $h(t)$ on the spectrograms of microphone channels at the X-end (EX), Y-end (EY), and corner station (CS). The noise in $h(t)$ follows whichever microphone signal is loudest at the time as the sound from the plane couples to the nearest interferometer mirrors [20]. After this initial airplane identification, additional evidence of airplane glitches were seen. While the correlation of these glitches with microphone channels means that they cannot be mistaken for astrophysical events, their elimination from $h(t)$, ideally by reducing the coupling, is a high priority for future work [21].

The noon UTC truck noise. It was noticed that almost every week, Monday through Thursday, the detector sensitivity as measured by the distance to which a binary neutron star inspiral could be detected (BNS range) showed a dip at about the same time every day. The range dip corresponded to an increase in seismic noise as measured in the corner station (but not in end-X or end-Y) in the 10 – 30 Hz band as is shown in Fig. 5. Further inspection showed a second dip at about 0:00 UTC on the same days. The local times at LHO were 5 am and 5 pm PDT respectively. In the previous month, before standard time (PST) changed to daylight-

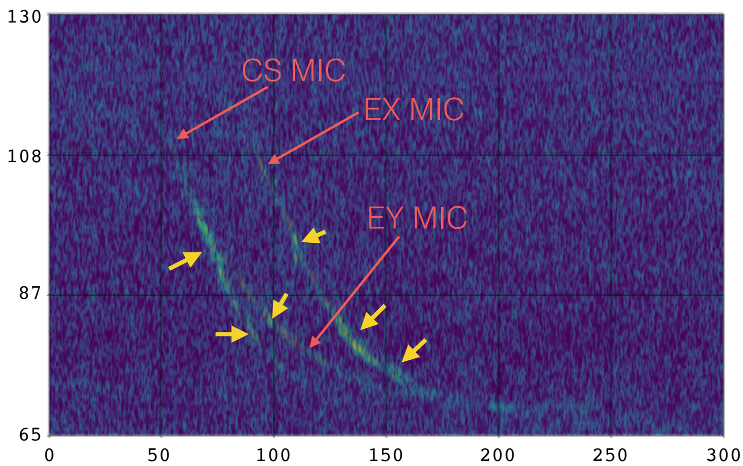

Figure 4. Airplane flyover glitch. This spectrogram overlays $h(t)$ and 3 microphone channels for time (horizontal axis) running for 300 seconds after 1 March 2017 01:50 UTC and frequencies (vertical axis) running from 65 Hz to 130 Hz on a linear scale. The yellow arrows point to bright regions in the display from the overlay of $h(t)$. The long arcs are the traces from the microphones located at the end of the X-arm (EX MIC) and the Y-arm (EY MIC) and at the corner station (CS MIC).

saving time (PDT), the same effect occurred at the same local times (5 am and 5 pm PST) but one hour later in UTC. Previously, it had been suggested that the culprit was truck traffic passing close to the corner station on the road that passes the LHO entrance. The observed behavior reinforced this conclusion. It was recognized that there was strong coupling of 8 – 18 Hz input beam vibration to the 70 – 200 Hz band of $h(t)$ which would account for the effect due to the truck traffic. It was suggested that the coupling was caused by a baffle in the input arm of the interferometer with several openings for various beams, nicknamed the Swiss Cheese Baffle [24], and could be reduced by adding dampers to the baffle. In May 2017, O2 was interrupted to make some repairs at both sites. The dampers were added at that time.[22, 23, 24] After the dampers were added, the seismic increase was still present but the range drop had disappeared.

3. Final thoughts

These are some examples of identifying features in $h(t)$ associated with particular types of noise. In some cases, the existence of the noise can be traced to a particular problem that can be fixed. Sometimes, even if the cause is known, the problem cannot be easily fixed. However, the now understood character of the noise can be used to avoid confusing it with a signal. While the 50 Hz glitches, phone, and airplane events would not have been misinterpreted as astrophysical events, they could mask actual signals. The 1083 Hz glitches interfered with with a search for unmodeled astrophysical events. The truck-caused range drop made the instrument less sensitive for a significant amount of time and thus less likely to detect a signal during that time. Thus understanding and mitigating these noise sources is a high priority for astrophysical event detection. For more on this topic see [25].

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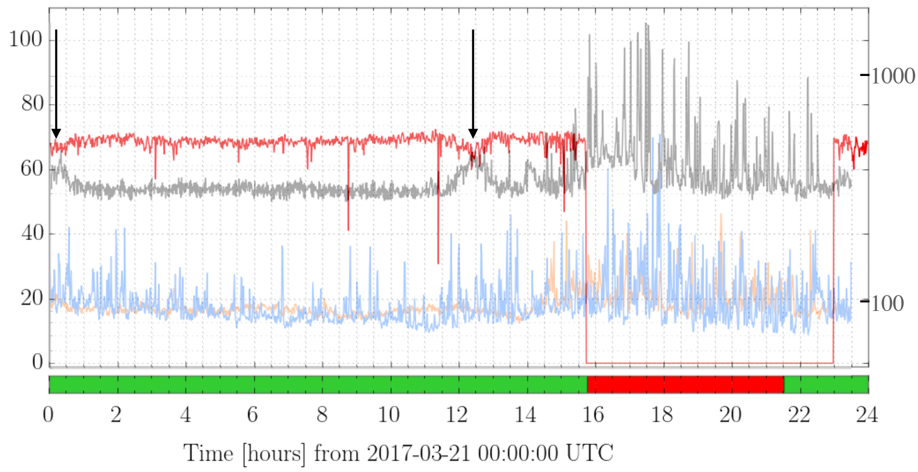

Figure 5. Truck noise at 12:00 UTC. The range dip and excess seismic noise are shown for the entire day of 21 March 2017. There is a corresponding dip and excess at about 0:00 UTC. Both times are marked by arrows. The BNS range is shown in red (left axis in Mpc) and the seismic noise (ground motion) in the 10 – 30 Hz band at the corner station is shown in gray (right axis in nanometers per second). The remaining traces show seismic motion at the end stations.

References

[1] Abbott, B.P. et al 2016 Phys. Rev. Lett. **116**, 061102
[2] Aasi, J. et al 2015 Class. Quantum Grav. **32** 074001
[3] Abbott, B.P. et al, arXiv:1710.02185 [gr-qc]
[4] Aasi, J. et al 2015 Class. Quantum Grav. **32** 105012
[5] Abbott, B.P. et al 2016 Class.Quant.Grav. 33, 134001
[6] aLIGO LHO Logbook, https://alog.ligo-wa.caltech.edu/aLOG/
[7] aLIGO LLO Logbook, https://alog.ligo-la.caltech.edu/aLOG/
[8] Abbott, B.P. et al 2017 Phys. Rev. Lett. **119** 141101
[9] https://github.com/gwpy/gwsumm/blob/master/docs/overview.rst
[10] LIGO Open Science Center, https://losc.ligo.org
[11] Robinet, F. 2015 Omicron: An Algorithm to Detect and Characterize Transient Noise in Gravitational-Wave Detectors. https://tds.ego-gw.it/ql/?c=10651
[12] Smith, J.R. et al 2011 Class. Quantum Grav. **28** 235005
[13] Areeda, J.S. et a; 2017 Astronomy and Computing **18** 2734 (2017)
[14] https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=21436
[15] https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=22119
[16] Cahillane, C. arXiv:1708.03023 [astro-ph.IM]
[17] https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=33104
[18] https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=32503
[19] Goetz, E. and Riles, K. PlaneMon: Airplane Detection Monitor, https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=33104
[20] https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=34547
[21] https://dcc.ligo.org/LIGO-T1700214/public, p. 74.
[22] https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=35166
[23] https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=35735
[24] https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=36147
[25] Nuttall, L.K., “Characterising transient noise in the LIGO detectors,” in preparation