Characterising Transient Noise in the LIGO Detectors

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Abstract. Data from the LIGO detectors typically contain many non-Gaussian noise transients which arise due to instrumental and environmental conditions. These non-Gaussian transients can be an issue for the modelled and unmodelled transient gravitational-wave searches, as they can mask or mimic a true signal. Data quality can change quite rapidly, making it imperative to track and find new sources of transient noise so that data are minimally contaminated. Several examples of transient noise and the tools used to track them are presented. These instances serve to highlight the diverse range of noise sources present at the LIGO detectors during their second observing run.

1. Introduction

The Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) detectors [1] are some of the most sophisticated scientific instruments in the world. They are designed to measure stretching and squeezing of spacetime due to the passage of gravitational waves like those produced in the collisions of black holes and neutron stars. The two LIGO detectors are twin dual-recycled Michelson interferometers located in Hanford, WA and Livingston, LA [2]. The interferometers are L-shaped, with arms stretching 4 km in length; we often refer to each arm separately as the X- and Y-arm. Since they began operations in 2015 they have completed two observing runs. The first observing run (O1) spanned from September 2015 to January 2016, accumulating approximately 49 days of coincident data. The second observing run (O2) accumulated 117 days of coincident data, from November 2016 to August 2017. Advanced Virgo [3], located in Italy, also joined the Advanced interferometric network for the final month of O2. To date, five gravitational-wave signals and one candidate signal have been detected from the merger of black holes, with progenitor masses spanning 7-36 $M_\odot$ [4, 5, 6, 7, 8, 9]. The first gravitational-wave signal from the coalescence of two neutron stars was recently announced [10], with much excitement for the coincident observations in the electromagnetic spectrum by many independent telescope facilities [11].

A clear understanding of these gravitational-wave detectors is paramount to measuring such signals [12]. The interferometers contain state-of-the-art hardware to isolate the instruments from their local environments and augment their interaction with a passing gravitational wave. The strong GW150914 signal only produced a relative length change, or strain, of the LIGO detector arms by 1 part in 10^{21}. Environmental and instrumental noise can cause relative length changes similar to or larger than true astrophysical signals. In addition, the characteristics of the detector output signal change on a daily basis due to environmental and hardware issues which unexpectedly arise. There are over two hundred thousand 'auxiliary channels' which measure environmental and instrumental behaviour for each of the LIGO sites. These channels enable researchers to locate the source of noise so that detector sensitivity can be restored and the output data are minimally affected.

LIGO data are typically non-stationary and non-Gaussian; detector noise can have varying effects on different types of gravitational-wave searches. Long duration gravitational-wave searches, such as those searching for signals from pulsars or the stochastic background, are most susceptible to sources of noise which manifest themselves at a specific frequency or which produce combs in the amplitude spectral density [13]. In contrast, searches for transient gravitational waves, both modelled and unmodelled‡, are most affected by non-Gaussian noise transients or 'glitches' [12, 14]. This noise can mask or mimic a transient gravitational-wave signal. However with

‡ Modelled refers to searches for gravitational waves from compact binary coalescences with a known waveform morphology, whereas unmodelled refers to searches for gravitational-wave bursts of no specific waveform morphology.

the correct understanding and treatment of noise, the sensitivity of gravitational-wave searches can be vastly improved. For example, one search for compact binary coalescences had as much as a 90% improvement in its sensitivity§ in parts of O1 [14].

This paper aims to highlight examples of non-Gaussian noise transients seen in the LIGO detectors which have adversely affected the search for transient gravitational waves in O2. Complementary examples are also presented in [15].

2. Example Tools used to Characterise the LIGO Data

A typical method to visualise the LIGO data from a transient search perspective is by representing each detector's data by an unmodelled or 'burst' transient identification algorithm. A method commonly used to characterise LIGO data is Omicron, which identifies excess power transients using a generic sine Gaussian time-frequency projection and reports transients at a given central time, central frequency, duration, bandwidth, Q-value and signal-to-noise ratio (SNR) (or normalised tile energy) [16]. Figure 1 shows Omicron applied to LIGO data in the ideal case of Gaussian noise (left) and typical operations (right). The Gaussian noise plot shows few features across the time-frequency space, whereas the typical data plot shows much more structure due to various issues taking place throughout the day. Examples of the nature of these glitches will be presented in the next Section.

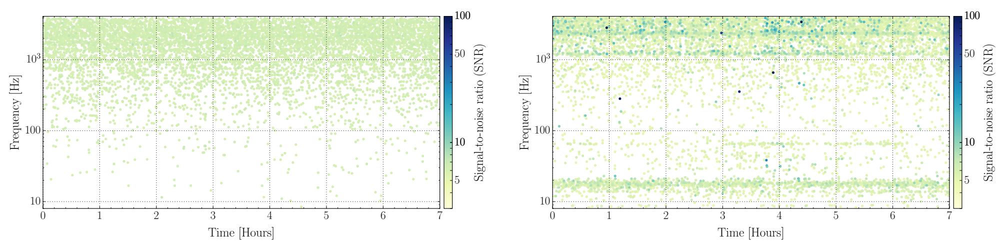

Figure 1: The distribution of Omicron triggers in frequency and SNR over a seven hour time period on Gaussian (left) and typical O2 (right) LIGO data. Note the log scale makes Omicron triggers appear more dense at high frequencies.

The main method to find the cause of transient noise in the gravitational-wave channel is to find time coincidences with auxiliary channels. For example, the Hierarchical Veto (HVeto) algorithm looks for time coincidences between glitches in auxiliary channels and the gravitational-wave channel [17]. This method firstly uses Omicron to identify transients in auxiliary channels before time-correlating them with the gravitational-wave channel. Many examples presented in the next section made use of HVeto to identify a suspect area of the detector to investigate.

LigoDV-web is a software suite that allows easy access to data [18]. Through its web interface, grabbing and viewing data is exceptionally simple; LigoDV-web is often

§ Search sensitivity refers to volume x time at a specific inverse false alarm rate whereas detector sensitivity refers to strain/$\sqrt{\text{Hz}}$.

initially used to view a variety of data, whether from the gravitational-wave or auxiliary channels.

GravitySpy is a citizen science project, aiming to classify glitches within the LIGO data using human classification to train a convolutional neural network [19]. This new tool has proved extremely useful in charactering glitches identified by Omicron, and grouping them in to known classes. A database now exists of all the glitches in the first and second observing runs. Investigations utilising this database are currently underway.

Many of the tools used to characterise the LIGO data are collated on the internal LIGO summary pages. A public viewable version of these pages is available at [20]. These pages house key information in an easily viewable format to keep track of the varying data quality of the detectors. The summary pages are vital in quickly identifying and finding the source of new noise. These pages and the figures presented in this paper make use of the GWpy software package [21].

3. Transient Noise Examples in LIGO

3.1. Thirsty Ravens

In the summer of 2017 many glitches around 90 Hz in the gravitational-wave channel were correlated with a microphone at the Y-end of the Hanford interferometer by HVeto. Listening to the microphone output at the time of these glitches implicated ravens that had been seen outside the Y-end of the detector. At the Y-end are cryopumps which store nitrogen for various detector operations. Ice accumulates on the vent lines transporting the nitrogen in to the Y-end building. Upon inspection of these vent lines, peck marks were observed consistent with the size of a raven's beak. To test this hypothesis imitation pecking was simulated by chipping at the ice and was found to be consistent with the observed noise. Further investigations concluded that the ravens peck the vent line which is connected to and vibrates the vacuum enclosure and other instrumental components. This causes the optical path length of the main laser beam to vary. The laser light is scattered from the Y-end test mass, is reflected off other surfaces and recombines in to the main laser beam causing noise pollution [22]. The source of this noise can be easily solved by insulating the vent lines to prevent ice accumulating or adding an additional casing around the vent lines to prevent the ravens accessing the ice. There are plans to implement one or both of the proposed mitigation solutions before the next observing run (expected late 2018) [23].

3.2. Optical Lever Glitches

Optical lever lasers are used to sense and stabilise the angular alignment of interferometer optics. In February 2017, HVeto discovered time coincidences between glitches seen in the Hanford gravitational-wave channel and a channel which monitors the power to the optical lever at the Y-end test mass. These glitches were found to adversely affect the modelled transient searches, as the transient noise manifested itself across frequencies ¡ 200 Hz and were sufficiently loud (i.e. a high SNR). It was found that the optical lever laser was glitching, and the radiation pressure from this glitching was coupling in to the gravitational-wave channel. The output power of the laser was adjusted to return to an almost glitch-free operating power. At various points in the second observing run the optical lever laser at the intermediate Y-test mass also needed power adjustments and the X-end laser needed replacing.

3.3. Magnetic Glitches

In February 2017 a group of glitches around 50-60 Hz appeared at the Livingston detector which accounted for approximately 15% of all glitches between 10-1000 Hz. These correlated in time with glitches in magnetometers and channels monitoring the AC power mains at the X-end; they were initially identified by HVeto [24]. Further investigations found that the glitches related to the switching on of a compressor, as shown in Figure 2. To mitigate the effect of these glitches grounding modifications to the X-end electronics rack were needed. Since this work, the 50-60 Hz glitches disappeared and have not been seen since at Livingston.

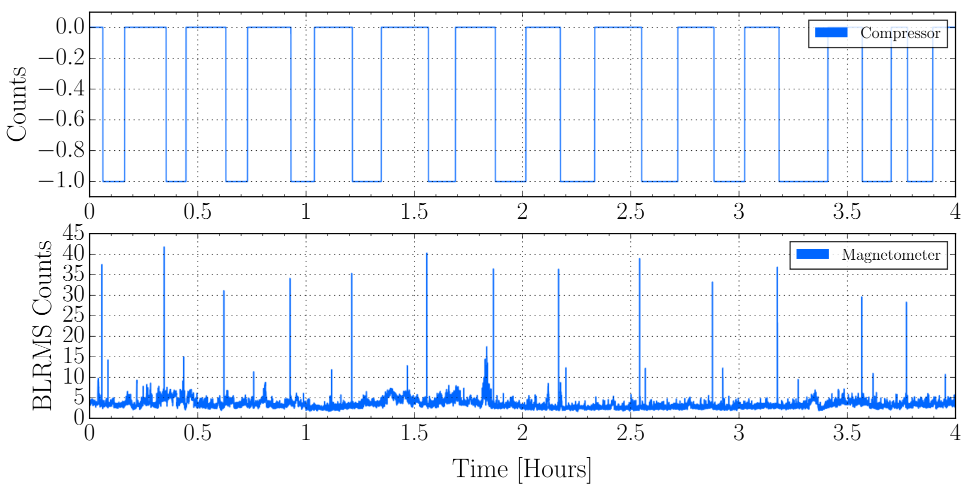

Figure 2: The time coincidence between the switching on of a compressor and glitches in a magnetometer at the X-end. Top: Time series of a channel which monitors the state of the compressor. Bottom: The band limited root-mean-square (BLRMS) series over a channel which monitors an X-end magnetometer. The BLRMS between 75-100 Hz calculated once per second of this magnetometer channel provided good evidence for the link between the switching on of the compressor and glitches in the magnetometer and, subsequently, the gravitational-wave channel.

3.4. Scattered Light

Light scattering is a common source of noise at both interferometers. Any motion or slight misalignment can cause parts of the main laser beam to scatter off moving surfaces, in any of the several chambers, and couple back in to the main beam. This example concerns the Y-end reaction mass at Livingston, which on occasions prior to February 2017, caused scattering in the gravitational-wave channel up to ~90 Hz. Figure 3 (left) shows the location of the reaction mass, in yellow, in relation to the main test mass and quadruple pendulum. The scattering arches seen in the gravitational-wave channel are shown in the right of Figure 3. These are very detrimental to the transient searches, both modelled and unmodelled, which typically analyse data above 20 Hz. The LIGO summary pages have a monitor for tracking scattering from a number of optics throughout each detector. This monitor searches for evidence of beam scattering based on the velocity of an optic's motion, and the scattering fringe frequency is predicted from [25]. This monitor originally suggested an optic at the Y-end as the source of the scattering. After further investigation the reaction mass, which serves to control the position of the Y-end test mass, was implicated. By changing the angle of the reaction mass, the scattering issue was resolved [26]. During upgrades, before the start of the third observing run, many baffles throughout each detector are being installed to mitigate the effects of scattering [2].

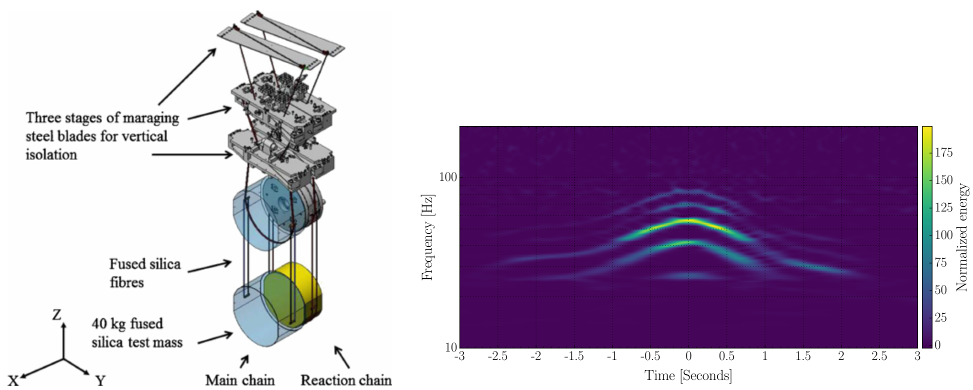

Figure 3: Left: Schematic of the quadruple pendulum and quadruple reaction pendulum [27]. The reaction mass is coloured in yellow. Right: Normalised spectrogram of gravitational-wave data with scattering noise present. Characteristics of scattering noise are arches. This figure shows arches affecting several seconds of data between 20-90 Hz.

3.5. Thunderstorms

Throughout the second observing run thunderstorms near the Livingston detector have had a negative impact on sensitivity. One way in which sensitivity is measured is by monitoring the binary neutron star inspiral range; the range at which a detection of a 1.4-1.4 $M_\odot$ neutron-star merger is made at a SNR of 8. Thunderstorms have resulted in a range decrease of 10 Mpc, approximately a 10% decrease, by causing an increase in noise between 40-60 Hz. This is caused by acoustic noise coupling in to the detector, causing vibrations and thus light scattering noise. Upon investigating the timing of the thunder claps in various microphones around the detector, it was found that acoustic noise coupled to a baffle between the two chambers which house a three-optic cavity that cleans the input laser light before it enters the interferometer arms [2, 28]. This baffle was also a dominant source of vibrational noise at Hanford [29]. Raising the resonant frequency of this baffle will reduce the scattering effect. During upgrades to the detectors before the start of the third observing run, the shiny parts of this baffle, which cause the most scattering, will be removed.

3.6. Excess Ground Motion

Throughout the second observing run excess ground motion at both sites has been shown to have an adverse affect on detector sensitivity. Different types of activity around each site can have varying effects, although ground motion due to earthquakes are a constant challenge. In addition the Hanford detector can experience winds with speeds in excess of 50 mph. During the winter months, which brought snow to the Hanford site, detector sensitivity was particularly impacted due to plows clearing the snow. This activity caused excess ground motion between 10-30 Hz measured by a seismometer located at the building which house the main detector optics. This noise could then be seen coupling in to the gravitational-wave channel, thereby affecting the inspiral range. These times of excess noise can often be detrimental to the transient searches, and motivating the removal of times associated with excess ground motion during O2. We expect ground motion to continue to adversely affect the astrophysical searches during future observing runs.

4. Concluding remarks

This paper presents some examples of transient noise seen in the LIGO detector during O2. In some instances the sources of noise could be fixed at the source, whereas others could simply be further understood and planned to be ameliorated in upcoming upgrade work, currently taking place at both sites. Another mitigation strategy to already collected data, is the use of data quality vetoes to remove or down-rank egregious data used in transient searches. Examples of this strategy are presented in [12, 14].

As the LIGO detectors are upgraded and commissioned to design sensitivity, new sources of noise will be uncovered. See for instance the different noise examples presented as the detectors were being commissioned before O1 [30], during O1[12, 14] and during O2 (this paper). At the same time, the rate of detectable gravitational-wave signals will also increase. Therefore the chances they will overlap with transient noise also increase, particularly for longer duration (minute time-scale) signals. It is extremely important to investigate ways of tracking new groups of transient noise and methods for excising them from future data so the astrophysical potential of the LIGO detectors is realised.

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