Development of a Burst Gravitational Wave Detectable Range Visualization

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Abstract

The Laser Interferometer Gravitational-wave Observatory (LIGO) measures gravitational waves of astrophysical origin. A common measure of detector performance used by LIGO is the distance to which a standard binary neutron star merger can be detected. While all the detected gravitational waves to date have been of this kind, it is expected that the next class of detected gravitational waves will be from unmodelled or unanticipated sources, also known as "bursts." This research focuses on developing a measure of the detectable distance for a burst gravitational wave that is sensitive to the near-real time data quality of the detector. We have developed software that collects results from the primary burst search algorithm to determine what signal-to-noise ratio is needed to achieve an acceptable false-alarm rate and combines this with the power spectral density of the noise to calculate the detectable distance for a standard burst source. The result can be visualized as a time-frequency representation or an average distance over the sensitive frequency range. Ultimately, this measure will be automatically generated during the next observing run and used to determine the effect of current data quality on the search for burst gravitational waves.

Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is composed of 2 observatories (one in Hanford, Washington state and another in Livingston, Louisiana) and observe the Universe through propagating changes in gravitational field called gravitational waves. Since the first detection of a gravitational wave in 2015, there have been ~90 confident gravitational wave detections. All these detections have been from a single class of gravitational wave called binary coalescences. The next class anticipated to be detected is burst gravitational waves whose sources are either unanticipated or we are unable to confidently model.

We have developed a tool to calculate the detectable distance to a burst gravitational wave source so that we can also measure the impact of real-time data quality on the search.

Of primary importance is how the range changes over time; deteriorations in range indicates that the current data quality is having a negative impact on the search for gravitational wave bursts. True ranges to any confirmed detections will be calculated in detail after the fact.

Binary Coalescence Range

There are currently tools that focus on the measuring the impact of current detector performance on the search for gravitational waves and almost all of them concentrate on the search for binary coalescences. One of those tools is the calculation of the distance from the Earth a 1.4/1.4 M_{sun} neutron star binary would be detectable with a fixed SNR of 8 (see Fig. 1) [1]. This calculation is aided by the fact that the waveform for the neutron star source is known.

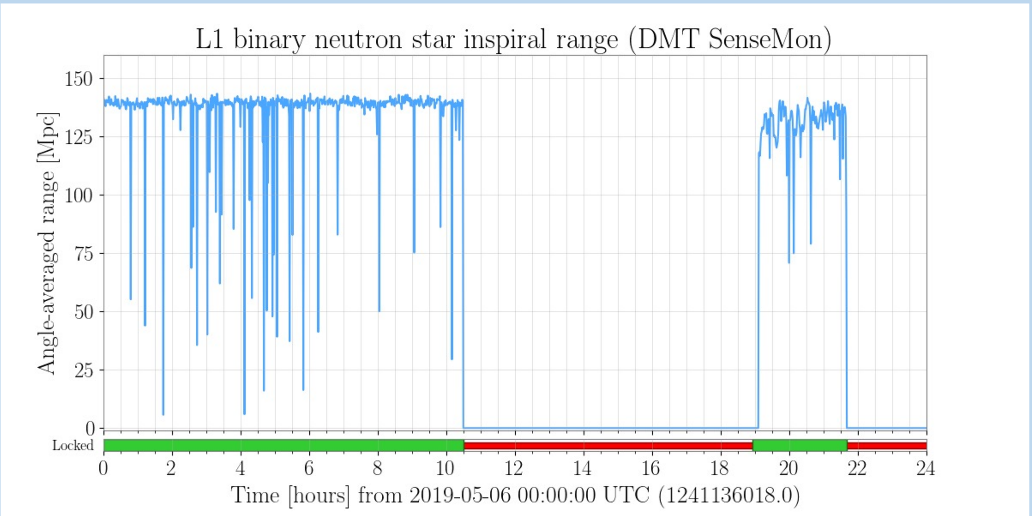

Figure 1: The binary coalescence range for 5 May 2019. The dips in the range are from loud transient noise events (glitches).

The Search for Burst Gravitational Waves

The Algorithm: Coherent WaveBurst (cWB)

The primary search algorithm for burst gravitational waves is **Coherent WaveBurst (cWB)** [4]. This method identifies excess power in the wavelet time-frequency representations of the detector strain data that is coherent between multiple detectors and reconstructs the source sky location and signal waveforms by using the constrained maximum likelihood method. cWB measures event strength using a quantity ρ, which is analogous to the signal-to-noise ratio.

Background Distribution

The burst searches must also estimate how likely it is that noise in the detectors would create a false positive, called the **background** rate. To determine how often a search detects a signal that is not astrophysical, the analysis must be performed on long periods of data that are created as to not contain true coincident gravitational waves. This is implemented by artificially introducing time shifts (*lags*) of one detector's data with respect to the others by an amount greater than the light travel time between the interferometers (~10 ms) and running cWB over this new data set, referred to as *nonzero-lag* data. Gravitational wave searches are produced on data that is not time shifted, *zero-lag* data.

Using triggers generated from time-shifted data, we can calculate the rate of accidental triggers (false alarm rate) with respect to strength and the probability that a trigger with a given strength is accidental (false alarm probability). The false alarm rate is calculated by counting the number of triggers with a given strength or greater and dividing by the total accumulated background time (total time obtained from time shifts). Many time-shifted analyses are performed to create statistics sufficient to give false alarm rates over an analysis period equivalent to thousands of years. The false alarm probability (FAP) is calculated using Poisson statistics and the false alarm rate (FAR), $FAP = 1 - e^{-(FAR)t_0}$, where t_0 is the total zero-lag time of the data.

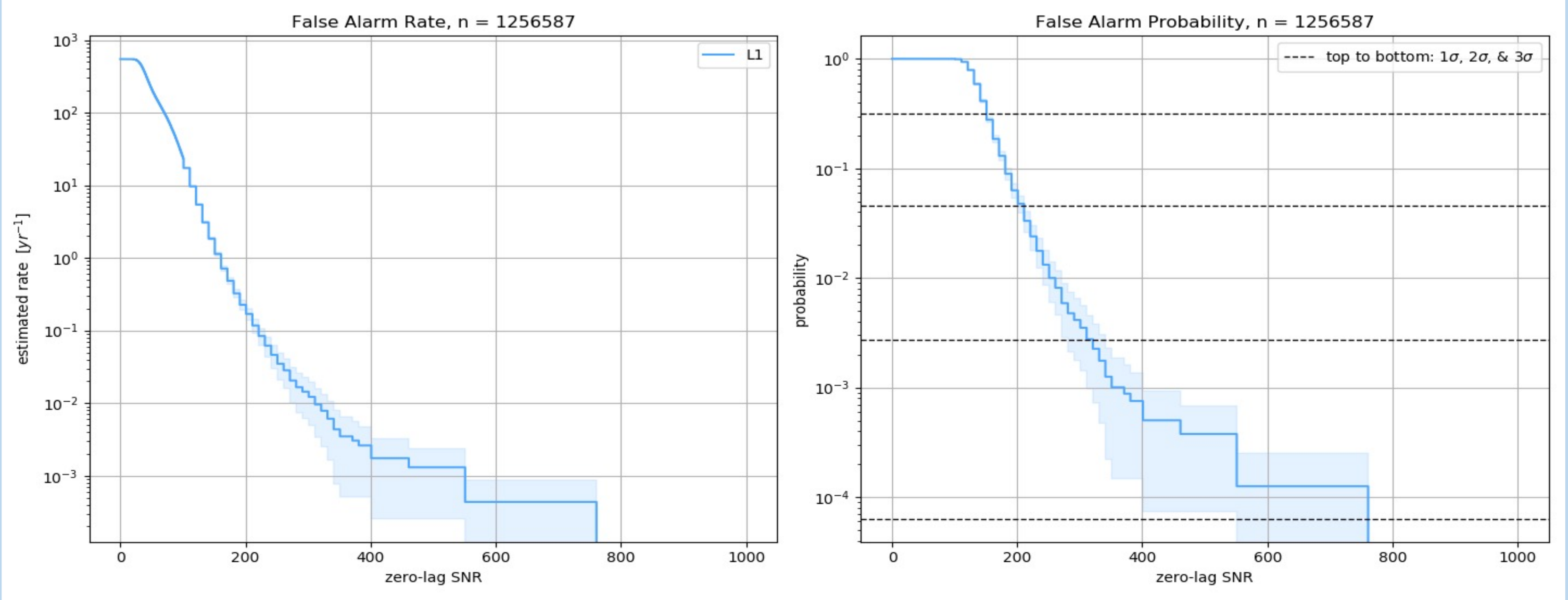

Figure 3: The background distribution of cWB events for the first of the 3rd observing run at the Livingston observatory. The background for the 1-hour segments used in the burst range calculation typically have a few tens of events (compared to the 1.2 million shown here) and yield a minimum false alarm rate on the order of 10/year.

Choosing Optimal Threshold Values

We conducted a study to determine what threshold value of false-alarm rate or false-alarm probability to use to determine the ρ_{det} to use in the range calculation. A rate/probability threshold value that is too low will output the strongest event in that segment, when that event most likely corresponds to a higher rate/probability. If this happens, the determined ρ_{det} is near-meaningless. Since the threshold is defined by a detectable rate/probability, a threshold that is too high runs the risk of not being a good approximation for a detectable gravitational wave.

Therefore, we designed our threshold study to determine what fraction of 1-hour segments had a given rate/probability is bounded between that of the strongest event (minimum) and the maximum observed value. The **actualization fraction** is defined to be fraction of segments where the given threshold was between these bounds. The Figure 4 shows the results for the first half of the 3rd observing run (O3a) at the Livingston Observatory; the results a very similar for the Hanford Observatory.

The results are broken down to the minimum amount of time that was contained in each 1-hour segment (there is not always data available for the full hour and the minimum amount of time processed by cWB was 600 seconds). For the false-alarm rate, we see that the actualization fraction reaches its maximum at about the same threshold value of 100 event/year regardless of the amount of data available in that hour. For the false alarm probability, we see that the actualization fraction reaches it maximum at different probabilities: around 0.005 for lowest minimum data available (600 seconds) to around 0.01 for the highest minimum data available (3000 seconds). This suggests that if we were to use false alarm probability to determine ρ_{det} for the range calculation, we may want to also place a threshold on the minimum amount of data available for the hour. That is, we may want to choose to only process data for the range calculation that meets this criterion. Therefore, we have chosen to keep as much data as possible, and calculate as many burst ranges as possible, by choosing to use the false-alarm rate of 100 event/year to calculate ρ_{det}.

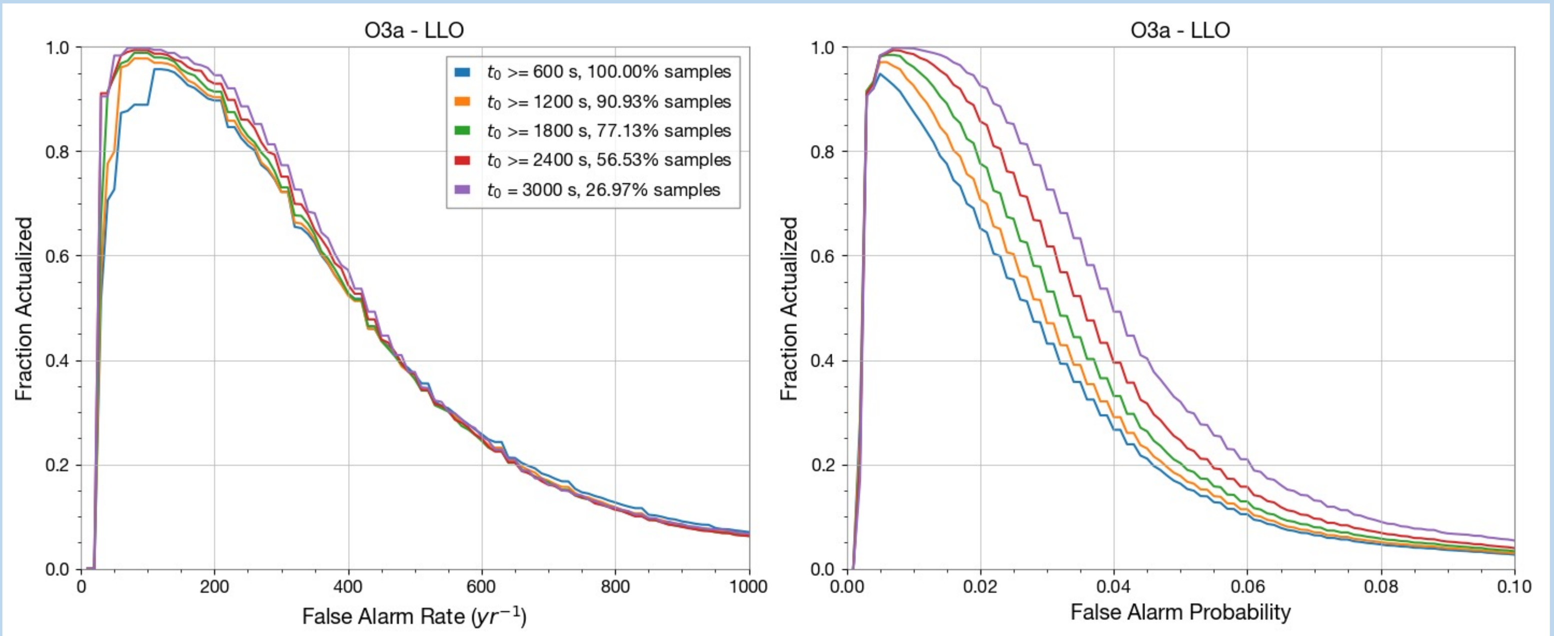

Figure 4: The actualization fraction (fraction of segments where the given threshold was between these minimum and maximum observed bounds in rate or probability) for a given proposed threshold value of false-alarm rate (left) or false-alarm probability (right) for 1-hour segments. Each trace indicated the minimum amount of data that was available in the hour segment. Ultimately, the false-alarm rate of 100 events/year was chosen to determine ρ_{det} due to this threshold being independent of the amount of data contained in the hour segment.

Burst Range

Theory

To make a similar calculation for burst gravitational waves where the waveform is not known, we base our new detectable distance (range) calculation on an isotropic, homogenous distribution of sources, the energy carried in burst gravitational waves from those sources, and how that translates into a signal to noise ratio measured by our detectors. Ultimately, the effective range is expressed as:

$$R_{eff}(f) \cong \left[\frac{G}{2\pi^2 c^3}\frac{E_{GW}}{S(f)f^2\rho_{det}^2}\right]^{1/2}$$

where E_{GW} is the energy carried in gravitational waves, $S(f)$ is the one-sided noise power spectrum, f is the frequency of a narrowband burst gravitational wave, and ρ_{det} is the detectable SNR above which the burst gravitational wave is considered detectable [2]. $R_{eff}(f)$ produces a range calculation over the range of frequencies that are included in the background distribution's search. This can also be averaged to calculate a single effective burst range as shown in Fig. 2.

Method

To produce Fig. 1, we used the results of the first half of the third observing run (O3a) Livingston-Hanford all-sky cWB search between 16-2048 Hz (the sensitive frequency range for this search). The range was calculated for *10-minute segments* by calculating $S(f)$ during that time and determining the SNR, ρ_{det}, for the *previous hour* ending at the conclusion of the 10-minute segment. **The SNR used in the range calculation was determined by finding the SNR where the false alarm rate crosses 100 triggers/year value using background distributions like those shown in Fig. 3.** E_{GW} is effectively a proportionality constant and 10-8 $M_{sun}c^2$ was chosen for this study to reflect a range for a typical core-collapse supernova [3].

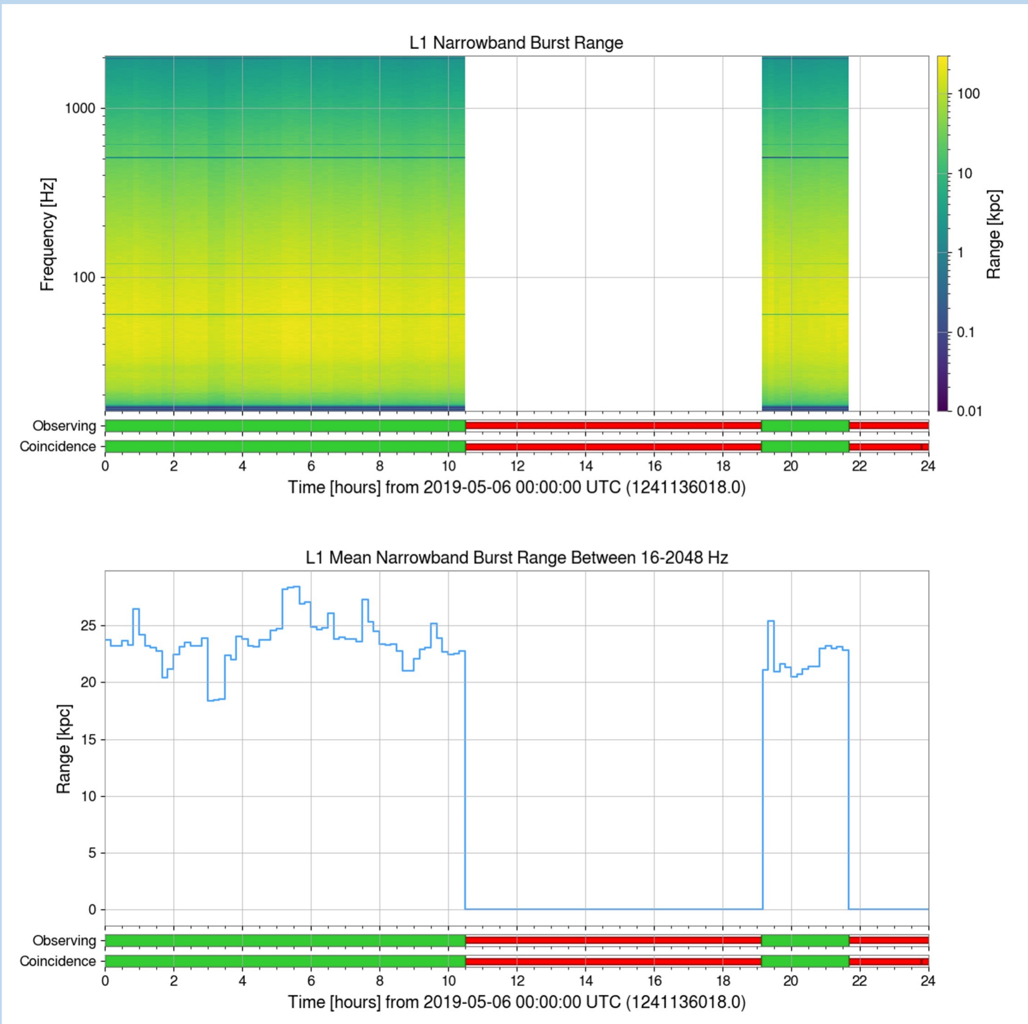

Figure 2: Example burst range calculation for 6 May 2019 at the LIGO Livingston Observatory (L1). The top graph shows a time-frequency representation of the range in 10-minute segments while the bottom shows the average range over the frequency range for each 10-minute segment.

Conclusions

This research has developed the core software needed to calculate a detectable distance (range) to a burst gravitational wave source that directly reflects the impact of the current data quality of the detector on the search gravitational waves.

Future Work

This work can also be used to study the effectiveness of other data quality mitigation efforts and determine what data quality issues the burst search is sensitive. Therefore, we are executing this over the full third observing run (O3) results and will attempt correlate times of poor range with specific data quality issues

For near-real time execution in the next observing run (O4) we automate production of range plots similar to Fig. 2, incorporate these into the LIGO summary web pages (which collect data quality and analysis results for the collaboration), test automated calculations during the O3 data playback before O4, and implement at the start of O4 (mid-December 2022).

Acknowledgments

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Sources

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