Development of a Burst Gravitational Wave Detectable Range Visualization

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Abstract

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 applying a measure of the detectable distance for a burst gravitational wave that is sensitive to the near real-time data quality of the detector and the impact this data quality has on the search for bursts. We are using software developed using data from the third LIGO-Virgo-KAGRA observing run that collects results from Coherent WaveBurst, a burst search algorithm, and calculates 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. We present the results of thresholding studies based on the fourth observing run (O4) data and how it compares to the results of the O3 data. We also compare the average ranges for similar times of the year from O3 and O4 to determine if the improved O4 data quality results in better ranges. Ultimately, this work may provide near real-time feedback on how instrument changes or complications are affecting the search for burst gravitational waves.

Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is composed of 2 observatories (one in Hanford, Washington 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 near 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.

The Search for Burst Gravitational Waves

The Algorithm: Coherent WaveBurst (cWB)

The primary near real-time search algorithm for burst gravitational waves is **Coherent WaveBurst (cWB)** [3]. 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 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 other 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 the time-shifted data, we can calculate the rate of accidental triggers (false alarm rate or FAR) with respect to strength. 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 a period equivalent to thousands of years.

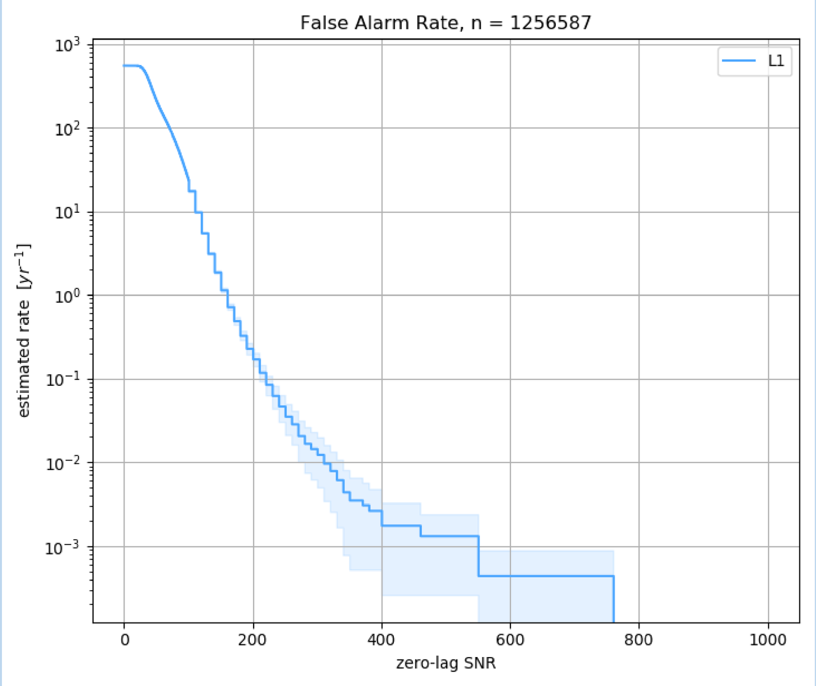

Figure 2: The background distribution of cWB events for O3a at the Livingston observatory. The background for the 1-hour segments used in the burst range calculation typically have a few tens of events (compared to the 1.2 million shown here) and yield a minimum false alarm rate on the order of 10/year.

Choosing Optimal Threshold Values

We conducted a study to determine what threshold value of false-alarm rate (FAR) to use to determine ρ_{det} in the range calculation. Since the range calculation is defined by a detectable SNR, a rate threshold value too low or too high runs the risk of not being a good approximation for a detectable gravitational wave.

We designed our threshold study to determine what fraction of 1-hour segments had a given rate bounded between that of the strongest event (minimum FAR) and the maximum observed FAR. The **actualization fraction** is defined to be the fraction of segments where the given threshold was between these bounds.

Figure 3 shows the results for O3a and O4a at the Livingston Observatory; Hanford had very similar results. Each trace indicates the minimum amount of data that was available in the hour segment; O4a has segments of data of 1200 and 2400 seconds. In O3a and O4a, the actualization fraction reaches its maximum at about the same threshold value of 100 events/year regardless of the amount of data available in that hour.

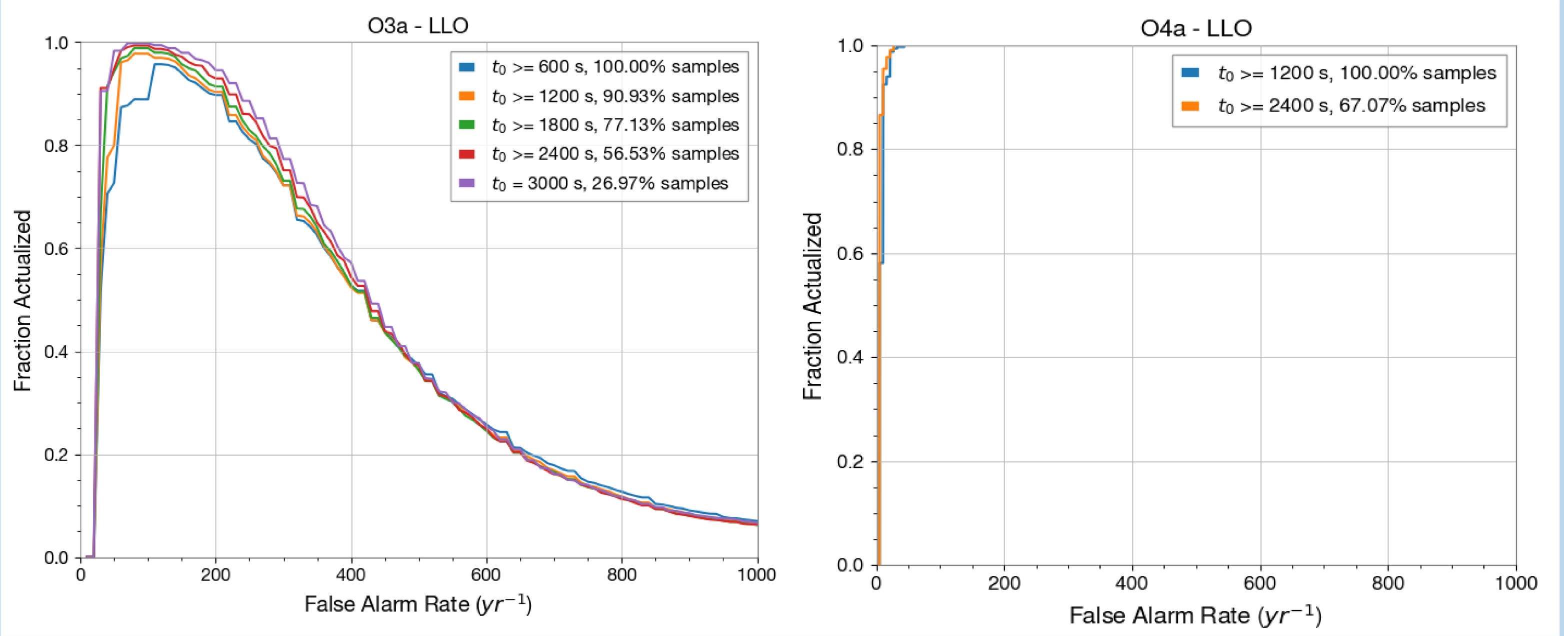

Figure 3: The actualization fraction (fraction of segments where the given threshold was between these minimum and maximum observed bounds) for a given proposed threshold value of false-alarm rate for 1-hour segments. Each trace indicates the minimum amount of data that was available in the hour segment. 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

We base the detectable burst 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 signal-to-noise ratio (SNR) above which the burst gravitational wave is considered detectable [1]. 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 [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 Figure 2.

Method

To produce Figure 2, we used the results from a day in the first half of the 4th observing run (O4a) using the Livingston-Hanford all-sky cWB search between 32-2048 Hz (the sensitive frequency range for this search). The range was calculated for *10-minute segments* by calculating $S(f)$ and determining the SNR and 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 Figure 2.**

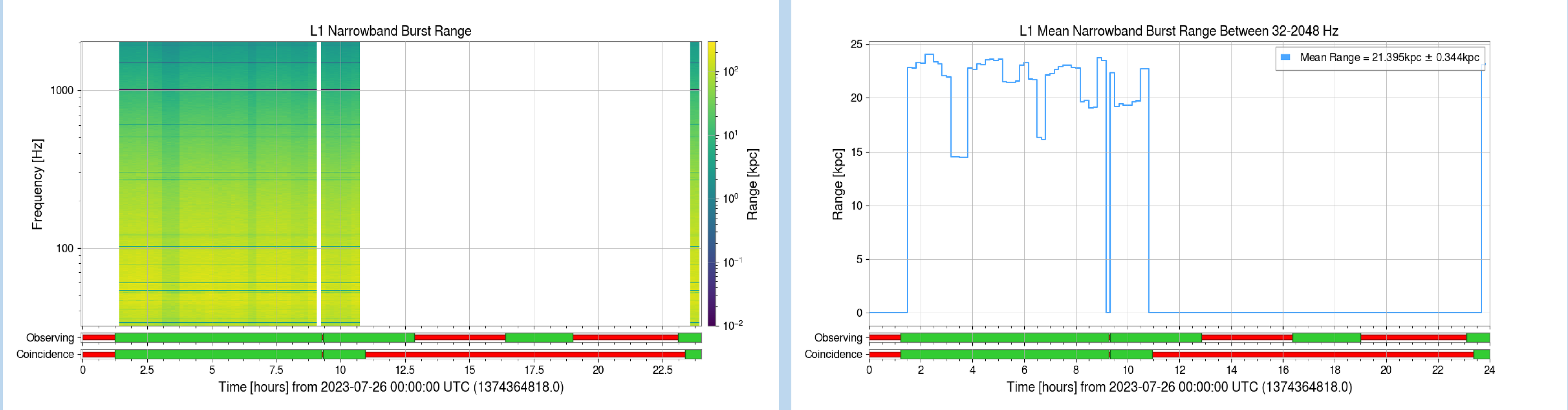

Figure 2: Example burst range calculation for 26 July 2023 at the LIGO Livingston Observatory (L1). The left graph shows a time-frequency representation of the range in 10-minute segments while the right shows the average range over the frequency range for each 10-minute segment. The average mean range in kpc is displayed on the plot.

O3 to O4a Range Comparisons

We chose the week of July 20th in O3 (2019) and O4a (2023) to compare the computed mean ranges and observe any differences in data quality. We observe the same dates in each run to account for any "seasonal noise" occurring near the detectors. This week was chosen because of the ample data available in both runs by both detectors.

We expect to see a higher average mean range for dates in O4, compared to O3, due to the instrument improvements made between the observing runs, making the detectors more sensitive and able to detect sources farther away

Table 1 presents the mean ranges calculated for the week of July 20 in O3 and O4, in both detectors (H1 and L1), and the average for the whole week. For this week, H1 shows marginal improvement in range, where L1 shows greater improvement. We can credit this improvement to the instrument improvements made between the observing runs, increasing sensitivity in the detectors, though a larger sample is needed.

Table 1: The top chart shows a full week of mean ranges in both detectors in the 3rd observing run (O3). The last row is the average mean range of the week in kpc. The bottom chart shows the same week in the 4th observing run (O4). By comparing these ranges, we can determine if instrument improvements are increasing detector sensitivity and ultimately helping the burst search.

Mean Ranges (kpc) for Week of July 20, 2019	
O3 H1	O3 L1
20.822 ± 0.165	16.291 ± 0.228
19.654 ± 0.186	16.357 ± 0.189
19.356 ± 0.393	15.983 ± 0.354
21.309 ± 0.147	15.277 ± 0.270
19.398 ± 0.443	16.678 ± 0.555
22.534 ± 0.280	18.610 ± 0.607
21.983 ± 0.202	18.960 ± 0.274
20.722 ± 0.259	**16.879 ± 0.354**

Mean Ranges (kpc) for Week of July 20, 2023	
O4 H1	O4 L1
21.669 ± 0.507	20.550 ± 0.388
23.701 ± 0.367	21.347 ± 0.400
23.000 ± 0.293	21.630 ± 0.276
24.641 ± 0.245	23.265 ± 0.182
24.685 ± 0.310	22.997 ± 0.244
23.186 ± 0.570	21.853 ± 0.440
24.103 ± 0.217	21.395 ± 0.344
23.569 ± 0.358	**21.862 ± 0.325**

Conclusions

This research has developed the software needed to calculate a detectable distance to a burst gravitational wave source that directly reflects the impact of the current data quality of the detector. The software has been updated to be applicable to O4 (via the thresholding study) and preliminary analysis shows improvement in data quality for O4 when compared to the same date in O3.

Future Work

As O4 continues, the range for a large sample of days will be calculated and significance tests will be run to determine the improvement of data quality from O3 to O4.

We will continue to execute this software over the 4th observing run (O4) results and will attempt to correlate times of poor range with specific data quality issues. We would like this software added to the LIGO Summary Pages to provide near real-time feedback on how instrument changes or complications are affecting the search for burst gravitational waves.

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Sources

[1] P. Sutton, "A Rule of Thumb for the Detectability of Gravitational-Wave Bursts," *arXiv,* no. 1304.0210.

[2] K. Kotake, "Multiple physical elements to determine the gravitational-wave signatures of core-collapse supernovae," *C.R.Physique*, vol. 14, pp. 318-351, 2013.

[3] S. Kilmenko, G. Vedovato, M. Drago, F. Salemi, V. Tiwari, G. Prodi, C. Lazzaro, K. Ackley, S. Tiwari, C. Da Silva and G. Mitselmakher, "Method for detection and reconstruction of gravitational wave transients with networks of advanced detectors," *PRD,* vol. 93, no. 4, p. 042004, 2016.