All-sky search for long-duration gravitational-wave bursts in the third Advanced LIGO and Advanced Virgo run

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After the detection of gravitational waves from compact binary coalescences, the search for transient gravitational-wave signals with less well-defined waveforms for which matched filtering is not well-suited is one of the frontiers for gravitational-wave astronomy. Broadly classified into "short" $\lesssim 1$ s and "long" $\gtrsim 1$ s duration signals, these signals are expected from a variety of astrophysical processes, including non-axisymmetric deformations in magnetars or eccentric binary black hole coalescences. In this work, we present a search for long-duration gravitational-wave transients from Advanced LIGO and Advanced Virgo's third observing run from April 2019 to March 2020. For this search, we use minimal assumptions for the sky location, event time, waveform morphology, and duration of the source. The search covers the range of 2 – 500 s in duration and a frequency band of 24 – 2048 Hz. We find no significant triggers within this parameter space; we report sensitivity limits on the signal strength of gravitational waves characterized by the root-sum-square amplitude h_{rss} as a function of waveform morphology. These h_{rss} limits improve upon the results from the second observing run by an average factor of 1.8.

I. INTRODUCTION

The third observing run of the Advanced LIGO [1] and Advanced Virgo [2] detectors has revealed a large number of new gravitational-wave signals from the collision of compact objects. Many binary black hole systems [3] have been identified. These include GW190521 [4] with the largest progenitor masses discovered so far, and GW190814, a merger containing an object in the "mass-gap" between neutron stars and black holes [5]. A second binary neutron star (BNS) system was also discovered, GW190425 [6], following the first BNS system GW170817 [7], which also produced GRB 170817A [8] and an optical transient, AT 2017gfo [9]. In addition, two neutron star-black hole (NSBH) binary coalescences (GW200105_162426 and GW200115_042309) have also been detected [10].

Searches for "long" $\gtrsim 1$ s duration signals cover a variety of astrophysical phenomena [11]. While well-modeled compact binary coalescences can have similar durations in the sensitive band of the interferometers and the methods employed in this paper are also sensitive to them, this search is not aimed at these systems as matched filtering is much more sensitive. However, there are less well-defined waveforms for which matched filtering is not well-suited. Plausible processes include fallback accretion onto a rapidly rotating black hole [12] or in newborn neutron stars [13–15]. They also include non-axisymmetric deformations in magnetars [16] or accretion disk instabilities and fragmentation of material spiraling into a black hole [17–19] and in the central engine of super-luminous supernovae [20, 21]. Figure 1 shows several different realizations of the corresponding waveform morphologies.

In this paper, we present the results of unmodeled long-duration transient searches from the third observing run, updating the results from the first two observing runs [22, 23]. As in previous analyses [22–25], three pipelines are used; their different assumptions and data handling techniques yield complementary coverage of the signal models.

The paper is organized as follows. The data used in the analysis is described in Section II. The algorithms used to analyze the data are outlined in Section III. The results of the analysis and their implications are discussed in Section IV.

II. DATA

The third observing run (O3) of Advanced LIGO and Advanced Virgo spanned April 1, 2019 - March 27, 2020. O3 was broken up into two segments, with O3a running April 1, 2019 - Oct 1, 2019 and O3b running November 1, 2019 - March 27, 2020; together, these correspond to 330 days. It is customary to assess detector sensitivities in terms of a binary neutron star inspiral range (BNS range), which is the average distance to which these signals could be detected [28, 29]. Detector upgrades to the LIGO detectors in Hanford, WA and Livingston, LA yielded binary neutron star ranges of ∼115 Mpc and 133 Mpc respectively, amounting to improvements of ∼50% with respect to O2. Similarly, Advanced Virgo reached a binary neutron star range of ∼50 Mpc, a ∼100% improvement. In the following, the algorithms employed require at least two detectors to be available to process the data; therefore, only data where both LIGO detectors are simultaneously available is used. Due to the significant difference in detector alignment and sensitivities, the Virgo data in the analysis would not improve the coincidence selection when the other two detectors are active, while the high rate of non-Gaussian noise would increase the overall false-alarm rate. We plan to include Virgo in the analysis of the next observing run.

A major challenge in searches for gravitational-wave transients is non-Gaussian noise. Known sources of noise, including non-linear sources such as time-varying spectral lines, from, e.g., machinery on-site, side-bands from the 60 Hz power lines, can be witnessed and subtracted

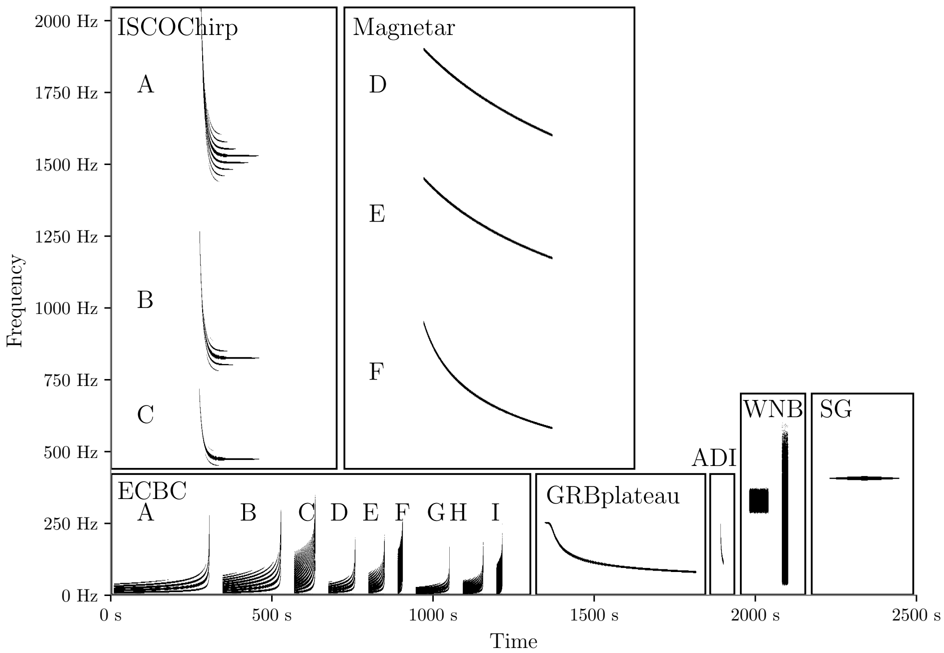

FIG. 1. Time-frequency spectrogram of the reference waveforms used in this search. We show examples of astrophysical waveforms such as post-merger magnetars (Magnetar) [26], black hole accretion disk instabilities (ADI) [18], newly formed magnetar powering a gamma-ray burst plateau (GRBplateau) [16], eccentric inspiral-merger-ringdown compact binary coalescence waveforms (ECBC) [27], broadband chirps from innermost stable circular orbit waves around rotating black holes (ISCOchirp) [12], and "ad-hoc" waveforms, band-limited white noise burst (WNB) and sine-Gaussian bursts (SG). The ISCOChirp waveforms have been shifted up in frequency by 50 Hz for readability. Durations range from 6 s (ADI-B) to 470 s (GRBplateau).

using both linear Wiener filters [30] and machine learning techniques [31, 32]. The analyses that follow use data for which some of the identified sources of noise that couple in linearly to the detector have been subtracted. Beyond spectral features, there are transient noise triggers known as *glitches*, which have a variety of origins [33], such as the light reflected from surfaces such as the chamber walls and scattered back into the main beam [34]. Glitch rejection procedures rely on correlations with auxiliary channels [35, 36] such as seismometers and magnetometers; yet, noise transients not witnessed by auxiliary sensors remain and reduce sensitivity of the searches [37, 38]. Each pipeline, described in the next section, implements different strategies to reduce the impact from glitches. Altogether, during the third observing run, coincident data of sufficient quality to be analyzed totaled 204.4 days. Since some time segments are too short to be processed by search pipelines, a small fraction ($< 2\%$) of this coincident data is not analyzed.

III. SEARCHES

Long-duration unmodeled searches are now briefly reviewed, and we refer the reader to previous publications for further detail [22, 23]. Most unmodeled searches use time-frequency spectrograms with statistics derived from Fourier transforms or wavelet analysis performed on consecutive time segments. Pattern-recognition algorithms then are employed to search for gravitational waves in these spectrograms. These algorithms can be classified as: "seed-based" [39, 40], for which pixels above pre-determined thresholds are clustered, and "seedless" [41, 42], for which sequences of pixels are derived from generic models, such as Bézier curves [41–45]. Seedless clustering algorithms are sensitive to narrowband signals at the price of sensitivity to broadband sources, while seed-based algorithms are generally more sensitive to more generic waveform morphologies. These algorithms identify candidate gravitational-wave events known as *triggers*. To estimate the background, all pipelines use "time-slides," [46, 47], where detector data is shifted by non-physical time delays and reanalyzed; this procedure is repeated a sufficient number of times such that at least 50 years of coincident live time is analyzed, allowing for a false alarm rate of 1 per 50 years to be estimated.

Three pipelines are deployed in the analysis: two different versions of the Stochastic Transient Analysis Multi-detector Pipeline - all sky (STAMP-AS) pipeline [11, 40, 45] and the long-duration configuration of coherent WaveBurst (cWB) [48]. The cWB pipeline is seed-based while the two STAMP-AS algorithms, Zebragard and Lonetrack, use seed-based and seedless clustering algorithms respectively. Altogether, the analyses are sensitive to transients lasting 2 – 500 s and covering a frequency band of 24 – 2048 Hz. Due to the short duration of binary black hole signals and the weakness of the coalescences containing neutron stars observed during O3 [6], we are not sensitive to and therefore do not excise any time around known compact binary coalescences. All false alarm rates reported are per pipeline, with no combination of searches made outside of reporting the most sensitive limit across the parameter space below.

STAMP-AS. Spectrograms, with duration 500 s and frequency band 24 – 2048 Hz and a pixel size of 1 s × 1 Hz, are derived with cross-power SNR as the statistic computed in the maps. Non-stationary, high-amplitude spectral features are masked to limit their effect on the search. Zebragard uses cuts on the fraction of SNR per time bin (summing all pixels of the same time index) and the ratio in SNR between detectors to remove data transients [22]; Lonetrack does not require this cut due to the narrowband assumption. During a short period of time, a time segment veto that flags periods of instabilities in the high-power laser at Hanford is applied on Zebragard triggers [38].

cWB. The algorithm used by cWB [48] is based on a maximum likelihood approach applied to the multiresolution time-frequency representation of the time series of the detectors' data. Candidate triggers are identified as a cluster if there is a coherent excess power in the time-frequency pixel representation over the network data. The search is performed in the frequency range 24 – 2048 Hz. Selection criteria are applied on the duration and on the coherence of the trigger; the coherence coefficient, measuring the degree of correlation between the detectors, must be larger than 0.6 [48]. Moreover, the trigger energy-weighted duration, defined as

$$d = \sqrt{\frac{\sum w_i (t - t^*)^2}{\sum w_i}} \quad ,$$

where t is the central time of the pixel, w the energy of the pixel, t^* the mean time and the sum is computed over the selected pixels of the event in all the resolutions, is required to be greater than 1.5 s. Since observed glitch excess in the 16 – 48 Hz band, associated with elevated anthropogenic noise, is different between the first and second part of the run, the acceptance criteria in the latter one have been slightly modified. The triggers have an energy-weighted duration larger than 0.5 s and a total duration greater than 5 s, this to ensure increased acceptance for the eccentric compact binary waveforms family discussed in the next section.

IV. RESULTS AND FUTURE PROSPECTS

The detection threshold is defined to be a false alarm rate lower than 1/50 years (equivalent to 6.3×10^{-10} Hz). None of the pipelines found triggers consistent with such a false alarm rate; the most significant triggers, non-overlapping between the different pipelines and consistent with the background, are listed in Table I. The most significant event reported by the cWB algorithm (statistical significance $\sim$1.7 σ, p-value 0.088) shows a time-frequency map composed of two separated excess power cluster pixels, respectively, at 838 Hz and 861 Hz mean frequency. This trigger appears to be associated with a random (time) coincidence of pixels belonging to two different non-stationary spectral lines of unknown origin, at 838 Hz (present in H1 and L1) and 861 Hz (present in H1). The STAMP-AS Zebragard and Lonetrack pipeline triggers are consistent with typical events identified in the background.

Pipeline	FAR [Hz]	p-value	Frequency [Hz]	Duration [s]	Time [GPS]
cWB	1.0×10^{-8}	0.088	838-861	16	1252808855
Zebragard	5.6×10^{-8}	0.40	1650-1769	21	1244819393
Lonetrack	1.7×10^{-8}	0.14	1510-1937	417	1253105020

TABLE I. Properties of the most significant coincident triggers found by each of the long-duration transient search pipelines during the third observing run. FAR stands for false alarm rate, while the p-value is the probability of observing at least 1 noise trigger at higher significance than the most significant coincident trigger.

To place these results in context, upper limits are derived on the gravitational-wave strain amplitude using a set of simulated waveforms added coherently into detector data. Waveforms that span the parameter space in both frequency and time, as well as a sampling of potential astrophysical models, are used. For the astrophysical models, post-merger magnetars (Magnetar) [26], black hole accretion disk instabilities (ADI) [18], newly formed magnetar powering a gamma-ray burst plateau (GRBplateau) [16], eccentric inspiral-merger-ringdown compact binary coalescence waveforms (ECBC) [27], and broadband chirps from innermost stable circular orbit waves around rotating black holes (ISCOchirp) [12] are used (see Ref. [49] for further developments). To include signal morphologies otherwise not addressed by the astrophysical models, "ad-hoc" waveforms, band-limited white noise burst (WNB) and sine-Gaussian bursts (SG) are also used. Their time-frequency spectrograms are shown in Figure 1.

The upper limits on the gravitational-wave strain amplitude are typically reported for unmodeled searches using the root-sum-square gravitational-wave amplitude at the Earth, $h_{\rm rss}$,

$$h_{\rm rss} = \sqrt{\int_{-\infty}^{\infty} \left(h_+^2(t) + h_\times^2(t)\right) \mathrm{d}t}, \tag{1}$$

where h_+ and $h_\times$ are the two signal polarizations. Simulations are varied with $h_{\rm rss}$ and injected uniformly in time, sky location, polarization angle and the cosine of the inclination angle of the assumed source.

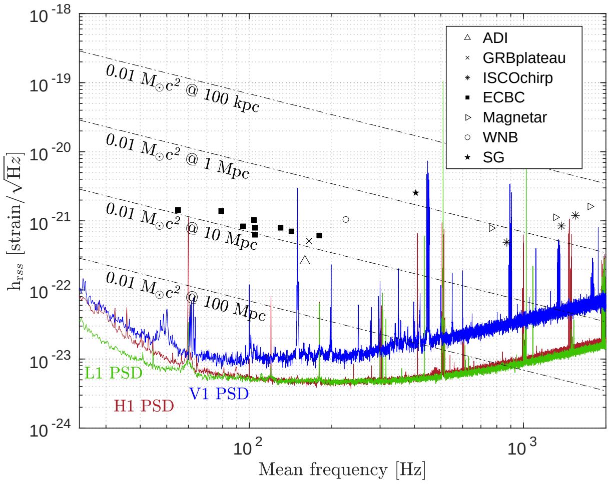

FIG. 2. The GW root-sum-square strain amplitude versus mean frequency at 50% detection efficiency and a FAR of 1/50 years. The red, green and blue curves are the averaged amplitude spectral noise densities for Hanford, Livingston and Virgo detectors to show that the search results follow the detectors' sensitivity frequency. We also show in dashed-dotted lines the gravitational-wave amplitudes corresponding to the energy of 0.01 $M_\odot c^2$ at various distances, with examples at 100 kpc, 1 Mpc, 10 Mpc and 100 Mpc shown.

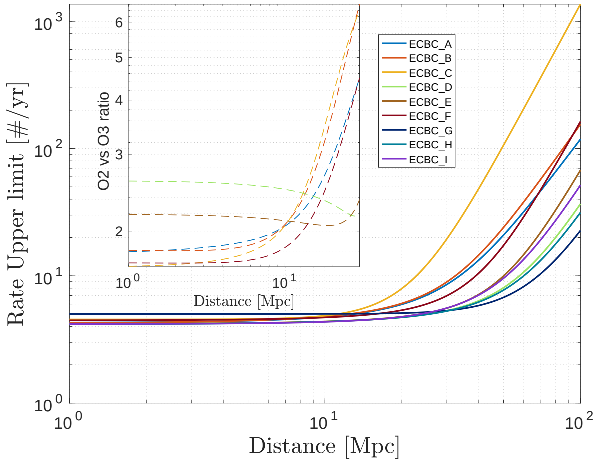

FIG. 3. Upper limits at 90% confidence level on the rate of eccentric compact binary coalescences as a function of the distance. Only the best result is shown for each waveform. The inset shows the ratio of the rates with respect to O2 results [23] for ECBC_A to ECBC_F (see Table II for parameters).

Waveform	$M_1[M_\odot]$	$M_2[M_\odot]$	e	$\mathcal{R}_{90\%}$ [$\text{Gpc}^{-3}\text{yr}^{-1}$]
ECBC_A	1.4	1.4	0.2	9.97×10^2
ECBC_B	1.4	1.4	0.4	8.09×10^2
ECBC_C	1.4	1.4	0.6	3.21×10^3
ECBC_D	3.0	3.0	0.2	3.99×10^2
ECBC_E	3.0	3.0	0.4	8.89×10^2
ECBC_F	3.0	3.0	0.6	2.43×10^3
ECBC_G	5.0	5.0	0.2	1.50×10^3
ECBC_H	5.0	5.0	0.4	5.10×10^2
ECBC_I	5.0	5.0	0.6	6.98×10^2

TABLE II. Rate upper limits per unit volume at 90% confidence level on eccentric compact binary coalescences with various masses and eccentricity e, computed with equation 2.

Upper limits on gravitational-wave strain versus mean frequency for sources detected with 50% efficiency and a false alarm rate of 1 event in 50 years are shown in Figure 2. The strongest bounds obtained from the three pipelines are shown on the plot. Because each pipeline uses a different clustering algorithm, their relative sensitivities vary with waveform morphology. Lonetrack, which uses seedless clustering, performs best on magnetar signals (Magnetar and GRBplateau) but is not sensitive to white noise bursts. Zebragard and Coherent WaveBurst give the most constraining values with similar sensitivities for most of the remaining waveforms. On average, for all waveforms considered in this paper, the h_{rss} sensitivity improved by a factor of 1.8 upon the analysis from the second observing run [23].

For the eccentric binary waveforms, we determine 90% confidence level limits on the rate of events. We do this using the "loudest event statistic" method, which uses the candidate with the largest value to estimate rate constraints [50]. Taking as an example the eccentric binary waveforms, the 90% upper limits on the event rates as a function of distance are highlighted in Figure 3. In addition, Table II gives the upper limits $\mathcal{R}_{90\%}$ at 90% confidence on the rate of eccentric binary coalescences per unit volume. Following [51], and assuming an isotropic and uniform distribution of sources, $\mathcal{R}_{90\%}$ is given by

$$\mathcal{R}_{90\%} = \frac{2.3}{4\pi T \int_0^{r_{\max}} dr\, r^2\, \epsilon(r)}, \tag{2}$$

where $\epsilon(r)$ is the detection efficiency as a function of distance, computed as the fraction of transients detectable at a given distance [51], $r_{\max}$ is the maximum detectable distance, and $T = 204.4$ days is the total observing time. For $1.4 - 1.4$ solar masses eccentric binaries, rate upper limits are $\sim 1.5 - 2$ lower than the ones computed in [52] for O2 data. Such improvement can be explained by both the increased sensitivity of the search and the increased livetime between O2 and O3. For comparison, estimated merger rates from the second LIGO-Virgo GW transient catalogue [53] are $23.9^{+14.3}_{-8.6}\ \text{Gpc}^{-3}\text{yr}^{-1}$ and $340^{+490}_{-240}\ \text{Gpc}^{-3}\text{yr}^{-1}$ for binary black holes and binary neutron stars respectively. With eccentric systems expected to be only a small fraction of the total binary systems, the upper limits derived are compatible with an absence of detection of such systems in this search; for this reason, we do not constrain the fraction of eccentric binary systems, but this may become possible in the future with more sensitive detector data.

It is expected that continued improvements both to the gravitational-wave detectors and to the search algorithms, e.g. [49, 54, 55], will lead to either detections or improved limits on this portion of parameter space. Going forward, increasing the parameter space searched, such as for longer signals, is a high priority; these signals may include long-lived remnants of binary neutron star mergers, whose detection in gravitational waves may constrain the nature of the remnant [12, 25]. In addition, integration of Advanced Virgo into the analyses will be important, especially in case of a genuine signal for characterization. With range improvements of ∼50% expected for the fourth observing run and more than a factor of 2 expected by the fifth observing run [28], significant gains in detection possibilities can be expected.

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