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Open Data from the Third Observing Run of LIGO, Virgo, KAGRA, and GEO

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Open Data from the Third Observing Run of LIGO, Virgo, KAGRA, and GEO

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Abstract

The global network of gravitational-wave observatories now includes five detectors, namely LIGO Hanford, LIGO Livingston, Virgo, KAGRA, and GEO 600. These detectors collected data during their third observing run, O3, composed of three phases: O3a starting in 2019 April and lasting six months, O3b starting in 2019 November and lasting five months, and O3GK starting in 2020 April and lasting two weeks. In this paper we describe these data and various other science products that can be freely accessed through the Gravitational Wave Open Science Center at https://gwosc.org. The main data set, consisting of the gravitational-wave strain time series that contains the astrophysical signals, is released together with supporting data useful for their analysis and documentation, tutorials, as well as analysis software packages.

Unified Astronomy Thesaurus concepts: Gravitational wave astronomy (675); Experimental data (2371)

1. Introduction

Gravitational-wave (GW) detectors develop through successive generations of instruments with increasing sensitivity (Abbott et al. 2020a). The US-based Advanced LIGO[306] detectors (Aasi et al. 2015) were the first two instruments of the current generation to begin operation, collecting data during the first observing run (O1) from 2015 September to 2016 January, including the first direct detection of GWs (Abbott et al. 2016). The second observing run (O2) followed from 2016 November to 2017 August, with the European detector Advanced Virgo (Acernese et al. 2015) joining in 2017 August. The GEO 600 detector in Germany (Dooley et al. 2016) serves as a center of research and development, and is used to test a number of critical detector technologies. Another GW detector, the Japan-based KAGRA (Akutsu et al. 2021), has also been rapidly developing.

This article focuses on the data collected during the third observing run, O3, that took place from 2019 April 1 to 2020 April 21. The bulk of this observing run collected data only from LIGO and Virgo, and is divided into two main operational phases: O3a from 2019 April 1 to 2019 October 1, and O3b from 2019 November 1 to 2020 March 27, with a one month maintenance break between the two phases. KAGRA was expected to join O3, but this initial plan changed due to the outbreak of COVID-19. Instead, KAGRA and GEO 600[307] operated during an extended observing phase, O3GK, from 2020 April 7 to April 21 (Abbott et al. 2022).

The analysis of the O3 data has led to numerous publications. Those include several updates to the Gravitational-Wave Transient Catalog (GWTC; Abbott et al. 2021a, 2021b, 2021c) that compiles transient sources analyzed and reported by the combined LIGO–Virgo–KAGRA (LVK) Collaboration. The cumulative GWTC catalog currently includes nearly 100 candidate sources (with a probability of astrophysical origin >50%), all associated with the coalescence of compact star binaries composed of either neutron stars, black holes, or both.

Following the policy defined in the LIGO Data Management Plan (LIGO Laboratory 2022) and the Memorandum of Understanding (LIGO Scientific Collaboration & Virgo Collaboration 2019), the O3 data set and associated science products are published through the Gravitational-Wave Open Science Center (GWOSC) at https://gwosc.org,[308] allowing reproducibility of the analyses performed by the LVK Collaboration and increasing the impact of the data through

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[304] Deceased, 2021 December.
[305] Deceased, 2022 March.
[306] Laser Interferometer Gravitational-Wave Observatory

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[307] The GEO 600 detector collected data during the O3a and O3b phases of the O3 science run, as indicated in the time line (https://gwosc.org/timeline/show/history/G1_SCI/1238166018/31203000), in the so-called "Astrowatch" mode. Because of the substantial sensitivity difference between GEO and LIGO or Virgo, the data are not employed in the various analyses and hence are not released publicly. The Astrowatch data can be used in the case of an extraordinary astrophysical event (such as a Galactic core-collapse supernova) during the periods when the other detectors are down.
[308] This website is also accessible at https://gw-openscience.org.

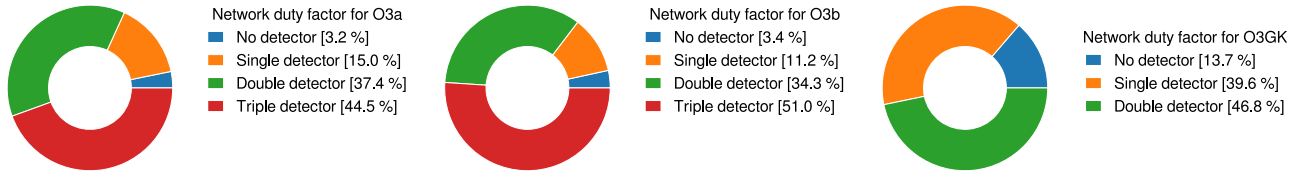

Figure 1. Duty factors for the LIGO and Virgo detector network during O3a (left) and O3b (center), and for the KAGRA and GEO 600 detector network during O3GK (right). These factors measure the fraction of time spent as a function of the number of detectors in operation. The same plots (with the caveat of a difference in the color code) can be found on the GWOSC web summary pages for O3a (see footnote 311) and O3b (see footnote 312) and have been produced from Abbott et al. (2022) for O3GK.

its wider use. This paper provides a description of the publicly released data[309] along with additional information on their usage.

To date hundreds of scientific articles have been written using the data available from the GWOSC website (all data sets combined).[310] These analyses confirm, complement, and extend the results published by the LVK Collaboration. They cover a wide range of topics, including searches for GW signals (Nitz & Wang 2022; Olsen et al. 2022; Nitz et al. 2023; Steltner et al. 2023; Whelan et al. 2023), studies of compact binary populations (see, e.g., Roulet et al. 2021; Callister & Farr 2023; Périgois et al. 2023), tests of general relativity (see, e.g., Capano et al. 2021, 2022; Estellés et al. 2022; Lyu et al. 2022; Wang et al. 2022), or methodological contributions (see, e.g., Davis et al. 2022), demonstrating the broad impact on the scientific community of the GW data releases.

This paper is organized as follows. Section 2 summarizes the status of the detectors during the observing run O3, together with high-level indicators such as their distance reach and duty cycle of operation. This section also provides insights about how the data are collected and calibrated, about data quality, and about simulated signal injections. Section 3 describes the format, content, and provenance of the strain data files distributed through the GWOSC, including the nomenclature used for the calibration versions and channel names. Section 4 describes the Event Portal, a searchable GW event database accessible online. Details about the technical validation and review of the data and documentation are given in Section 5. Finally, Section 6 provides some guiding principles to the novice user and suggests software tools that can be used to analyze the data.

2. Instruments

The Advanced LIGO (Aasi et al. 2015) and Advanced Virgo (Acernese et al. 2015) detectors are enhanced Michelson interferometers with arm lengths of 4 km and 3 km, respectively. Advanced LIGO comprises two detectors located at two different sites in the US, namely, in Hanford, WA and Livingston, LA, while Advanced Virgo has a single site in Cascina, close to Pisa, Italy. The various instrument upgrades realized between the science runs O2 and O3 for the LIGO and Virgo detectors are described in Buikema et al. (2020), Abbott et al. (2021a, 2021c), and Acernese et al. (2022a). They involve many parts of the instruments, including the main laser source and the core optics along with the installation of mitigation systems for a range of technical noises. One of the major novelties in O3 both for LIGO and Virgo is the use of squeezed light sources (see Tse et al. 2019 for LIGO and Acernese et al. 2019 for Virgo), a technique (Schnabel et al. 2010; Barsotti et al. 2019) that significantly reduces quantum noise, thus enhancing the sensitivity at high frequency. Due to the implementation of this technique, the binary neutron star (BNS) inspiral range (see next section) has increased by 14%, 12%, and 5%–8% for LIGO Livingston, LIGO Hanford, and Virgo, respectively.

GEO 600 (Dooley et al. 2016) is a British–German interferometric GW detector with 600 m arms located near Hannover, Germany. As in LIGO and Virgo, quantum squeezing is used to reduce noise in the output measurement quadrature (Lough et al. 2021). This technique was first demonstrated by GEO 600 (Abadie et al. 2011). KAGRA is an underground laser interferometer with 3 km arms, located underground at the Kamioka Observatory in Gifu Prefecture, Japan. An important feature of its design is the cooling system intended to bring the large mirrors of the interferometer to cryogenic temperature (around 20 K) in order to reduce thermal noise (Chen et al. 2014; Akutsu et al. 2016). During the O3GK run however, the detector was operated at room temperature (Akutsu et al. 2018, 2021).

2.1. Detector Performance

A GW detector's performance is often globally characterized by two measures: its duty factor, defined as the fraction of time the detector is recording observational quality data, and its distance reach, conventionally measured as the BNS inspiral range (Finn & Chernoff 1993; Chen et al. 2021), the distance to which a BNS inspiral could be detected with a signal-to-noise ratio (S/N) of 8, assuming 1.4 $M_\odot$ component objects and averaging over source position and orientation. The choice of this metric is a standard convention. The value of 1.4 $M_\odot$ is close to the measured masses of the stars in the Hulse–Taylor binary (Weisberg & Huang 2016) and within the narrow range predicted by stellar evolution for neutron star masses. The distance reach of the detectors strongly depends on the source mass. For example, binary black hole (BBH) systems can typically be detected at much greater distances, up to several gigaparsecs (e.g., Abbott et al. 2021c, Table 4).

The GWOSC website hosts summary pages for O3a[311] and O3b,[312] which describe the LIGO and Virgo operations and sensitivity. The duty factors during O3a are 71% for LIGO Hanford (H1), 76% for LIGO Livingston (L1), and 76% for Virgo (V1). During O3b, the corresponding percentages are 79%, 79%, and 76%, respectively. Those translate into the observing factors shown in Figure 1 that quantify the fraction

[309] See https://gwosc.org/O3/O3a/, https://gwosc.org/O3/O3b/, and https://gwosc.org/O3/O3GK/.
[310] See https://gwosc.org/projects for a list of articles that refer to the data published on the GWOSC website.
[311] https://gwosc.org/detector_status/O3a
[312] https://gwosc.org/detector_status/O3b

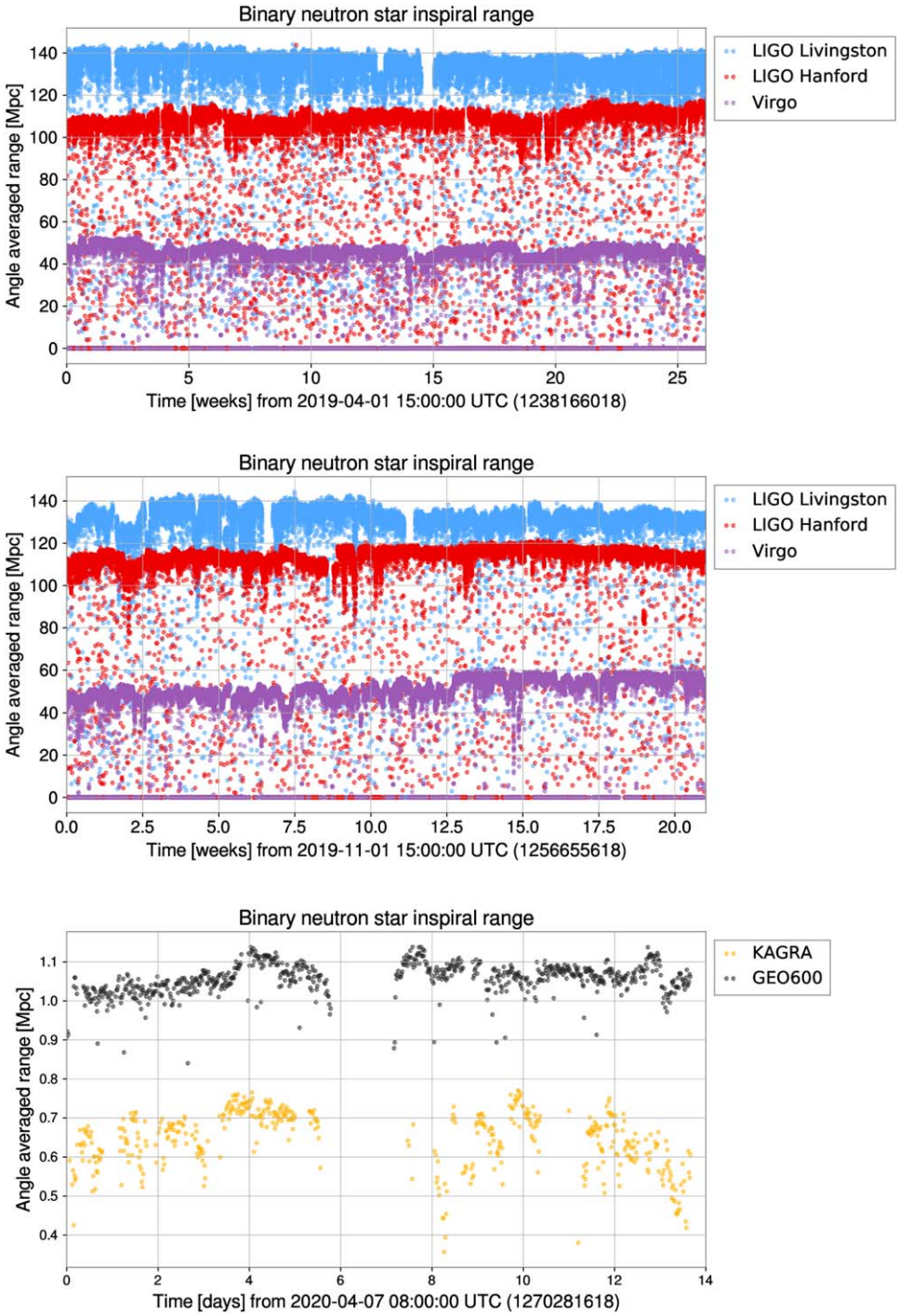

Figure 2. BNS ranges for O3a (upper plot), O3b (middle plot) with LIGO Hanford (red), LIGO Livingston (blue), and Virgo (purple), and for O3GK (bottom plot) with GEO 600 (black) and KAGRA (yellow). Similar plots (besides style differences) can be found on the GWOSC web pages for O3a (see footnote 311) and O3b (see footnote 312) and in Abbott et al. (2022) for O3GK.

of observing time spent with one, two, or three instruments in operation.

During the O3GK run, the duty factors of KAGRA (K1) and GEO 600 (G1) are 53% and 80%, respectively, leading to a coincident observing factor of 47% (Abbott et al. 2022). The lower duty cycle of KAGRA is due to the fact that alignment sensing and control with wave front sensors was not yet implemented at the time of the run, leading to a higher susceptibility to microseismic ground vibrations.

The median values of the BNS range over the whole observing run are 108 Mpc, 135 Mpc, and 45 Mpc for H1, L1, and V1, respectively, during O3a, and 115, 133, and 51 Mpc during O3b for the same detectors. The median values of the BNS range over the O3GK period are 0.66 Mpc for KAGRA and 1.06 Mpc for GEO 600. Figure 2 displays the median BNS range computed over regular intervals (5 minutes scale for LIGO and Virgo and 20 minutes scale for GEO 600 and KAGRA). The drops that can be observed in both plots are due to transient noise artifacts (discussed in Section 2.3) reducing the detector sensitivity temporarily. The BNS range shown in the recent GWTC publications such as Abbott et al. (2021a, Figure 3) and Abbott et al. (2021c, Figure 3) are averaged over

Table 1
The Channel Names and Frame Types Listed in This Table are Unique Identifiers in the LIGO, Virgo, GEO 600, and KAGRA Data Archives that Allow Tracing the Provenance of the Strain Data Released on GWOSC

Run	Det.	Channel Name	Frame Type
O3a	H1	H1:DCS-CALIB_STRAIN_CLEAN-SUB60HZ_C01	H1_HOFT_CLEAN_SUB60HZ_C01
O3a	L1	L1:DCS-CALIB_STRAIN_CLEAN-SUB60HZ_C01	L1_HOFT_CLEAN_SUB60HZ_C01
O3a	V1	V1:Hrec_hoft_16384Hz	V1Online
O3a (last two weeks)	V1	V1:Hrec_hoft_V1O3ARepro1A_16384Hz	V1O3Repro1A
O3b	H1	H1:DCS-CALIB_STRAIN_CLEAN-SUB60HZ_C01	H1_HOFT_CLEAN_SUB60HZ_C01
O3b	L1	L1:DCS-CALIB_STRAIN_CLEAN-SUB60HZ_C01	L1_HOFT_CLEAN_SUB60HZ_C01
O3b	V1	V1:Hrec_hoft_16384Hz	V1Online
O3GK	G1	G1:DER_DATA_HD_CLEAN	G1_RDS_C02_L3
O3GK	K1	K1:DAC-STRAIN_C20	K1_HOFT_C20

Note. H1 and L1 indicate the two LIGO detectors (Hanford and Livingston, respectively), V1 refers to Virgo, G1 refers to GEO 600, and K1 refers to KAGRA. The attribute `CLEAN-SUB60HZ` in H1 and L1 indicates that the noise-subtraction procedure described in Vajente et al. (2020) was used. The attributes `C01`, `V1Online`, and `V1O3Repro1A` refer to the calibration version.

a longer period (1 hr) and are thus less affected by transient noise. The longer gaps in the BNS inspiral range are due to maintenance intervals, instrumental issues, and earthquakes.

2.2. Calibration

The GW strain $h(t)$ is obtained and calibrated from variations of the optical power measured at the output port of each detector. The calibration procedure and the corresponding characterization of the systematic and statistical uncertainties are described in Viets et al. (2018) and Sun et al. (2020, 2021) for Advanced LIGO and Acernese et al. (2022b) for Advanced Virgo. Calibration is performed in two stages: an initial, online calibration used for low-latency analysis, and a final, offline calibration that applies any needed corrections to the initial result. The offline calibration may correct for computer failures, incomplete modeling of the detectors, or any systematic errors characterized after the observing period. The uncertainties in the calibration procedure for both the magnitude and phase of $h(t)$ as a function of frequency are documented (LIGO Scientific Collaboration & Virgo Collaboration 2021a).

The calibration process also includes a noise subtraction step that is based on independent measurements of a number of noise sources by witness sensors, as described in Davis et al. (2019), Vajente et al. (2020), Mukund et al. (2020), Estevez et al. (2019), and Acernese et al. (2022b). The 60 Hz noise subtraction has increased the range for heavy BBH mergers with a total mass of 70 $M_\odot$ by 25 Mpc for LIGO, while for Virgo, the overall sensitivity was enhanced, resulting in a gain of up to 7 Mpc in the BNS inspiral range. For the last two weeks of O3a, the Virgo data were reprocessed with a new configuration of the noise subtraction (Rolland et al. 2019; Acernese et al. 2022b), resulting in a different calibration being available for this period (see Table 1).

GWOSC releases two types of strain data: bulk data spanning an entire observing run, and smaller data snippets around the time of each GW event. Data snippets are based on the calibration version available at the time of publication of the related GW event. Events that appear in multiple publications may have multiple data snippets available, sometimes with different calibration versions. Naturally, the time segments released as data snippets are also available in the bulk data set, but the bulk data of the entire O3a, O3b, and O3GK observation runs provided through GWOSC correspond to the final (most up-to-date) calibration. These differences in calibration can lead to discrepancies between the data snippets and the corresponding data in the bulk data release, potentially leading in turn to differences in the source parameter values that can be estimated from the data. However, as discussed in Section 3.3, in addition to the main bulk data release, several alternate strain channels with different calibration versions are also made public.

The detector strain $h(t)$ in O3 is calibrated only between 10 and 5000 Hz for Advanced LIGO, between 20 and 2000 Hz for Advanced Virgo, between 30 and 1500 Hz for KAGRA, and between 40 Hz and 6000 Hz for GEO 600. Any apparent signal outside these ranges cannot be trusted because it is not a faithful representation of the GW strain at these frequencies. In addition, Advanced Virgo data between 49.5 and 50.5 Hz are characterized by a large increase of calibration errors because of effects related to mains power lines (Acernese et al. 2022b). Because of this increased systematic error, data in this narrow frequency band were considered to be uninformative for source parameter estimation (see Appendix E of Abbott et al. 2021c for relevant methods).

2.3. Detector Noise Characterization and Data Quality

The data are dominated by instrumental noise that can be well described as Gaussian and stationary over limited timescales and frequency ranges. The data also contain intermittent short-duration noise artifacts, or glitches (Glanzer et al. 2023; Acernese et al. 2022c), that contribute to the noise background as well. Any analysis of GW data must account for the presence of these various noise components (see Section 6 for more information about using the data). A summary of efforts to characterize data quality in O3 can be seen in Davis et al. (2021) for Advanced LIGO, Acernese et al. (2022a, 2022c) for Advanced Virgo, and Abe et al. (2022) for KAGRA. The overall quality of data for transient searches is recorded as data quality segments, described in more detail in Section 3.2.

2.4. Signal Injections

Hardware injections are simulated GW signals added by physically displacing the test masses (i.e., the interferometer mirrors; Biwer et al. 2017). The simulated signal initiates a response that mimics that of a true GW. By looking for discrepancies between the injected and recovered signals, it is possible to characterize the performance of analyses and the

coupling of instrumental subsystems to the detectors' output channels.

During the third observing run O3, hardware injections were performed in the Advanced LIGO and Advanced Virgo detectors. A record of all injections is available through the GWOSC web pages.[313] This list is provided to prevent potential confusion with an actual astrophysical signal. For Virgo, those injections were removed ex post facto when producing the calibrated strain (see Acernese et al. 2022b for details on this subtraction), so the injection times are not marked in the GWOSC files. On the other hand, in the case of Advanced LIGO the injections are still present in the calibrated data, and their times are marked in the GWOSC files. As further detailed in Section 3.2, hardware injections of both short-duration transient signals and long-duration continuous signals were performed. These signals remain in the data so that they may used by analysts for testing purposes. Transient hardware injections were done on a small number of occasions primarily for detector characterization, representing a negligible fraction of the data (less than 300 s).

No injections were performed during O3GK.

3. Strain Data

All O3 open data are distributed under the Creative Commons Attribution International Public License 4.0, including strain data from O3a, O3b, and O3GK.[314] Small batches of files can be conveniently downloaded from the GWOSC website directly.[315] However, when downloading large amounts of data (such as an entire observing run) the use of the distributed file system `CernVM-FS` (Weitzel et al. 2017) is recommended.[316] Once configured, `CernVM-FS` allows access to all GWOSC data locally on the user's computer.

The O3 calibrated strain data are distributed in files that contain 4096 s of data. Published GW signals are also released in separate files containing data snippets of 4096 s or 32 s, centered on the event's detection time and released under the GWOSC Event Portal.[317] The description of the data records that follows is valid both for single event releases and for bulk data releases.

GWOSC calibrated strain data are repackaged from data stored in the LVK archives. The data source is uniquely identified by a channel name and a frame type (see Table 1). At times when data are unavailable or of quality too poor to be analyzed, the strain values are represented with `NaN`s. Strain data are made available both at the sampling rate of 16,384 Hz, and at a downsampled rate of 4096 Hz[318]. Downsampling is achieved using the standard decimation method implemented in `scipy.signal.decimate`[319] from the `Python` package SciPy (Virtanen et al. 2020). The highest frequency available is determined by the Nyquist–Shannon sampling theorem (Nyquist 1924), and is equal to half the sampling rate specified in a particular data set. This is an important consideration to keep in mind when deciding which sample rate to download from GWOSC. Because the antialiasing filters used in resampling roll off at the upper end of the working frequency interval, the valid frequency range is reduced to a bit less than the Nyquist frequency. So, for the 4 kHz data the maximum usable frequency is approximately 1700 Hz. Higher-sample-rate data will require more hard drive space to store and longer times to download. The user can decide which data set meets their needs.

3.1. GWOSC File Formats

The GWOSC open data are delivered in two different file formats: `hdf` and `gwf`. The Hierarchical Data Format (`hdf`; Koziol & Robinson 2018) is a portable data format readable by many programming languages. The Frame format (`gwf`; LIGO Scientific Collaboration & Virgo Collaboration 2009) is a specialized format used by the GW community. Data associated with GW events are also released as plain text files containing two columns with the global positioning system (GPS) time in the first column and the corresponding strain value in the second column.

For both formats the file naming follows the naming convention:

obs—FrameType—GPSstart—duration.extension

where *FrameType* for the main O3 data release is *ifo*_`GWOSC`_*ObservationRun*_*s*`KHZ_R`*n* and

1. *obs* is the observatory, i.e., the site, so can have values L, H, V, G, or K;
2. *ifo* is the interferometer and can have values H1, L1, V1, G1, or K1;
3. *ObservationRun* encodes the observing run name, so in this case is O3a, O3b, or O3GK;
4. *s* is the sampling rate in kHz with either a value 4 or 16 (4096 Hz or 16,384 Hz, respectively);
5. *n* is the version number of the file (typically 1);
6. *GPSstart* is the start time of the data contained in the file, as a 10 digit GPS value (in seconds);
7. *duration* is the duration in seconds of the file, typically either 4096 or 32 s; and
8. *extension* represents the file format and can be `gwf` or `hdf`.

The folders (or groups) included in the `hdf` files are:

1. *meta*: metadata of the file containing the following fields:
   (a) *Description*, e.g., "Strain data time series from LIGO;"
   (b) *DescriptionURL*: URL of the GWOSC website;
   (c) *Detector*, e.g., L1, and *Observatory*, e.g., L;[320]
   (d) *Duration*, *GPSstart*, *UTCstart*: duration and start time (using GPS and UTC standards, respectively) of the segment of data contained in the file;
   (e) *StrainChannel*: channel name used in the LVK archives; and
   (f) *FrameType*: frame type used in the LVK archives.
2. *strain*: array of $h(t)$, sampled at 4 or 16 kHz depending on the file. For the times when the detector is not in science

[313] http://gwosc.org/O3/o3_inj

[314] See https://gwosc.org/O3/O3a/, https://gwosc.org/O3/O3b/, and https://gwosc.org/O3/O3GK/.

[315] https://gwosc.org/data

[316] For `CernVM-FS` installation instructions, see https://gwosc.org/cvmfs.

[317] See https://gwosc.org/eventapi.

[318] For simplicity, in the rest of the paper the sampling rates will be indicated in kHz and rounded to the closest integer, i.e., 4 and 16 kHz means 4096 and 16,384 Hz, respectively.

[319] This method applies an antialiasing filter based on an order-8 Chebychev type I infinite impulse response filter (Ellis 2012) before decimation.

[320] The observatory refers to the site and it is indicated by one letter, like L for Livingston. The addition of a number after the letter to indicate the detector, e.g., L1, could be useful if multiple detectors are installed in the same site, as was the case for Initial LIGO (Abbott et al. 2009).

Table 2
Channel Names of the GWOSC Frame Files (Format gwf)

	Channel name
Strain	*ifo*:GWOSC-*s*KHZ_R1_STRAIN
Data quality mask	*ifo*:GWOSC-*s*KHZ_R1_DQMASK
Injections mask	*ifo*:GWOSC-*s*KHZ_R1_INJMASK

Note. In this nomenclature, *ifo* is a place holder for the interferometer name, i.e., H1, L1, V1, G1, or K1, and $s = 4$ or 16 kHz denotes the sampling rate. The R1 substring represents the revision number of the channel name so it will become R2 in case there is a second (revised) release, and so on.

mode or the data does not meet the minimum required data quality conditions (see next section), the strain values are set to NaNs. The strain $h(t)$ is a function of time, so it is accompanied by the attributes Xstart and Xspacing defining the start GPS time of the data contained in the array and the corresponding distance in time between the points of the array.

3. *quality*: this folder contains two subfolders, one for data quality and the other for injections, each including a bitmask to indicate at each second the status of the data quality or the injections and the description of each bit of the mask (see Section 3.2 for details).

The gwf files have a similar content but with a different structure. They contain three channels, one for the strain data, one for the data quality, and one for the injections. The channel names are described in Table 2. The original files produced internally, whose channel names are listed in Table 1, contain only the strain channel, while the GWOSC files conveniently combine the strain data with the data quality and injection information in the same file.

3.2. Data Quality and Injections in GWOSC Files

The LVK performs several types of searches on LIGO, Virgo, GEO 600, and KAGRA data. Those searches are divided into four families named after the types of signals they target: compact binary coalescence (CBC), GW burst (BURST), continuous wave (CW), and stochastic background (STOCH). As each type of search has a unique sensitivity to instrumental artifacts, a detailed characterization of detector noise and data quality is essential to eliminate spurious signals of terrestrial origin found by the searches. LIGO, Virgo, GEO 600, and KAGRA have dedicated teams responsible for detector characterization and data quality, as described in Davis et al. (2021), Acernese et al. (2022a), Abbott et al. (2022), and Abe et al. (2022).

CBC analyses (Sachdev et al. 2019; Davies et al. 2020; Aubin et al. 2021) seek signals from merging neutron stars and black holes by filtering the data with waveform templates. BURST analyses (Klimenko et al. 2016; Cornish et al. 2021) search for generic GW transients with minimal assumptions on the source or signal morphology by identifying excess power in the time–frequency representation of the GW strain data. CW searches (Krishnan et al. 2004; Aasi et al. 2014; Astone & Colla 2014) look for long-duration, continuous, periodic GW signals from asymmetries of rapidly spinning neutron stars. STOCH searches (Allen & Romano 1999; Abbott et al. 2021e, 2021f) target the stochastic GW background signal which is formed by the superposition of unresolved sources from various stages of the evolution of the universe.

Table 3
Data Quality Bitmasks Description

Bit	Short Name	Description
0	DATA	Data present
1	CBC_CAT1	Pass CAT1 test
2	CBC_CAT2	Pass CAT1 and CAT2 tests for CBC searches
3	CBC_CAT3	Pass CAT1, CAT2, and CAT3 tests for CBC searches
4	BURST_CAT1	Pass CAT1 test
5	BURST_CAT2	Pass CAT1 and CAT2 tests for BURST searches
6	BURST_CAT3	Pass CAT1, CAT2, and CAT3 tests for BURST searches

Note. For O3, the CBC_CAT1 and BURST_CAT1 segment lists are equivalent (see the definition of CAT1 in the text). Note that any data that are not present are replaced by NaN values in the corresponding strain time series. In each bitmask, a value of 1 corresponds to the data quality check passing (good data), and a zero means the check has failed (bad data). CBC_CAT3 and BURST_CAT3 are equivalent to CBC_CAT2 and BURST_CAT2 in O3.

Table 4
Meaning of the Injection Bits

Bit	Short name	Description
0	NO_CBC_HW_INJ	No CBC injections
1	NO_BURST_HW_INJ	No burst injections
2	NO_DETCHAR_HW_INJ	No detector characterization injections
3	NO_CW_HW_INJ	No continuous wave injections
4	NO_STOCH_HW_INJ	No stochastic injections

Note. A value of 1 indicates TRUE (no injection), while a value of 0 is FALSE (injection is present).

Because of the fundamental differences in the search methodologies, certain noise types are relevant to specific searches (Davis et al. 2021). CBC and BURST searches look for short, transient signals, with durations from less than a second to several tens of seconds (see, e.g., Sathyaprakash & Schutz 2009). Data quality information for these searches is recorded as sets of time intervals when data are relatively free of corruption, known as segment lists, described in Davis et al. (2021). This information is provided inside the GWOSC files for the two GW transient searches CBC and BURST. The data quality information most relevant for CW and STOCH searches is in the frequency domain and it is provided as lists of instrumental lines in separate files, available for download on GWOSC.[321]

Data quality and signal injection information for a given GPS second are indicated by bitmasks with a 1 Hz sampling rate. The bit meanings are given in Tables 3 and 4 for the data quality and injections, respectively. To describe data quality, different categories are defined. For each category, the corresponding bit in the bitmask shown in Table 3 has a value of 1 (good data) if in that second of time the requirements of the category are fulfilled, otherwise 0 (bad data).

The meanings of the categories are described in Davis et al. (2021) and Acernese et al. (2022c). The specific categories are described in Section 5.2 of Davis et al. (2021) and in Sections 4 and 6.4.1 of Acernese et al. (2022c). The complete list of channels used to construct the segment lists are available on the

[321] See https://gwosc.org/O3/o3speclines for L1, H1, and V1, https://gwosc.org/O3/O3GKspeclines for K1, and https://gwosc.org/O3/O3GK_GEO_speclines for G1.

Table 5
Total Time Satisfying the Data Quality Criteria for Each SEARCH Type (CBC or BURST) and Each CATEGORY (CAT1, CAT2, or CAT3) Spanning the Full DURATION of Each Observing RUN (O3a, O3b, or O3GK) and Each DETECTOR (H1, L1, V1, G1, or K1)

			Data Quality Flags (Total Time in Seconds)						
RUN	DURATION	DETECTOR	DATA	CBC_CAT1	CBC_CAT2	CBC_CAT3	BURST_CAT1	BURST_CAT2	BURST_CAT3
		H1	11,218,675	11,218,675	11,177,046	11,177,046	11,218,675	11,125,849	11,125,849
O3a	15,811,200	L1	11,956,179	11,956,179	11,943,913	11,943,913	11,956,179	11,879,365	11,879,365
		V1	12,038,929	12,038,929	12,038,929	12,038,929	12,038,929	12,038,929	12,038,929
		H1	9,967,195	9,967,195	9,964,945	9,964,945	9,967,195	9,915,276	9,915,276
O3b	12,708,000	L1	9,810,816	9,810,816	9,782,946	9,782,946	9,810,816	9,760,960	9,760,960
		V1	9,591,207	9,591,207	9,591,207	9,591,207	9,591,207	9,591,207	9,591,207
O3GK	1,180,800	G1	940,133	940,133	940,133	940,133	940,133	940,133	940,133
		K1	628,055	628,055	628,055	628,055	628,055	628,055	628,055

Note. DURATION includes all time in seconds between the official start and end of each RUN, including times when the instruments are not collecting data for astrophysical analysis. When the criteria for a given flag are satisfied, the corresponding bit will have the value 1 (good data by these criteria); otherwise, it will have the value 0 (bad data). The data in the table can be retrieved at https://gwosc.org/timeline/show/[RUN]_16KHZ_R1/[DETECTOR]_[SEARCH]_[CATEGORY].

GWOSC website.[322] Here, we provide a brief summary of each category:

DATA: failing this level indicates that strain data are not publicly available at this time because the instruments were not operating in nominal conditions. For O3, this is equivalent to failing Category 1 criteria, defined below. For intervals of bad or absent data, NaNs have been inserted in the corresponding strain data array.

CAT1 (Category 1): failing a data quality check of this category indicates a critical issue with a key detector component not operating in its nominal configuration. GWOSC data during times that fail CAT1 criteria are replaced by NaN values in the strain time series. For O3, CBC_CAT1, BURST_CAT1, and DATA lead to identical segment lists. Applying CAT1 flags removes around 0.3%, ∼1%, and 0.2% of observing time for LIGO Hanford, LIGO Livingston, and Virgo, respectively (Davis et al. 2021; Acernese et al. 2022a).

CAT2 (Category 2): failing a data quality check of this category indicates times when excess noise is present in a sensor with an understood physical coupling to the strain channel (LIGO Scientific Collaboration & Virgo Collaboration 2016). The fraction of time removed by this category is less than 1% of the data, and is detailed in Table 6.

CAT3 (Category 3): failing a data quality check of this category indicates times when there is statistical coupling between a sensor/auxiliary channel and the strain channel which is not fully understood. This category was not used in O3 LVK searches, although it was used in previous observing runs (Abbott et al. 2021d).

Data quality categories are cascading: a time which fails a given category automatically fails all higher categories. Since CAT3 flags were not used in O3, the CAT3 segment lists are identical to the corresponding CAT2 lists. However, the different analysis groups qualify the data independently: failing BURST_CAT2 does not necessarily imply failing CBC_CAT2. See Table 5 for the amount of time associated with each category.

Simulated signals added to the detectors for testing and calibration are referred to as hardware injections. GWOSC data releases provide a time series with each one second sample representing a bitmask vector of the state of the injection at that time. The injections are categorized according to the type of injected signal relevant to each astrophysical search. There are also injections used for detector characterization (DETCHAR). The injection bitmask marks the injection-free times. The bit corresponding to a given type of injection is defined in Table 4. A bit is set to 1 if there is no injection, otherwise it is set to 0. The full details of the complete set of hardware injections for O3 can be found at https://gwosc.org/O3/o3_inj.

Table 6
Fraction of Observing Time Removed by Applying CAT2 Vetoes

Detector	O3a		O3b	
	CBC	BURST	CBC	BURST
H1	0.37%	0.83%	0.02%	0.52%
L1	0.01%	0.64%	0.28%	0.51%

Note. The percentages represent the amount of time in the DATA segment list relative to the total duration of observing time. CAT2 vetoes were not used for Virgo, KAGRA, or GEO 600.

There were no CBC injections during O3. As documented in the above page of the GWOSC website, the time lines of H1 and L1 contain a segment erroneously marked as associated with a CBC injection. Those segments are between GPS 1251662270 (2019-09-04T19:57:32 UTC) and GPS 1251662279 (2019-09-04T19:57:41 UTC) and between GPS 1251585495 (2019-09-04T00:37:57 UTC) and GPS 1251585503 (2019-09-04T00:38:05 UTC) for H1 and L1, respectively.

No injections of BURST signals were performed during O3a and O3b.

Some signal injections of the DETCHAR type were injected during O3a and O3b for both H1 and L1, while there were none for Virgo. The waveform model used for those injections is $h(t) = a\ e - (t - t_0)^2/\tau^2 \sin[2\pi f(t - t_0) - \phi]$, where t_0 is the time of the injection. The signal parameters τ, ϕ, and f were randomly chosen and are documented in separate databases for H1[323] and for L1.[324]

[322] https://gwosc.org/O3/auxiliary

[323] See https://gwosc.org/static/injections/o3a/H1_detchar_inj.txt for O3a and https://gwosc.org/static/injections/O3b/inj_o3b_H1.txt for O3b.

[324] See https://gwosc.org/static/injections/o3a/L1_detchar_inj.txt for O3a and https://gwosc.org/static/injections/O3b/inj_o3b_L1.txt for O3b.

Table 7
Names of Alternate Strain Channels in the O3 Data Release

Channel Name	Description
ifo:DCS-CALIB_STRAIN_C01_AR	LIGO calibrated strain, offline calibration.
ifo:DCS-CALIB_STRAIN_CLEAN_C01_AR	LIGO calibrated strain, after applying linear noise subtraction.
ifo:DCS-CALIB_STRAIN_CLEAN_SUB60HZ_C01_AR	LIGO calibrated strain, after applying both linear and nonlinear noise subtraction. This is the recommended channel (main release).
V1:Hrec_hoft_16384Hz_AR	Virgo calibrated strain for most of O3a and O3b (main release).
V1:Hrec_hoft_V1O3AReprolA_16384Hz_AR	Virgo calibrated strain for the last two weeks of 2019 September, near the end of O3a with an enhanced noise subtraction (main release).

Note. *ifo* is a place holder for the name of the LIGO interferometer, i.e., H1 or L1.

Four STOCH signals were injected during O3. These hardware injections consisted of a simulated stochastic GW background of a 13 minute long duration and were generated using the NAP package (Acernese et al. 2005) and rescaled to have an amplitude of $\Omega_0 = 2.0 \times 10^{-5}$ with the default Hubble constant value $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. Two of these injections were added only in H1 starting at GPS 1249200018 (2019-08-07T08:00:00 UTC) and GPS 1258273818 (2019-11-20T08:30:00). The other two injections were performed coherently at L1 and H1 during O3b starting at GPS 1258345818 (2019-11-21T04:30:00) and GPS 1258353018 (2019-11-21T06:30:00). The detectors were in observing mode for all of these stochastic injections.

CW injections were performed in H1 and L1 during both O3a and O3b, using a set of pulsar parameters provided on the GWOSC website.[325] CW hardware injections are extremely helpful for a variety of reasons. Critically, they allow an end-to-end test of a signal that is physically present in the instrument that goes through the control loops, calibration, cleaning, intermediate data products, and analysis. The output of the analysis is compared with the expected waveform. Any inconsistency could point to a problem somewhere that could be further investigated. In contrast, a software injection can only be added after the calibration step, meaning only half the pathway from physical signal to analysis result would be tested. As a secondary benefit, the hardware injections also allow a direct comparison of analysis methods and results on a consistent set of signals without having to coordinate different software injection campaigns where different choices can yield different answers.

The CW injections are always present except during defined intervals for O3a[326] and O3b.[327] No CW injections were performed in V1 during O3a, but there were CW injections in V1 during O3b between GPS 1263945616 (2020-01-24 23:59:58 UTC) and GPS 1266019220 (2020-02-18 00:00:02 UTC). The injected signal was removed a posteriori in the strain data as described in Acernese et al. (2022b). A residual signal after removal may still be present with an amplitude between 20 and 100 times lower than that of the injection. The residual amplitude is smaller than or at most the same order as the calibration uncertainty.

No signal hardware injections of any type were performed during O3GK.

[325] https://gwosc.org/O3/O3April1_injection_parameters

[326] https://gwosc.org/timeline/show/O3a_16KHZ_R1/H1_NO_CW_HW_INJ*H1_DATA*L1_NO_CW_HW_INJ*L1_DATA/1238166018/15811200

[327] https://gwosc.org/timeline/show/O3b_16KHZ_R1/H1_NO_CW_HW_INJ*H1_DATA*L1_NO_CW_HW_INJ*L1_DATA/1256655618/12708000/

3.3. Alternate Versions of the Strain Data

In addition to the main strain data release described above, the O3 data release includes several alternate strain channels, as described at https://gwosc.org/O3/O3alt. This alternate data release is available via both CernVM-FS or streaming via a network data server (NDS2; Zweizig et al. 2021). The alternate strain channels reflect different choices for how aggressively to apply noise-subtraction strategies to remove different sources of contamination. Some LVK analyses used different versions of the strain channels. The alternate strain channel release was designed to reflect the internal formatting used by the LVK as much as possible. In particular, the release uses only the gwf file format, does not include any NaN values, and does not include any data quality information. The channels found in the alternate calibration release are described in Table 7. For LIGO, the alternate channel release includes all times covered by the main strain data set, but also includes times in observing mode that fail the CAT_1 data quality flag. For Virgo, the alternate channel release covers the same times as the main strain data set.

4. Online Event Catalogs

Ninety-three GW transient events or notable candidates were discovered based on the LVK's analyses of the O3 data (Abbott et al. 2021a, 2021b, 2021c). Data associated with these signals are available online through the GWOSC Event Portal,[328] along with other scientific products. For all events in the Event Portal, snippets of strain data are released in the form of a segment of 4096 s around the time of the event. The data snippets are made available no later than when the event discovery becomes public in a refereed, scientific journal. In addition, the Event Portal includes a concise summary of the source properties (i.e., parameters of the compact star binaries associated with each of the detected signals), links to a number of science products (posterior samples), links to any associated low-latency alerts, and a documentation page for each release containing publication information. The list of O3 event data releases is as follows:

1. O3_Discovery_Papers: notable events first published individually (Abbott et al. 2020b, 2020d, 2020e, 2020f, 2021g). Associated data releases may contain preliminary versions of data quality segments and calibration;
2. O3_IMBH_marginal: marginal candidates associated with the search for intermediate-mass black hole (IMBH) binary mergers;
3. GWTC-2: confident events from the O3a observation run (first search);

[328] https://gwosc.org/eventapi

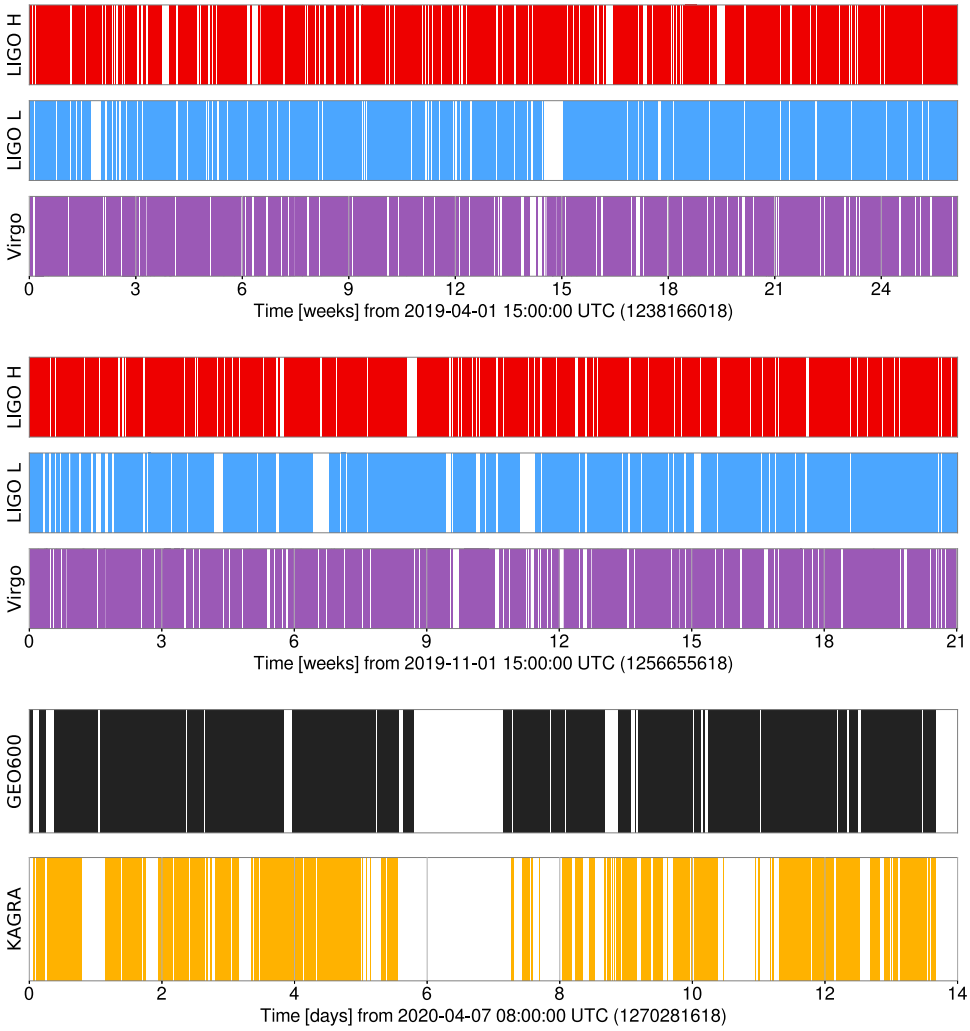

Figure 3. Time lines for the full O3a (top) and O3b (middle) and O3GK (bottom) observing runs based on the data quality bitmask `CBC_CAT1` for each detector (see Table 3). Color bars represent times when data are available, and white areas show times when data are not available. Similar plots can be generated from the GWOSC web pages (see footnote 336).

4. `GWTC-2.1-confident`: confident events from the O3a observation run (updated search);
5. `GWTC-2.1-marginal`: marginal candidates from the O3a observation run (updated search);
6. `GWTC-2.1-auxiliary`: candidates from GWTC-2 which, based on the updated analysis presented in the GWTC-2.1 catalog paper, do not satisfy the criteria for inclusion in the GWTC-2.1-confident or GWTC-2.1-marginal releases;
7. `GWTC-3-confident`: confident events from the O3b observing run; and
8. `GWTC-3-marginal`: marginal candidates from the O3b observing run.

Some events are listed in the database with multiple versions, typically corresponding to the event's inclusion in multiple releases. The cumulative `GWTC` catalog includes all confident GW events published by the LVK Collaboration, and currently includes 93 events. Events in the `GWTC-2.1-confident` and `GWTC-3-confident` releases all have a probability of astrophysical origin greater than 0.5[329] in at least one of the search pipelines, and are included in the cumulative `GWTC`.

The online catalogs are searchable via a web user interface. The Event Portal database can be queried based on specific source properties, namely the primary mass, secondary mass, total mass, chirp mass, final mass (of the merger remnant), luminosity distance, redshift, effective inspiral spin, or other properties associated with the observed signal, such as UTC or GPS event time, detector frame chirp mass, network S/N, false alarm rate, and the posterior probability of astrophysical origin. The events can also be selected by identification such as partial event name, release catalog, or group of catalogs. The output format can be one of the following: HTML, JSON, CSV, or plain ASCII text.

To ease the analysis of multiple events, the catalogs can be queried programmatically with scripts using the REST API that returns all catalog lists in a JSON format. Catalogs can be queried with a `GET` request. As an example, to request all merger events for which the primary mass is less than 3 $M_\odot$, the URL for the `GET` request would be https://gwosc.org/eventapi/html/query/show?max-mass-1-source=3. A detailed explanation of the query API nodes can be found on the GWOSC website.[330]

[329] See Abbott et al. (2021c), Appendix D.7 for a definition and details about its estimation.

[330] https://gwosc.org/apidocs

4.1. Parameter Estimation and Other Science Data Products

In addition to the information provided by GWOSC, complementary data about various aspects of the GWTC catalog production are available on the Zenodo open repository, see LIGO Scientific Collaboration & Virgo Collaboration (2021b, 2021c, 2022a) for GWTC-2 and GWTC-2.1 and LIGO Scientific Collaboration, Virgo Collaboration & KAGRA Collaboration (2021a, 2021b, 2021c, 2023a) for GWTC-3. They are linked from the documentation in GWOSC.[331] Those include lists of candidate events, the description of the search pipeline sensitivity, and data quality products.

The additional data release also include posterior samples from Bayesian inference analyses, see LIGO Scientific Collaboration & Virgo Collaboration (2022b) for GWTC-2.1 and LIGO Scientific Collaboration, Virgo Collaboration & KAGRA Collaboration (2021d) for GWTC-3. For convenience, those data are directly linked from the single event page of the online catalog. They can also be programmatically accessed through the JSON API as downloadable links to the files on Zenodo.

The parameter names in the posterior samples follow a standard nomenclature[332] (Hoy & Raymond 2021). Parameter estimates may change with the different versions of the event or catalog release. The users should refer to the release pages on Zenodo (LIGO Scientific Collaboration, Virgo Collaboration & KAGRA Collaboration 2021d; LIGO Scientific Collaboration & Virgo Collaboration 2022b) and their associated publications (Abbott et al. 2021b, 2021c) to obtain the full details about the configuration and assumptions made by the different analyses that are denoted by the set of version numbers for each event (depending on the number of releases in which that event appears). For each detected source the Event Portal displays the 90% credible intervals for a selection of parameters that reflect the values given in the relevant publication. Those credible intervals are computed from the posterior samples.

In some cases, the parameter estimation made use of "glitch-subtracted frames," where a model for an apparent instrumental artifact was computed and subtracted from the strain data. These glitch-subtracted frames are made available via Zenodo (LIGO Scientific Collaboration, Virgo Collaboration & KAGRA Collaboration 2021e; LIGO Scientific Collaboration & Virgo Collaboration 2022c).[333]

For GWTC-3, there are other data releases associated with studies of compact binary populations or cosmology (LIGO Scientific Collaboration, Virgo Collaboration & KAGRA Collaboration 2021f, 2023b)

4.2. Low-latency Alerts

During O3, public alerts were communicated with low latency to report the occurrence of a notable trigger detected in the data.[334] The alerts are sent with a latency of few minutes after detection. They include a number of preliminary parameter estimations that are useful for the localization of the source through a probability skymap. This information can be used by other, non-GW instruments to search for potential electromagnetic counterparts in follow-up observations. The complete list of alerts sent during O3 can be found publicly in the GraceDB website[335] and, as described below, in GWOSC.

The Event Portal references the GraceDB entry for the original trigger alert of the event. Links to GraceDB entries are available through the GWOSC web interface and the JSON API. Events first detected offline do not trigger low-latency alerts and thus lack a GraceDB entry.

5. Technical Validation

The O3 GWOSC data release is repackaged for the broader user community beginning with the internal strain data products used for data analysis by the LVK Collaboration for publication purposes. The repackaging produces new GWOSC `gwf` and `hdf5` files containing the previously discussed strain, data quality, and hardware injection information for each detector. The repackaging allows us to add data quality segments, remove times outside of observing mode, and simplify the channel names. In addition, versions of these GWOSC files at a reduced sampling rate of 4096 Hz for the strain channel of each detector are also produced. All data for the release are carefully reviewed by the internal GWOSC team and then reviewed by an independent review team made up of members from the LVK Collaboration. This review process checks that:

1. The strain vectors at the maximum sample rate (16 kHz) in the GWOSC `hdf` and `gwf` files are identical to machine precision to the corresponding strain vectors of the LVK main archives;
2. The strain vectors after resampling at 4 kHz do not have numerical artifacts that may arise from the resampling technique;
3. The data quality and injection information located in either the GWOSC `hdf` and `gwf` files or the online `Timeline` tool described in detail in Section 6, agree with all available records; and
4. The documentation associated with the O3 data products found online is correct and contains comprehensive information for the broader user community.

The data files and accompanying documentation are released to the public on the GWOSC website once all checks have passed at the designated date and time agreed to by the LIGO, Virgo and KAGRA Collaborations.

6. Usage Notes

6.1. Salient Features of GW Data

Working with GW data requires an awareness of the presence of noise in the data. An overview of LIGO/Virgo detector noise and some applicable signal processing methods are described in Abbott et al. (2020c); see also above in Sections 3.2 and 2.3 for a brief introduction to various classes of detector noise. In addition, as mentioned previously, the data are only valid within a fixed frequency range due to the limits of calibration (Section 2.2) as well as due to artifacts from the

[331] See https://gwosc.org/GWTC-2, https://gwosc.org/GWTC-2.1 and https://gwosc.org/GWTC-3

[332] See https://lscsoft.docs.ligo.org/pesummary/stable_docs/gw/parameters.html for a definition.

[333] See also https://dcc.ligo.org/LIGO-T2000470/public.

[334] See https://emfollow.docs.ligo.org/userguide for more details. This user guide is a living document that is being updated in preparation for the upcoming science run O4. Therefore, the information in this guide may not be necessarily relevant for O3 data.

[335] https://gracedb.ligo.org/superevents/public/O3

downsampling process (Section 3). All of these complications need to be considered when searching for astrophysical signals.

6.2. List of Observing Segments

Segment lists describe times when GW detectors are collecting data and are operating in a normal condition, as described in Section 3.2. The GWOSC website provides an online app called `Timeline` to discover, plot, and download segment lists.[336] The `Timeline` query page allows users to select observing runs from a drop-down menu, and then view the names of segment lists associated with the selected run. Segment lists may be downloaded as ASCII text files or in a JSON format. Alternatively, segment lists may be displayed in an interactive plot, as seen in Figure 3. To explore times within a run, a visitor can use the mouse to scroll and zoom on the `Timeline` plots. Hovering the mouse over a segment displays a tool tip with the exact start and stop times, in both GPS and UTC time.

6.3. Software and Support

The GWOSC website provides a number of resources for helping investigators learn to work with GW data, including:

1. Software libraries:[337] A number of software packages developed for GW analysis are open source. The GWOSC website provides a suggested list of packages, many of which were created by members of the LVK Collaboration. This list includes GstLAL (Sachdev et al. 2019), MBTA (Aubin et al. 2021), PyCBC (Davies et al. 2020), cWB (Klimenko et al. 2016), BayesWave (Cornish et al. 2021), GWpy (Macleod et al. 2021c), and Bilby (Ashton et al. 2019). Links to source code and documentation are provided for each package.
2. Tutorials:[338] GWOSC provides tutorials to demonstrate the basics of GW data analysis. Most tutorials are in `Python`, and provided in notebooks that can be run in the cloud to avoid the necessity for the user to install software.
3. Workshops and online course:[339] Annual open data workshops provide a complete course in working with GW data, including lectures, software tutorials, and challenge problems. Materials from past workshops are available as a free online course; students can enroll at any time. Future workshops will be posted on the GWOSC website, and are open to any interested participants.
4. Discussion forum:[340] a public discussion forum for GW topics provides space to ask for help with GW data analysis, discuss LVK papers, post questions about GW science, and connect with other researchers in the field.

7. Summary

The O3 data set described in this paper represents the most sensitive GW observations to date. The data contain over 80 compact object merger signals, as described in a number of catalog releases, including GWTC-2 (Abbott et al. 2021a), GWTC-2.1 (Abbott et al. 2021b), and GWTC-3 (Abbott et al. 2021c). O3 includes three main phases: O3a, O3b, and O3GK. O3a and O3b are both joint runs of LIGO and Virgo, while the O3GK run involved KAGRA and GEO 600. Data and documentation for all O3 data are available from the GWOSC website.

Looking ahead, LIGO, Virgo, and KAGRA are planning an O4 run, scheduled to begin in 2023, with improved sensitivity. Data from events discovered in O4 will be released as the events are published, and release of the next large strain data sets are planned for 2025. This will be followed by the O5 observing run, anticipated to be the first extended observing run with a span of over two years.[341] Planned instrument upgrades should increase the sensitivity of the network and thus extend the volume of space over which signals may be observed, so that future data sets will include more frequent detections and a corresponding expanded depth of science in this rapidly evolving field.

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Calibration of the LIGO strain data was performed with a GstLAL-based calibration software pipeline (Viets et al. 2018). Calibration of the Virgo strain data was performed with C-based software (Acernese et al. 2022b). Data quality products and event-validation results were computed using the DMT (https://labcit.ligo.caltech.edu/~jzweizig/DMT-Project.html), DQR (https://docs.ligo.org/detchar/data-quality-report/), DQSEGDB (Fisher et al. 2021), gwdetchar (Macloed et al. 2021a), hveto (Smith et al. 2011), iDQ (Essick et al. 2020), and Omicron (Robinet et al. 2020) software packages and contributing software tools. Analyses relied upon the LALSuite software library (LIGO Scientific Collaboration 2018). PESummary was used to postprocess and collate parameter estimation results (Hoy & Raymond 2021). For an exhaustive list of the software used for searching the GW signals and characterizing their source, see Abbott et al. (2021c). Plots were prepared with Matplotlib (Hunter 2007), seaborn (Waskom 2021), GWSumm (Macleod et al. 2021b), and GWpy (Macleod et al. 2021c). NumPy (Harris et al. 2020) and SciPy (Virtanen et al. 2020) were used in the preparation of the manuscript.

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[336] See https://gwosc.org/timeline.
[337] https://gwosc.org/software
[338] https://gwosc.org/tutorials
[339] https://gwosc.org/workshops
[340] https://ask.igwn.org
[341] https://observing.docs.ligo.org/plan/

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