# Description of Trigger Data File Contents to Accompany *GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run*

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February 23, 2021

This document has number LIGO-T2100064

**Abstract**

This document describes the contents of trigger data files for O3a events presented in the GWTC-2 catalog of compact binary mergers [1] observed by LIGO [2] and Virgo [3], generated by the PyCBC [4, 5, 6] and GstLAL [7, 8, 9] searches.

# 1 Trigger Files

The triggers are stored in the HDF5 file format [10] in the files listed below.

`GW190521_triggers_gstlal.hdf5`

> The GstLAL trigger with the maximum signal-to-noise ratio originally published in [11]. Note that in [11], the sub-threshold signal-to-noise ratio from Virgo was not included, while it is in Table IV of [1]. The minimum false alarm rate trigger for GW190521 was obtained in a different template, and this trigger is recorded in the `O3a_triggers_gstlal.hdf5` file.

`O3a_triggers_gstlal.hdf5`
`O3a_triggers_pycbc.hdf5`

> Triggers produced by the GstLAL and PyCBC searches over the first half of the third observing run (O3a) of Advanced LIGO and Advanced Virgo, which took place from 2019-04-01 to 2019-10-01.

`O3a_triggers_pycbc_bbh.hdf5`

> Triggers produced by the PyCBC binary black-hole focused search over the first half of the third observing run (O3a) of Advanced LIGO and Advanced Virgo, which took place from 2019-04-01 to 2019-10-01.

# 2 Datasets

Each file contains a subset of the following datasets. These datasets contain triggers that were found with false alarm rates below the threshold of 2 per year as measured by their respective search. Each dataset in a file will contain values indexed by an ordinal trigger number. The datasets all have the same length. If data is missing for a particular trigger in one of the datasets, for example, if a trigger is produced in H1 and L1 data but not in V1 data, then the value in the dataset for which there is no value for that trigger index will be set to NaN. A description of the dataset contents is provided below.

`false_alarm_rate`

The rate of false alarms ($\text{year}^{-1}$) expected above the trigger ranking statistic. See [6] for PyCBC and [7] for GstLAL. Note: for GstLAL, a prior distribution (a power law distribution in signal-to-noise ratio with a large negative exponent) is assumed for the background distribution where no measurable background is available; consequently, the false alarm rate value assigned to highly significant signals in the GstLAL search is determined by this prior distribution [12].

`h1_chisq`

Signal consistency test value $\chi^2$ (PyCBC) or $\xi^2$ (GstLAL) for the trigger in H1.

For GstLAL this quantity is given by Eq. (4) of [7]. Note that this is a reduced quantity so there is no `h1_chisq_dof` dataset for GstLAL (treat as 1).

For PyCBC this quantity is given by Eq. (7.10) of [13]; see also Eq. (9.4) and (C1) of [14].

`h1_chisq_dof` **(PyCBC Only)**

Degrees of freedom associated with the $\chi^2$ test for the trigger in H1. See Eq. (7.11) of [13].

`h1_end_time`

GPS time (seconds since 1980-01-06T00:00:00Z) of the trigger coalescence time in H1. See Eq. (3.2) and Eq. (8.14a) of [14] where it is called the *termination time*.

`h1_sigmasq` **(PyCBC Only)**

The value of the variance of the matched filter for a template signal at effective distance of 1 Mpc in H1. See Eq. (4.3) and Eq. (8.8) of [14].

`h1_snr`

Signal-to-noise ratio of trigger in H1. See Eq. (4.4b) and (8.12) of [14].

`l1_chisq`

Signal consistency test value $\chi^2$ (PyCBC) or $\xi^2$ (GstLAL) for the trigger in L1.

For GstLAL this quantity is given by Eq. (4) of [7]. Note that this is a reduced quantity so there is no `l1_chisq_dof` dataset for GstLAL (treat as 1).

For PyCBC this quantity is given by Eq. (7.10) of [13]; see also Eq. (9.4) and (C1) of [14].

`l1_chisq_dof` **(PyCBC Only)**

Degrees of freedom associated with the $\chi^2$ test for the trigger in L1. See Eq. (7.11) of [13].

`l1_end_time`

GPS time (seconds since 1980-01-06T00:00:00Z) of the trigger coalescence time in L1. See Eq. (3.2) and Eq. (8.14a) of [14] where it is called the *termination time*.

`l1_phase_minus_h1_phase`

Difference between twice the termination phase of the trigger in L1 and twice the termination phase of the trigger in H1 (radians). See Eq. (3.2) and Eq. (8.14a) of [14] for the definition of termination phase.

`l1_sigmasq` **(PyCBC Only)**

The value of the variance of the matched filter for a template signal at effective distance of 1 Mpc in L1. See Eq. (4.3) and Eq. (8.8) of [14].

`l1_snr`

Signal-to-noise ratio of trigger in H1. See Eq. (4.4b) and (8.12) of [14].

`log_likelihood_ratio` **(GstLAL Only)**

The natural log of the likelihood ratio used as the GstLAL trigger ranking statistic. See Eq. (9) of [7]. Note that the distributions used in forming the numerator and denominator are not normalized, so the `log_likelihood_ratio` has an unspecified constant offset.

`mass1`

Primary detector-frame mass $m_1$ ($M_\odot$) of the template signal.

`mass2`

Secondary detector-frame mass $m_2$ ($M_\odot$) of the template signal.

`spin1z`

Primary z-component of spin $c\hat{\mathbf{L}} \cdot \mathbf{S}_1/(Gm_1^2)$ (dimensionless) of the template signal where $\hat{\mathbf{L}}$ is the unit vector in direction of the orbital angular momentum vector and $\mathbf{S}_1$ and $m_1$ are the spin vector and the mass of the primary component. The templates used had spin vectors aligned with the orbital angular momentum vector.

`spin2z`

Secondary z-component of spin $c\hat{\mathbf{L}} \cdot \mathbf{S}_2/(Gm_2^2)$ (dimensionless) of the template signal where $\hat{\mathbf{L}}$ is the unit vector in direction of the orbital angular momentum vector and $\mathbf{S}_2$ and $m_2$ are the spin vector and the mass of the secondary component. The templates used had spin vectors aligned with the orbital angular momentum vector.

`v1_chisq` **(GstLAL Only)**

Signal consistency test value $\xi^2$ (GstLAL) for the trigger in V1.

This quantity is given by Eq. (4) of [7]. Note that this is a reduced quantity so there is no `v1_chisq_dof` dataset (treat as 1).

`v1_end_time` **(GstLAL Only)**

GPS time (seconds since 1980-01-06T00:00:00Z) of the trigger coalescence time in V1. See Eq. (3.2) and Eq. (8.14a) of [14] where it is called the *termination time*.

`v1_phase_minus_h1_phase` **(GstLAL Only)**

Difference between twice the termination phase of the trigger in V1 and twice the termination phase of the trigger in H1 (radians). See Eq. (3.2) and Eq. (8.14a) of [14] for the definition of termination phase.

`v1_phase_minus_l1_phase` **(GstLAL Only)**

Difference between twice the termination phase of the trigger in V1 and twice the termination phase of the trigger in L1 (radians). See Eq. (3.2) and Eq. (8.14a) of [14] for the definition of termination phase.

`v1_snr` **(GstLAL Only)**

Signal-to-noise ratio of trigger in V1. See Eq. (4.4b) and (8.12) of [14].

# 3 Tutorial

The following Python code `tutorial.py` demonstrates how to read the trigger files and prints out certain information about the triggers.

```
import h5py

# open trigger file
fname = 'O3a_triggers_pycbc.hdf5'
trigger_set = h5py.File(fname, 'r')

# print the properties of the most significant triggers
print('Properties of most significant triggers in file {0}'.format(fname))

for i, far in enumerate(trigger_set['false_alarm_rate']):

    # only consider triggers with false alarm rate < 1/year
    if far < 1.0:
        print('')
        print('Trigger number {0}:'.format(i))

        # print all the properties of the found triggers
        for key in trigger_set.keys():
            print('... {0}: {1}'.format(key, trigger_set[key][i]))
```

# Acknowledgements

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN), the French Centre National de la Recherche Scientifique (CNRS) and the Netherlands Organization for Scientific Research, for the construction and operation of the Virgo detector and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, the Department of Science and Technology, India, the Science & Engineering Research Board (SERB), India, the Ministry of Human Resource Development, India, the Spanish Agencia Estatal de Investigación, the Vicepresidència i Conselleria d'Innovació, Recerca i Turisme and the Conselleria d'Educació i Universitat del Govern de les Illes Balears, the Conselleria d'Innovació, Universitats, Ciència i Societat Digital de la Generalitat Valenciana and the CERCA Programme Generalitat de Catalunya, Spain, the National Science Centre of Poland and the Foundation for Polish Science (FNP), the Swiss National Science Foundation (SNSF), the Russian Foundation for Basic Research, the Russian Science Foundation, the European Commission, the European Regional Development Funds (ERDF), the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the French Lyon Institute of Origins (LIO), the Belgian Fonds de la Recherche Scientifique (FRS-FNRS), Actions de Recherche Concertées (ARC) and Fonds Wetenschappelijk Onderzoek – Vlaanderen (FWO), Belgium, the Paris Île-de-France Region, the National Research, Development and Innovation Office Hungary (NKFIH), the National Research Foundation of Korea, the Natural Science and Engineering Research Council Canada, Canadian Foundation for Innovation (CFI), the Brazilian Ministry of Science, Technology, Innovations, and Communications, the International Center for Theoretical Physics South American Institute for Fundamental Research (ICTP-SAIFR), the Research Grants Council of Hong Kong, the National Natural Science Foundation of China (NSFC), the Leverhulme Trust, the Research Corporation, the Ministry of Science and Technology (MOST), Taiwan and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, INFN and CNRS for provision of computational resources.

# Bibliography


[1] R. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run*, LIGO Technical Document LIGO-P2000061.

[2] J. Aasi et al. (LIGO Scientific Collaboration), *Advanced LIGO*, Class. Quantum Grav. **32** 074001 (2015).
DOI: 10.1088/0264-9381/32/7/074001

[3] F. Acernese et al. (LIGO Scientific Collaboration), *Advanced Virgo: a second-generation interferometric gravitational wave detector*, Class. Quantum Grav. **32** 024001 (2015).
DOI: 10.1088/0264-9381/32/2/024001

[4] Tito Dal Canton, Alexander H. Nitz, Andrew P. Lundgren, Alex B. Nielsen, and Duncan A. Brown *Implementing a search for aligned-spin neutron star-black hole systems with advanced ground based gravitational wave detectors*, Phys. Rev. D **90** 082004 (2014).
DOI: 10.1103/PhysRevD.90.082004

[5] A. H. Nitz, I. W. Harry, J. L. Willis, C. M. Biwer, D. A. Brown, L. P. Pekowsky, T. Dal Canton, A. R. Williamson, T. Dent, C. D. Capano, T. J. Massinger, A. K. Lenon, A. B. Nielsen, and M. Cabero, PyCBC Software.
URL: http://github.com/ligo-cbc/pycbc.

[6] Samantha A. Usman, Alexander H. Nitz, Ian W. Harry, Christopher M. Biwer, Duncan A. Brown, Miriam Cabero, Collin D. Capano, Tito Dal Canton, Thomas Dent, and Stephen Fairhurst, *The PyCBC Search for Gravitational Waves from Compact Binary Coalescence*, Class. Quantum Grav. **33** 215004 (2016).
DOI: 10.1088/0264-9381/33/21/215004

[7] Surabhi Sachdev, Sarah Caudill, Heather Fong, Rico K. L. Lo, Cody Messick, Debnandini Mukherjee, Ryan Magee, Leo Tsukada, Kent Blackburn, Patrick Brady, Patrick Brockill, Kipp Cannon, Sydney J. Chamberlin, Deep Chatterjee, Jolien D. E. Creighton, Patrick Godwin, Anuradha Gupta, Chad Hanna, Shasvath Kapadia, Ryan N. Lang, Tjonnie G. F. Li, Duncan Meacher, Alexander Pace, Stephen Privitera, Laleh Sadeghian, Leslie Wade, Madeline Wade, Alan Weinstein, and Sophia Liting Xiao, *The GstLAL Search Analysis Methods for Compact Binary Mergers in Advanced LIGO's Second and Advanced Virgo's First Observing Runs*, arXiv:1901.08580.

[8] Chad Hanna, Sarah Caudill, Cody Messick, Amit Reza, Surabhi Sachdev, Leo Tsukada, Kipp Cannon, Kent Blackburn, Jolien D. E. Creighton, Heather Fong, Patrick Godwin, Shasvath Kapadia, Tjonnie G. F. Li, Ryan Magee, Duncan Meacher, Debnandini Mukherjee, Alex Pace, Stephen Privitera, Rico K. L. Lo, and Leslie Wade, *Fast evaluation of multidetector consistency for real-time gravitational wave searches*, Phys. Rev. D **101**, 022003 (2020).
DOI: 10.1103/PhysRevD.101.022003

[9] Cody Messick, Kent Blackburn, Patrick Brady, Patrick Brockill, Kipp Cannon, Romain Cariou, Sarah Caudill, Sydney J. Chamberlin, Jolien D. E. Creighton, Ryan Everett, Chad Hanna, Drew Keppel, Ryan N. Lang, Tjonnie G. F. Li, Duncan Meacher, Alex Nielsen, Chris Pankow, Stephen Privitera, Hong Qi, Surabhi Sachdev, Laleh Sadeghian, Leo Singer, E. Gareth Thomas, Leslie Wade, Madeline Wade, Alan Weinstein, and Karsten Wiesner, *Analysis framework for the prompt discovery of compact binary mergers in gravitational-wave data*, Phys. Rev. D **95**, 042001 (2017).
DOI: 10.1103/PhysRevD.95.042001

[10] URL: https://www.hdfgroup.org

[11] R. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *GW190521: A Binary Black Hole Merger with a Total Mass of* $150\,M_\odot$, Phys. Rev. Lett. **125** 101102 (2020).
DOI: 10.1103/PhysRevLett.125.101102

[12] B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), *GW150914: First results from the search for binary black hole coalescence with Advanced LIGO*, Phys. Rev. D. **93**, 122003 (2016).
DOI: 10.1103/PhysRevD.93.122003

[13] B. Allen, $\chi^2$ *Time-Frequency Discriminator for Gravitational Wave Detection*, Phys. Rev. D 71, 062001 (2005).
DOI: 10.1103/PhysRevD.71.062001

[14] Bruce Allen, Warren G. Anderson, Patrick R. Brady, Duncan A. Brown, and Jolien D. E. Creighton, *FINDCHIRP: An algorithm for detection of gravitational waves from inspiraling compact binaries*, Phys. Rev. D **85**, 122006 (2012).
DOI: 10.1103/PhysRevD.85.122006