PROCEEDINGS OF SCIENCE

Gravitational-wave event validation by Advanced LIGO and Advanced Virgo detectors

Procedures and challenges for the upcoming observing runs

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The observations of the Advanced LIGO and Advanced Virgo gravitational-wave detectors have led so far to the confident identification of 90 signals, from the merger of compact binary systems composed of black holes and neutron stars. These events have offered a new testing ground for General Relativity and better insights into the nuclear equation of state for neutron stars, as well as the discovery of a new population of black holes. For each detection, a thorough event validation procedure has been completed in order to carefully assess the impact of potential data quality issues, such as instrumental artifacts, on the analysis results. This has increased the confidence in the astrophysical origin of the observed signals, as well as in the accuracy of the estimated source parameters. In this contribution, we will describe the most relevant steps of the validation process, in the context of the last observing run (O3) of the advanced gravitational-wave detectors. Moreover, these detectors are currently ongoing a phase of upgrades in preparation for the next joint observing run (O4), scheduled to begin in 2023. The predicted improvement in sensitivity is expected to produce a higher rate of candidate events, which will constitute a new challenge for the validation procedures.

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1. Introduction

The Advanced LIGO [1] and Advanced Virgo [2] gravitational-wave (GW) detectors have reported, up to the end of their third joint observing run (O3), the confident detection of 90 signals from compact binary coalescences (CBCs), namely binary systems made up of black holes and neutron stars [3–5]. These observations have offered a new testing ground for fundamental physics [6] and general relativity in the strong field regime [7], better insights into the nuclear equation of state for neutron stars [8], and have led to the characterization of a new population of black holes [9]. Their signals are identified by multiple search algorithms [10–14] that operate both online, producing event triggers and alerts [15] in low-latency after data acquisition, and offline, before catalogs and exceptional events are published. The data associated with all of these events is made available through the Gravitational-Wave Open Science Center (GWOSC), which includes the results on the source properties [16].

The extraction of the information about the astrophysical signal is obtained from the differential strain induced by the wave on the detector arms [17]. Several other mechanisms of no astrophysical origin can produce an effect equivalent to a strain, hence constituting a source of noise that limits the sensitivity of our detectors and the significance to be attributed to each event. In particular, non-stationary noise artifacts are especially detrimental for transient searches because they can mimic the waveforms of the actual signals and can bias the analysis results of the parameters of the putative astrophysical source [18]. For these reasons, a thorough procedure of *validation* is implemented to assess the data quality (DQ) in the correspondence of each trigger and determine if this should be considered as a "candidate event" [19, 20] or, otherwise, reduce the significance of that event and even confute its astrophysical origin.

This contribution outlines the procedures used within LIGO and Virgo for the validation of candidate transient GW events during O3. Although the main focus will be on signals from CBCs, which as of O3 have been the only transient GWs detected by LIGO and Virgo, most of the considerations apply also to other kinds of transient signals, such as those from core-collapse supernovae [21] and cosmic strings [22].

2. Validation of transient candidate events

Event validation is applied to all the triggers produced by GW transient searches that have passed some preliminary automated DQ checks and have a false alarm rate (FAR) below a certain alert threshold, typically one per 10 months for modelled CBC searches and one per 4 years for unmodelled searches.[1] This procedure has the role to verify if DQ issues, such as instrumental artifacts, environmental disturbances, or anomalies in the search pipelines, can impact the analysis results and decrease the confidence of detection, or even foster a rejection [18]. As described by the flowchart in Fig. 1, this activity takes on a pivotal role in the data processing carried out by LIGO and Virgo; the data flow goes from the detectors and their auxiliary sensors through several analysis steps, represented by the blocks in the diagram, concluding with the publication of the analysis results into discovery papers and catalogs [3–5] and their release to the GWOSC [16].

[1] LIGO–Virgo Public Alerts User Guide, https://emfollow.docs.ligo.org/userguide/.

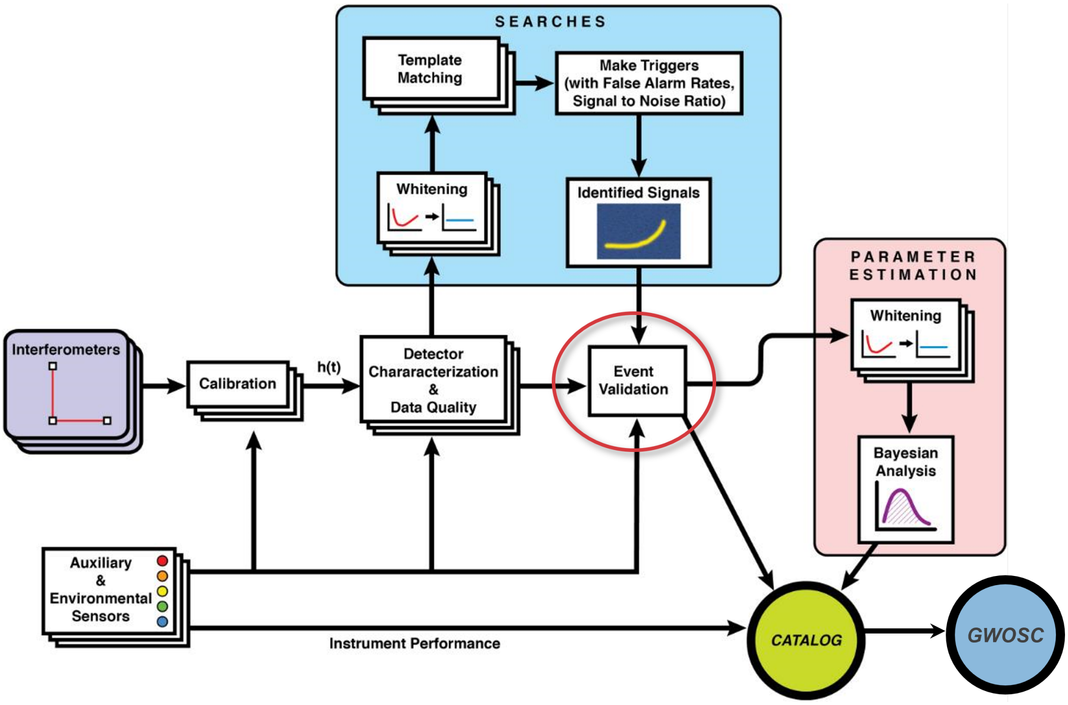

Figure 1: Flowchart outlining the data path and analysis steps carried out in LIGO–Virgo. Event validation has the central role of applying detector characterization and DQ studies to the results from the searches, producing recommendations for parameter estimation analyses and leading to the final list of confident detections. Figure readapted from [17], licensed CC BY 4.0.

Two separate stages of validation are typically accomplished. For those triggers found by online searches, a prompt evaluation is started within minutes after the trigger is detected with FAR below the alert threshold, and follows every preliminary Gamma-ray Coordinate Network (GCN) notice automatically issued [5]. The main purpose at this level is to check for evidence of severe contaminations from noise artifacts that would prompt a non-astrophysical origin for the event. If this is the case, the preliminary notice is retracted to avoid wasting time and resources on observational campaigns of unlikely sources. Besides the determination of a preliminary detection confidence, also the impact of noise transient on the sky localization is evaluated. If the trigger passes human vetting it is formally considered a candidate event, and a GCN circular is issued to the astronomy community to support multi-messenger follow-up observations [15]. These operations should be completed within a few tens of minutes to be effective. The rapid-response team (RRT), a joint LIGO–Virgo group of commissioning, computing, and calibration experts from each of the detector sites, pipeline experts, detector characterization experts, and follow-up advocates, is assigned to that. The decision about the event is primarily based on the quick results provided by the data quality reports (DQRs) [19, 20],[2] a framework developed by LIGO and Virgo and consisting in a set of semi-automated detector characterization and DQ tests, involving, in addition to the strain channel, the signals from a number of auxiliary detector sensors and controls. A DQR is automatically generated for triggers with FAR lower than 1 per day, and produces a first set of key checks within about 6 minutes; refer to Table 4 and 5 of [20] for the performance of the Virgo DQR

[2]Data Quality Report's documentation, https://docs.ligo.org/detchar/data-quality-report/.

during O3b, the second half of O3, which lasted from November 2019 to March 2020.

The vetting of an event takes into account the evaluation of the operational status of the detector and its subsystems, the environmental conditions, as well as preliminary checks on the strain data. In particular, the RRT is asked to verify the presence of noise transients around the time of the trigger and the validity of the hypotheses of stationarity and Gaussianity of the data. These hypotheses are at the base of most of the analysis pipelines [17] and, if not satisfied, their results can be biased, including the significance to be attributed to the event trigger and the sky localization. Moreover, from the DQR the RRT examines the possible presence of correlations between the strain data and the auxiliary sensors, which may prompt to a non-astrophysical origin of the trigger. The GCN circular accompanying the candidate event usually contains a brief assessment of the above DQ results, highlighting in particular any issue that may affect the event significance estimate or the source sky localization.

With higher latency, and for those triggers identified by offline searches, a comprehensive final stage of validation is performed to check candidate events before every LIGO–Virgo publication, catalogs and exceptional events, and the release of the event data to the GWOSC. Besides of (double-)checking the astrophysical origin of the event trigger, now the main purpose is to carefully assess whether the presence of any noise artifact can affect the parameter estimation of the astrophysical source. This procedure takes advantage of dedicated reruns of the DQRs, as well as from additional tools and metrics, including, for example, signal consistency checks [19]. If no DQ issues are found, the candidate event is considered validated and pushed forward for parameter estimation reruns and additional analyses. For each event, the overall procedure typically requires 1 hour per person involved if no DQ issues are found.

For those events where non-stationary noise transients are found in the vicinity of the putative GW signal, or even overlapping with it, a procedure of *noise mitigation* is implemented [23]. This consists in the identification of the regions, in a time–frequency representation fo the data, where non-stationary noise manifests and to what extent. Then, for each of these regions, de-noised data frames are produced by means of the `BayesWave` [24] and `gwsubtract` pipelines [23]. Stationarity is then reassessed for these frames and, if needed, the procedure is iterated. If all the excess noise is removed, these frames are recommended to be used for further data analyses and parameter estimations. Otherwise, the recommendation issued is to exclude the non-stationary regions from the analyses, when possible, or to discard the event. Parameter estimation comparison tests are used to check for bias and systematic errors potentially caused by the subtraction process. This process involves lots of human input and slows down downstream analyses by several weeks. O3 has been the first observing run where noise mitigation has been routinely applied as part of event validation, with 16 events, the 20% of the total, requiring noise mitigation [5].

3. Conclusions and challenges for the upcoming observing runs

Event validation is an integrating part of GW data analysis. It has the role of enforcing the confidence in the astrophysical origin of the transient signals detected by search algorithms, and the reliability of the source parameter estimation results.

For the upcoming observing run, O4, we expect a rate increase in GW detections up to 4 times that in O3 [25], meaning up to about one event per day. Assuming the same person power and a similar fraction of events presenting DQ issues than in O3, there will likely be the risk of a bottleneck in the analysis with consequent delays in the delivery of the results. For these reasons the LIGO–Virgo–KAGRA community is working on the automatization of part of the validation procedure, reducing the requirement of human input, especially for "vanilla events," with no DQ issues. Furthermore, the cooperation is promoted by implementing common validation procedures and clear guidelines for typical scenarios to speed up the analyses. The training and support of the event validation team will be also organized jointly before the next observing run.

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