PROCEEDINGS OF SCIENCE

Virgo Detector Characterization and data quality studies: analysis of the Observing Run 3 (O3: 04/2019 → 03/2020) and ongoing developments to prepare the O4 run

Nicolas Arnaud[a,b,*] **for the Virgo Collaboration**

[a] *Laboratoire de Physique des 2 Infinis Irène Joliot-Curie (IJCLab, Université Paris-Saclay & CNRS-IN2P3),*
Bât. 100, 15 rue Georges Clémenceau, 91405 Orsay cedex, France

[b] *European Gravitational Observatory (EGO),*
Via E. Amaldi, 5, 56021 Santo Stefano a Macerata, Cascina (PI), Italy

E-mail: nicolas.arnaud@ijclab.in2p3.fr

Detector characterization and data quality studies (referred collectively as "DetChar" in the following) are key inputs to improve the sensitivity of a ground-based interferometric gravitational-wave (GW) detector like Virgo, to optimize the performance of the instrument during data taking periods and to vet GW candidate signals identified in low-latency or offline. DetChar is involved in the whole scientific dataflow, from the raw data recorded by the detector to the final list of GW events to be released publicly. These proceedings and the associated poster (linked in the bibliography section at the end) present the activities of the Virgo DetChar group during the LIGO-Virgo Observing Run 3 (O3, April 2019 – March 2020), summarizes its main findings and concludes by describing the upgrades and improvements that are foreseen to prepare the LIGO-Virgo-KAGRA O4 run that should start during Summer 2022.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

[*] Speaker

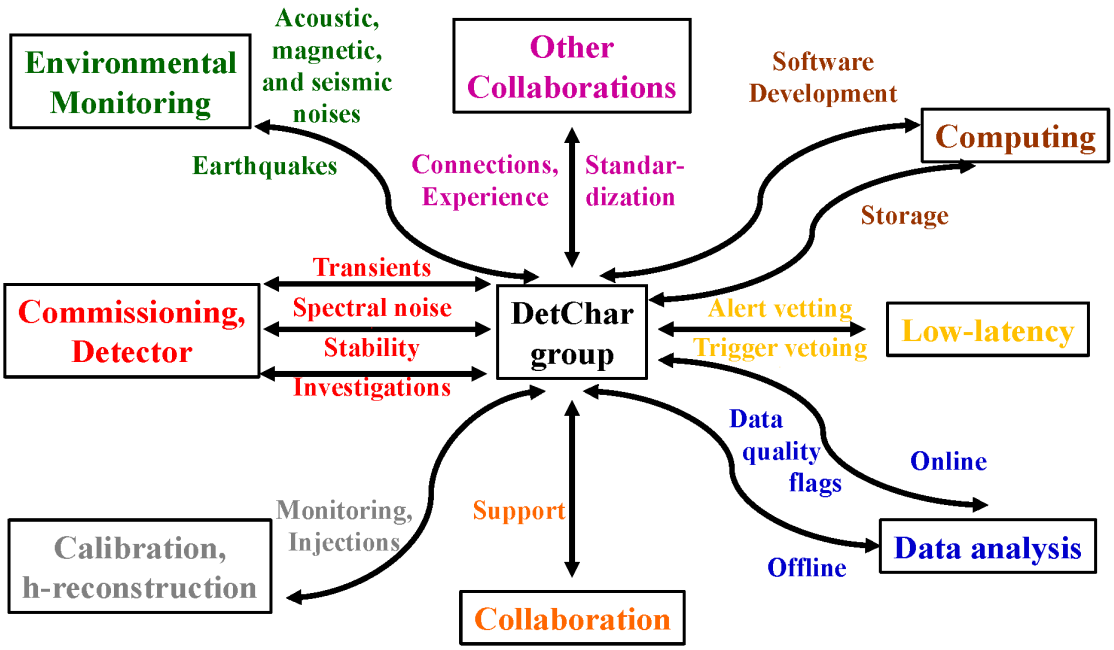

Figure 1: Schematics summarizing the interactions between the Virgo DetChar group and other parts of the Virgo Collaboration, as well as the LIGO and KAGRA partner Collaborations.

1. The Virgo DetChar group in a nutshell

Virgo *DetChar* activities (characterizing, monitoring and assessing the quality of the data recorded by the Advanced Virgo gravitational-wave (GW) detector [1]) are essential components of the data path that starts from the instrument front-end electronics and goes all the way to the final astrophysical searches. Figure 1 aims at summarizing the interactions, all bi-directional, between DetChar and the other main groups within the Virgo Collaboration. On this sketch, the left (right) side symbolizes the instrument (data analysis), with the DetChar group in the middle, connecting the two.

Interactions with the detector – whether it is in observing mode or in a commissioning period – are manifold: investigating new or changing noise characteristics; studying short-duration noise transients or spectral noise features; monitoring the stability of the instrument performance, etc. These are done using a variety of tools to analyze the data, display analysis outputs or archive them. Examples of these tools are displayed in the poster presented at this conference [2], while they are described in more details in a forthcoming article [3]. Similar – and in some cases common – tools are described in a recent LIGO DetChar article [4]. In addition, hundreds of probes have been deployed at EGO, the site of the Virgo detector, to monitor the environment and to allow detailed studies of how it impacts the performance of the instrument – see [5] and references therein. The DetChar group helps finding correlations between changes in the environment and noise variations. Contacts are also frequent with the team in charge of the calibration of the detector and of the reconstruction of the GW strain channel $h(t)$ [6], as the quality of the latter stream is continuously monitored and made available to the data analysis teams.

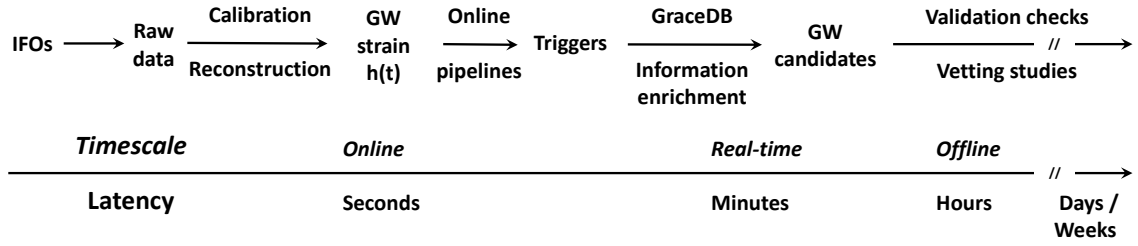

Figure 2: High-level dataflow highlighting the three main timescales at which the Virgo DetChar group has provided inputs during the O3 run.

Speaking about analysis, the DetChar group is responsible for providing data quality flags delineating usable datasets, both live – *online* – and later on – *offline*. In addition, its input is mandatory to vet transient GW signal candidates with the lowest possible latency and to turn them into public alerts used by telescopes to look for potential counterparts. All these activities rely on the Virgo computing resources, at EGO and in the Virgo computing centers. On the software side, tools are developed, tested, improved, automatized and shared, while storage areas are used to store the various DetChar products: from text files to large directories, by way of data acquisition channels and database entries.

Finally, the vertical directions on the diagram summarizes the interactions with the Virgo Collaboration as a whole on the one hand (that has to support DetChar activities by providing personpower to these) and with LIGO and now KAGRA that constitute with Virgo the global network of ground-based GW detectors. Each Collaboration has its own DetChar group; these three teams are collaborating closely.

2. DetChar and data quality activities during the O3 run

The LIGO-Virgo Observing Run 3 (*O3*) lasted 11 months: from April 2019 to March 2020, with a 1-month commissioning break in the middle – October 2019. The two halves of the O3 run are thus called *O3a* and *O3b* respectively. Our current GW transient catalog includes O3a [7].

Figure 2 shows the the main dataflow steps to which the DetChar group contributes, with the associated timescales. Initial data quality information is provided online, with a few second-latency, to the fast GW searches that jointly process in real time the $h(t)$ streams generated by all the instruments that are running at the time. Then, with a latency of a few tens of minutes at most, DetChar is required to vet the quality of the data for significant GW candidates found by the aforementioned searches. In each case, DetChar inputs, along with many others, were used by an ad hoc *rapid response team* to confirm the public alert or to retract it if investigations cast enough doubt on the astrophysical origin of the candidate. The validation of public alerts relies on a dedicated framework, called the *Data Quality Report*, and developed specifically for the O3 run. Its specifications were defined jointly by LIGO and Virgo (a standard example of collaborative work), while its actual implementation at the detector sites or in computing centers was left up to each collaboration to better match local resources, constraints and existing software

environment. Moreover, DetChar is responsible for providing the final dataset for each run and to validate extensively the GW events that will be published – that final list only partially overlaps with the one of the public alerts as the significance of borderline candidates can change as analysis improve and use a larger set of input information. The long delay (many months) between the data taking and the moment when the last GW candidates are released internally for data quality checks is actually a challenge: one needs to secure both an efficient access to the raw data and some dedicated personpower to these tasks, while the instrument has moved forward to a new phase (e.g. an upgrade) that requires different and possibly new DetChar inputs. Finally, DetChar takes part in the regular public releases of the Virgo data that follow each data-taking phase. Last but not least, DetChar orchestrates a global and continuous monitoring of the data taking: the detector, the online servers used to steer it and to acquire its data and the environmental probes. During the whole O3 run, and thanks to the support of the Virgo Collaboration, DetChar could provide a team of two on-duty *shifters*, renewed on a weekly basis who helped in the investigations described above.

3. Preparation of the O4 run

The LIGO-Virgo-KAGRA O4 run should start in the second half of 2022, with some delays mostly due to the worldwide covid-19 pandemic. Detectors are undergoing significant upgrades – see Ref. [8] for a description of the two-stage *Advanced Virgo Plus* project – that should lead to improved sensitivities and duty cycles. Preparation for O4 is ongoing as well within the Virgo DetChar group. The O3 run (the first long data-taking period for the second-generation Virgo detector) is used as a reference upon which to improve and extend the existing frameworks briefly described above. As more events are expected and as the goal is to reduce further the public alert latency, special emphasis will be put on making the DetChar tools more robust and more automated. These technical developments go along with an internal reorganization of the DetChar group, in order to better match the limited personpower available with the priorities, both in terms of detector characterization and data quality.

References

[1] F. Acernese *et al.* *CQG* **32** (2015) 024001 [arXiv:1408.3978 [gr-qc]].

[2] N. Arnaud, for the Virgo Collaboration, *EPS-HEP* (2021).

[3] Virgo Detector Characterization and Data Quality during the O3 run, *In preparation* (2021).

[4] D. Davis *et al.*, *CQG* **38** (2021) 135014 [arXiv:2101.11673 [astro-ph.IM]].

[5] The Virgo O3 run and the impact of the environment, *In preparation* (2021).

[6] F. Acernese *et al.* [arXiv:2107.03294 [gr-qc]].

[7] LIGO Scientific Collaboration, Virgo Collaboration *Phys. Rev. X* **11** (2021) 021053 [arXiv:2010.14527 [gr-qc]].

[8] R. Flaminio, *Proc. SPIE* **11445** (2021) 1144511.