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Data quality in gravitational wave bursts and inspiral searches in the second Virgo Science Run

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Abstract

In July 2009, Virgo started its second Science Run (VSR2) jointly with the LIGO detectors (S6). Great efforts have been made to understand the new sources of noise disturbance in Virgo data due to the detector or its environment. This understanding is crucial in order to reject noise events that could mimic a genuine gravitational wave (GW). One of the great challenges of VSR2 was to be able to monitor and deliver data quality information with low latency so that the online burst and inspiral GW searches could generate event candidates for follow-up studies. This paper reviews the sources of noise which have been identified and explains how it was possible to discard the associated noise events from the data. Finally, it presents the effect of data quality vetoes on Virgo triggers.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

The second Virgo Science Run (VSR2) started on 7 July 2009 and finished on 8 January 2010. 80% of that time was devoted to science. The achieved sensitivity was greatly improved with respect to the first Virgo Science Run (VSR1) and was very close to the Virgo design sensitivity curve [1]. The sensitivity of an interferometer can also be characterized by the horizon defined as the distance at which a gravitational wave produced by an optimally oriented neutron star binary system of 1.4–1.4 $M_\odot$ can be detected with a signal-to-noise ratio (SNR) of 8. In Virgo, the horizon was 8 Mpc at the beginning of VSR2 and reached 10 Mpc by the end of the run thanks to noise mitigation efforts.

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[1] A list of members of the LIGO Scientific Collaboration and the VIRGO Collaboration can be found at the end of this issue.

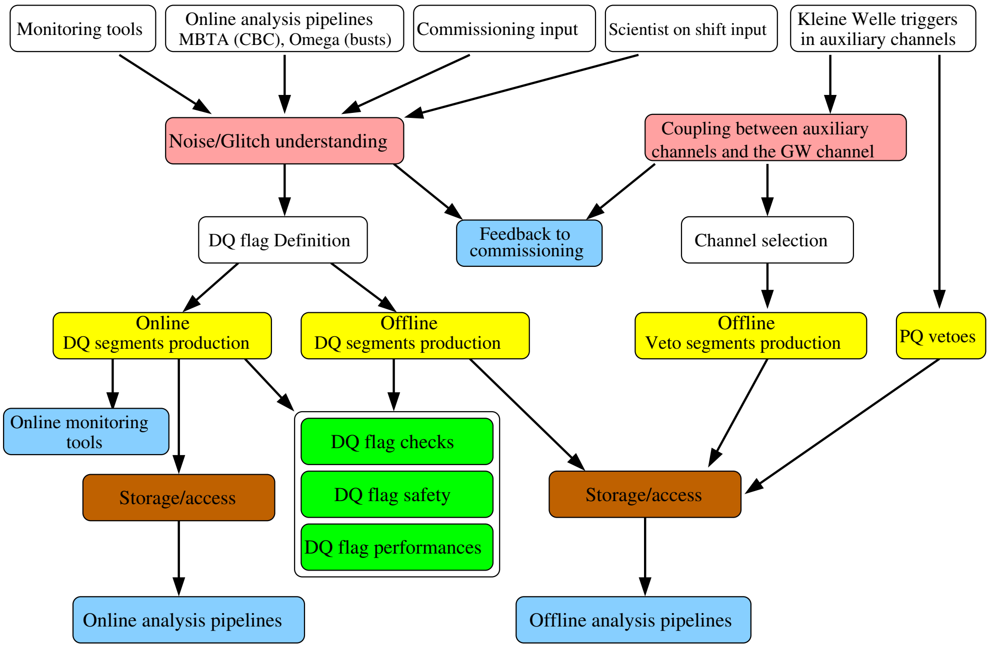

Figure 1. Flow chart describing the activities of the Virgo data quality group.

VSR2 was performed in coincidence with the two LIGO detectors H1 (Hanford, WA) and L1 (Livingston, LA) [2]. Using two or three detectors in coincidence can significantly reduce the false alarm rate of searches and greatly enhance their sensitivity. However, the noise of the detector remains strongly non-Gaussian and removing outliers is crucial for performing searches with a detection threshold as low as possible. The Virgo data quality group, the LIGO detector characterization group [3] and the commissioning experts work together to understand the noise of the detectors or their environment and to build tools to identify and remove noise events out of the data (see figure 1).

For the time being, the GW detector non-Gaussian noise cannot be modeled or simulated, and it is understood *a posteriori*. However, when the coupling between a noise source and the GW channel is well established, it is possible to build predictive tools which can flag noisy data in quasi-real time. This was one of the great challenges of VSR2; data quality information was produced online and transferred to computing centers where analysis pipelines were running [4]. By doing so, accidental coincident triggers were immediately removed and the most significant GW candidates could be provided to external collaborations for follow-up [5].

After reviewing the noise sources which have been identified, we will explain how it is possible to flag such noisy data periods. We will then show how much the data quality vetoes can impact the burst and compact binary coalescence (CBC) analyses. An analogous presentation of the vetoes based on auxiliary channel glitches will also be made. Finally we will briefly describe the tools used to store and access the data quality information.

2. Noise hunting

The VSR2 data quality (DQ) activities took advantage of the experience acquired during VSR1. Some noise sources of VSR2 were already present during the first Science Run.

The 50 Hz magnetic glitches, the seismic noise, the $h(t)$ reconstruction quality and the coil saturation are such examples. For an extensive description of those noise sources one can refer to [6]. Specific VSR2 noises were discovered when commissioning the detector or even during the data capture. Understanding a noise source can be a long process and requires the expertise of all the people involved in the experiment from the commissioning team to the data analysis groups. Many tools were developed in order to track the noise in the detector and to understand the coupling with the GW channel.

Here are some examples of information used for investigation.

- A burst and a CBC analysis pipeline were running online producing triggers. The daily loudest triggers and the variations of the trigger rate over a few hours are investigated. Noise triggers with the same characteristics can be grouped in families for a better understanding.
- Abnormal behavior of auxiliary channels (used for controlling the instrument and for environmental sensing) was monitored by several tools such as spectrograms, frequency band RMS, nonstationarity monitors, etc.
- Information provided by the commissioning team is important since they have a unique knowledge of the detector.
- Daily reports of operators and scientists in the control room can be helpful in the case of severe problems on the detector.
- One of the features of the burst pipeline *Omega* [10] is to be able to analyze channels around a given time and to establish time frequency maps of all channels having glitches. Many noise sources were identified thanks to this tool.

In addition to a day-by-day analysis of data quality, weekly shifts were organized by the Virgo DQ group in order to understand specific noises seen in the data. When possible, the noise source was mitigated, and if not, a DQ flag was defined and a monitor was built to produce this flag with a low latency so it could be used by online analyses. DQ flags are often improved during and after the run so that the offline analyses can benefit from the best knowledge of data quality.

3. Data quality flags

A DQ flag is a list of 1 s resolution time segments where the data are qualified as noisy. It is built using the information provided by one or several of the 2000 Virgo auxiliary channels other than the GW channel. DQ flags can also be built from the shifter's report (electronic failure, human intrusion, etc). Noise sources can be classified into three groups: environmental disturbances, detector instabilities and incidents occurring when recording or processing the data. The latter concern mostly the determination of the Virgo strain amplitude which can be corrupted by missing data or bad reconstruction conditions.

Seismic activity is a good example of an environmental noise which can affect the GW channel and produce noise glitches. Seismic transients are monitored by 42 seismometers and accelerometers installed at strategic points on the Virgo site. Using these sensors to look for an excess of energy in low-frequency bands (from 1 to 16 Hz) is an efficient way of flagging the seismic activity. However, seismic activity can be coupled with the GW channel in different ways and specific DQ flags were created for each coupling. For instance, the ground motion can shake the optical benches which have a poor seismic isolation; the resulting fluctuations of the scattered light on optical mounts can create glitches in the GW channel [7]. Position sensors can be used to derive the motion velocity. Removing time periods when the velocity exceeds a typical value of 15 $\mu\mathrm{m\,s^{-1}}$ is an efficient way of flagging scattered light glitches.

Seismic activity can also disturb the beam alignment and produce some glitches at fixed frequencies. Alignment control signals are therefore very useful to remove such noise events. Seismic DQ flags are crucial for VSR2 because, for the first time, the Virgo Science Run included the winter season. Bad weather conditions (strong winds, storms, rough seas, etc) can significantly affect data quality so efficient seismic flagging is absolutely required. Other known environmental disturbances affecting the GW channel have an acoustic and magnetic origin. Microphone and magnetometer signals are used to create the appropriate vetoes.

A sub-system of the detector can be unstable and disturb the GW signal. A striking example in VSR2 concerns the thermal compensation system (TCS) which uses a CO_2 annulus laser beam which heats the cavity mirrors to compensate for the deformation due to the main laser [8]. Before the installation of a power stabilization in October 2009 this system could create glitches in the GW channel. Monitoring the power variations had to be performed in order to flag occasional TCS glitches occurring in the first part of the run.

Finally, some glitches in the GW channel do not have a clear explanation as yet. However, if a glitch is systematically seen in coincidence in an auxiliary channel, it offers a way of flagging a family of glitches even if the coupling is not understood. Glitches in photodiode channels are a good illustration and many DQ flags were introduced based on optical signals. A more systematic approach has been adopted to study correlations between the GW and auxiliary channels to produce efficient vetoes, an approach which is detailed in section 5.

4. Reliability and performance checks

Before providing the data quality information to the analysis groups, the DQ segments are carefully checked and their reliability is studied. Some checks are systematically performed as soon as the offline segment list production is achieved. This work consists in

- checking that the different processes composing the DQ production chain have run without error,
- checking that no segment is missing,
- checking the long segments, typically longer than 30 s, and
- fixing the lists manually if necessary.

The Virgo data quality group also checks the performances of the DQ flags over different analysis pipelines. The goal is to provide a prescription on how to use the flags in the analyses. For that purpose, the flags are organized into five categories (CAT) depending on how well they perform as a veto. This categorization is also important since it indicates at which stage of the analysis a flag should be applied. Table 1 gives the definition of the categories. It should be noted that the category definition has changed with respect to what was used in the previous Virgo and LIGO runs [6].

Whereas labeling a flag as a CAT1 or CAT4 is straightforward, differentiating CAT2, 3 and 5 requires further studies. Moreover, the categorization can also depend on the type of analysis that is performed. That is why two sets of triggers were used to evaluate the performances of the DQ flags: one set for the CBC search produced by the multi-band template analysis (MBTA) pipeline [9] and another set for the burst search produced by the Omega pipeline [10]. Three figures of merit are used to characterize the performance of a flag:

- the *dead-time* (d) defined as the fraction of science time which is flagged,
- the *use-percentage* (UP) giving the fraction of DQ segments used to flag at least one trigger,

Table 1. Veto category definition and prescription for search analyses.

Category	Definition	Prescription for analyses
CAT1	Flags obvious and severe malfunctions of the detector	Science data are redefined when removing CAT1 segments. Offline analysis pipeline should run on data only after removing CAT1 time periods
CAT2	Flags noisy periods where the coupling between the noise source and the GW channel is well established	Triggers should be removed if flagged by a CAT2 veto. A significant trigger surviving the CAT2 vetoes is a good candidate for detection follow-up
CAT3	Flags noisy periods where the coupling between the noise source and the GW channel is not well established	CAT3 vetoes should not be applied blindly. Triggers flagged by a CAT3 veto should be followed up carefully. CAT3 vetoes are applied to compute upper limits
CAT4	Flags time periods where hardware injections were performed	Periods flagged by a CAT4 veto are used for specific studies. This category is applied for any search analysis
CAT5	Advisory flag to keep track of problems for which no (or very low) impact was seen in the GW channel	CAT5 are only used at the last stage of the detection follow-up. The validity of the flagging must be carefully checked by experts

Table 2. Impact on the burst triggers: the use-percentage (UP) is given for each category of flags. The dead-time (d) and the efficiency (ε) is given after applying the veto categories successively and for different SNR thresholds.

BURST	CAT1	CAT2	CAT3	KW vetoes
UP, SNR > 5	75.5%	87.5%	73.1%	91.2%
	CAT1	CAT1+2	CAT1+2+3	CAT1+2+3+KW vetoes
d	0.8%	5.0%	8.1%	8.2%
ε, SNR > 5	1.2%	16.5%	22.6%	24.2%
ε, SNR > 8	5.4%	61.8%	74.6%	76.3%
ε, SNR > 15	23.8%	86.4%	88.6%	89.2%

- the *efficiency over dead-time ratio* (ε/d) where the efficiency ε is the fraction of triggers which are flagged. $\varepsilon/d = 1$ means that the flagging is random while $\varepsilon/d > 1$ means that the flagging starts to be effective.

In addition, such numbers are computed for different SNR thresholds. First it shows what kind of glitch population is vetoed by a given flag; then, increasing the SNR threshold reduces the trigger rate and the random flagging and therefore the figures of merit are more significant. Tables 2 and 3 summarize the figures of merit for the bursts and CBC searches and figure 2 shows the SNR distribution after applying the different categories of vetoes. The effect of CAT1 vetoes is mostly visible for high SNR triggers which is expected given the severity of the problems this category is supposed to flag. CAT2 vetoes are quite effective and with a limited dead-time which shows that the noise source and the coupling with the GW channel is well understood. In figure 2, a shoulder can be seen for $12 < \text{SNR} < 40$ (burst case) which is the result of the micro-seismic activity which can be strong in the second half of VSR2. The micro-seismic flags described in section 3 and labeled as CAT2 are well able to remove such events. CAT3 vetoes, although less reliable, complement nicely the CAT2 flags;

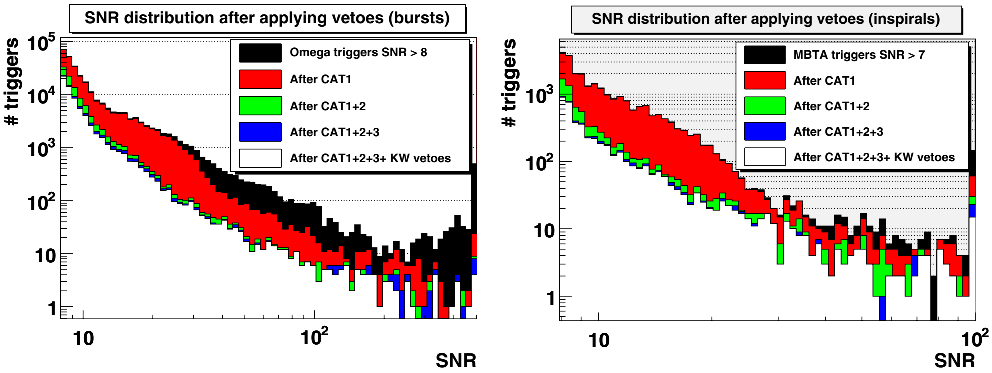

Figure 2. SNR distributions for the burst triggers (left-hand plot) and for the CBC triggers (right-hand plot) when applying category 1, 2 and 3 DQ flags and the KW vetoes.

Table 3. Impact on the CBC triggers: the use-percentage (UP) is given for each category of flags. The dead-time (d) and the efficiency (ε) is given after applying the veto categories successively and for different SNR thresholds.

CBC	CAT1	CAT2	CAT3	KW vetoes
UP, SNR > 5	63.0%	54.2%	34.1%	45.9%
	CAT1	CAT1+2	CAT1+2+3	CAT1+2+3+KW vetoes
d	0.8%	6.4%	20.8%	21.3%
ε, SNR > 5	0.4%	17.8%	37.1%	38.0%
ε, SNR > 8	1.8%	72.1%	80.0%	81.0%
ε, SNR > 15	3.4%	63.3%	67.6%	68.8%

the thresholds used to define CAT3 vetoes are usually loose and some events missed by CAT2 vetoes are thereby caught by a CAT3 flag with the drawback of an increased dead-time.

Finally, it is very important to check that none of the vetoes used by searches would reject a genuine signal. For this study, hardware fake signals (CAT4 time periods) are injected in the detector by pushing on one of the end-mirrors of the interferometer arms. $N = 1383$ ($N = 442$) hardware burst (inspiral) injections were performed during VSR2. Various waveforms were injected: Gaussians, sine-Gaussians, band-limited white noise, ringdown, core collapse supernova, cosmic string cusps for the burst signals and compact binary coalescence waveforms for the inspiral signals. Waveform parameters such as the frequency, the quality factor, the inspiral masses or the polarization were varied to span a large range of possibilities. In particular some large SNR signals (up to 100) were injected to better test the safety of the DQ flags. Given the dead-time d of a DQ flag, $d \times N$ injections are expected to be vetoed. A probability of being unsafe, based on a Poisson distribution, is associated with each DQ flag. All the VSR2 DQ flags used by data analyses are considered safe.

5. Auxiliary channel vetoes

A systematic study of coincidences between events in the GW channel and the auxiliary channels is performed in Virgo. A fast wavelet-based algorithm called KleineWelle (KW) [10] is used to produce triggers over more than 500 channels, the GW channel being one of them. With an appropriate time window, and after applying CAT1&2 DQ flags, coincidences between a given auxiliary channel and the GW channel can be counted and compared to the expected rate of a random trigger process. It is then possible to order and retain the most significant channels and define a powerful veto. Two channel selection processes actually co-exist in Virgo. The first one, called *h-veto*, uses an iterative procedure where channels are sorted by significance. Then only channels fulfilling the requirements $\varepsilon/d > 10$ and $\mathrm{UP} > 30\%$ are selected. The resulting veto segments are used in the burst searches. The second method, used by the inspiral search group, consists in increasing the significance threshold on each channel until observing a $\mathrm{UP} > 50\%$ [11]. If this requirement is fulfilled the channel is selected to produce vetoes. Those criteria are voluntarily chosen strict enough to counterbalance the lack of understanding underlying the intrinsic statistical approach. Such a channel selection safely ensures that the coupling between the auxiliary channel and the GW channel is founded. Moreover this study points out channels where noise investigation should be pushed further and such a tool therefore presents quite some interest for the Virgo commissioning group. For VSR2, the most significant channels are the photodiode signals polluted by scattered light glitches (see section 3) and the transmission channels from the input mode cleaner cavity to the injection bench where the glitches are yet to be understood.

For VSR1 another type of veto, named *PQ veto* [12], also based on the KW output was useful to reduce loud glitches. It consists in rejecting the events with a large energy deposit in the quadrature (ACq) interferometer output channel with respect to what is detected in the in-phase (ACp) channel, where GW signals would be expected. A very small fraction of a genuine GW signal is expected to be detected in ACq. Such a veto is only possible if the demodulation phase is well tuned. This is the case in Virgo since a servo ran online during VSR2 to tune the phase of the demodulated signal. Even if the origin of the glitches flagged by the PQ veto is not clear as yet, the performance of the rejection has been proven high.

The KW-based vetoes are assigned as CAT3 since the coupling is not fully understood. The reliability of all the KW-based vetoes has been checked the same way as the DQ flags including the safety checks, see section 4. Their performances are given in tables 2 and 3 (they are labeled as *KW vetoes*).

6. Storage, transfer and access

An important aspect of the VDQ work is to provide an easy access to the data quality information. All the DQ segments are centralized in a database architecture where specific queries can be made. The Virgo database (VDB) offers plenty of possibilities such as extracting DQ segments by name or category, applying AND/OR operations between lists and getting extra information like the dead-time. Moreover, a web interface has been set up [13] where all the above operations can be requested. Another practical functionality for event follow-up is to provide the list of DQ flags for a given GPS time. The content of VDB is synchronized with the LIGO database (SegDB) since network analyses require the full DQ information for all the detectors.

One of the great challenges of VSR2 was to provide the DQ flags with a very low latency to online analyses. The online DQ chain which contains the data provider, the DQ monitors and the segment builder is able to provide DQ flags within a few seconds. Then this information is transferred to the LIGO computing centers where the online analyses run. GW triggers can finally be filtered out in order to retain only the most significant candidates. The full procedure (DQ production + transfer) takes approximatively half an hour. This is the typical delay to provide a potential GW candidate to external collaborations for electromagnetic (or neutrino) follow-up [5].

7. Summary

The data characterization for the GW searches has become crucial to aim at a detection. In Virgo, great efforts have been made to understand the noise of the detector and its environment. A few noise sources encountered with VSR1 were still present with VSR2. However, the upgraded Virgo detector has introduced new noise sources which have been identified. The work of the data quality group has been to provide the best way of flagging noisy data and to pass the information to the analysis groups. To date, more than 75 DQ flags have been produced to remove bad quality time periods in the Virgo data. KW-based vetoes should be added to the list where a systematic study of correlations between the auxiliary channels and the GW channel is performed.

Some noise sources are still to be understood and removed from the data. For that purpose, the VDQ group tries to improve the interactions between the analysis groups and the commissioning team. Knowing the limitations of the GW searches can facilitate the noise understanding and provide a useful information for the detector experts allowing to clean the data even more and perform more sensitive searches.

The third Virgo Science Run (summer 2010) is in preparation. New noise sources are expected with the new detector configuration. The noise hunt will start as soon as the interferometer is up again.

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