PROCEEDINGS OF SCIENCE

Detector characterization of KAGRA for the fourth observing run

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KAGRA is a ground-based gravitational wave detector located at the Kamioka mine in Gifu prefecture, Japan. The fourth international joint observing run (Observation-4; O4) by LIGO, Virgo, and KAGRA is scheduled starting from May 2023. KAGRA detector characterization group aims to enhance the reliability of data analysis and GW detections by supporting the detector commissioning and improving our understanding of the detector instruments and acquired data. We provide various tools for monitoring, understanding, and mitigating noise sources, which is an essential component of enhancing the performance of the KAGRA detectors and data analysis. In this talk, we will report on the recent activities and status of the detector characterization of KAGRA for O4.

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1. Introduction

The gravitational wave (GW) is a wave solution obtained when the Einstein equation is solved under an approximation of a weak gravitational field. The GW propagates as a wave at the speed of light. The GW is predicted according to the theory of General Relativity which was established in 1915 by Einstein [1]. While the evidence of the existence of GWs has been inferred indirectly from the observation of the change in the revolution period of the binary pulsar PSR B1913+16 [2], the first direct detection of the GW was finally achieved by Advanced LIGO detectors on 15 September 2015 [3]. So far three international observation runs (called O1, O2, and O3) were performed, and 90 GW events [4] were detected by the LIGO [5] and Virgo [6]. From 25 May 2023, the fourth international observation (called O4) has started with the International Gravitational-Wave Observatory Network (IGWN) consisting of LIGO, Virgo, and KAGRA.

KAGRA is a cryogenic and underground gravitational wave detector consisting of a laser interferometer with 3 km arms, located in Kamioka, Gifu, Japan [7]. KAGRA has several features compared with other telescopes with km scale. The first feature is the underground environment to operate the detector in a silent environment. By installing the detector underground, the effect of noise such as wind, temperature, and human activities can be mitigated. The second feature is to cool down the mirrors to reduce the thermal noise. KAGRA plans to cool down the four sapphire mirrors consisting of the Fabry-Perot cavity to be about 20 K.

During the O3 run, KAGRA performed the first international observation run with GEO600 detector starting from April 2020, which is called O3GK [8]. The joint analysis of the GEO–KAGRA data for transient GW signals was performed [9]. To improve the sensitivity toward the O4 run, the contributions from various noise sources to the sensitivity (called a noise budget) were investigated for the better understanding of the noise limiting the sensitivity [8]. According to the obtained noise budget, the measured sensitivity could be approximated explained by adding up each noise. The sensitivity was dominated by noise from the sensors used for local controls of the vibration isolation systems, acoustic noise, shot noise, and laser frequency noise. The task toward O4 is to mitigate the noise and improve the sensitivity [10].

In this article, we describe the status of the detector characterization group in KAGRA toward the O4 run. The detector characterization (DetChar) group has mainly two roles. The first role is to improve the sensitivity and stability of the interferometer controls. We have investigated the noise origin and the path contaminating the external noise by analyzing the multiple control signals and the witness sensors for noise hunting [10]. We provide data monitoring tools to check the long-term stability. The section 2 describes the tools for the commissioning support. The second role is to provide the data quality information to prevent the false detection of GW in analyzing the data. The section 3 describes the activities related to the data quality.

2. Tools for noise hunting

2.1 Summary page

The interferometer is controlled by feedback controls of the mirror suspensions and the laser. Data acquisition and control are performed by the system called the real-time system. These signals are constantly monitored to know that they are stably working and that nothing abnormal is occurring. Currently, there are more than 100,000 channels related to the controls, and it is not realistic to monitor all of them. The summary page is a tool for the 24-hour monitoring of sensors and signals of particular importance to interferometer control.

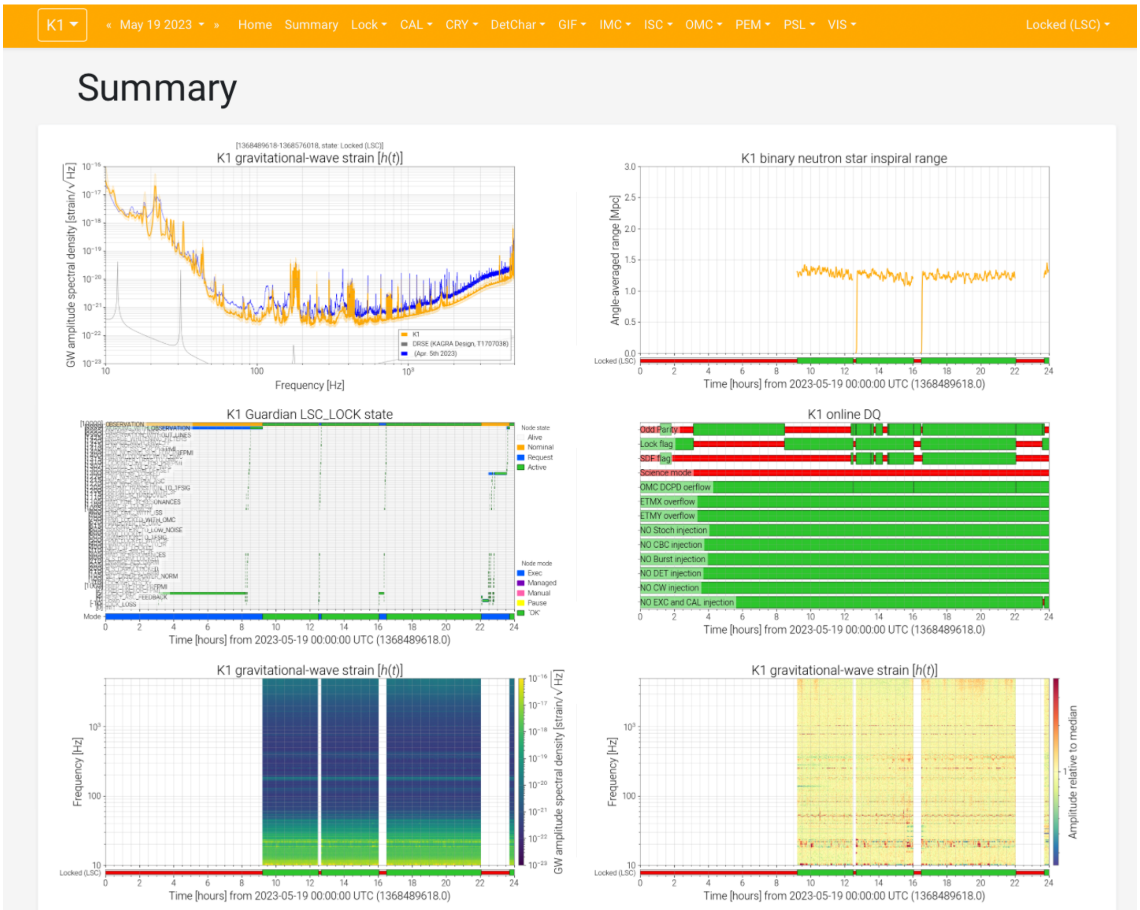

Figure 1: Example top page of summary page for May 19, 2023. Left top : Orange curve is the sensitivity of KAGRA in the lock state. Orange light curves show the deviation of the sensitivity. Blue curve is the reference sensitivity recorded on April 5th 2023. Right top : The time variation of inspiral range. The bottom bar shows the status of the interferometer. Green indicates the locked time, that is, the interferometer is under control. Red indicates the unlocked data, that is, the interferometer is not under control. Left middle : The state changes of guardian which manages the interferometer state step by step based on the commissioner's request. Right middle : The bit status of online data quality flag. Green (red) indicates that the bit flag is active (inactive). Left bottom : The time-frequency map (called spectrogram) of the strain data. The color bar shows the amplitude spectrum density. Right bottom : Whitened time-frequency map of the strain data. The color bar is the normalized spectrum divided by the median amplitude spectrum density, to improve the visibility of the transient signal.

Figure 1 shows the example top page of the summary page. Each plot summarizes the results for one day. Other plots for the past date are accumulated, and past pages can be easily viewed through the calendar feature. Pages are updated approximately every 15 minutes.

The summary page is created by a python package called *gwsumm*, which is developed by

LIGO members based on a python package called *gwpy* [11]. To create a page, it is necessary to set in advance what channels will be monitored and how they will be monitored, such as time series, whitened time series, amplitude spectrum density, spectrogram, and so on). Since O3GK, sensors (such as oplev for length direction and new physical environmental sensors) and new interferometer controls (such as angular sensing and controls, fiber noise cancellation, and phase locking loop) have been implemented and added to the summary page.

2.2 Pastavi

All data acquired at the KAGRA site is transferred to the main data storage located in Kashiwa, Chiba, Japan. To view past data, make plots, and perform various analyses, users need to log in to the main data storage and develop the code to read the data. The data is stored in the format called frame format and is divided into 32-second data. To read the data, it is necessary to know the channel names in advance and to correctly handle the divided data. Sometimes this is a barrier for users who are not familiar with code development and data handling. Therefore, we developed a web-based tool to assist users in easily plotting and analyzing past data. This will be a tool as a complement to the automatically generated summary page. To ensure computing resources, Pastavi is running on the dedicated server.

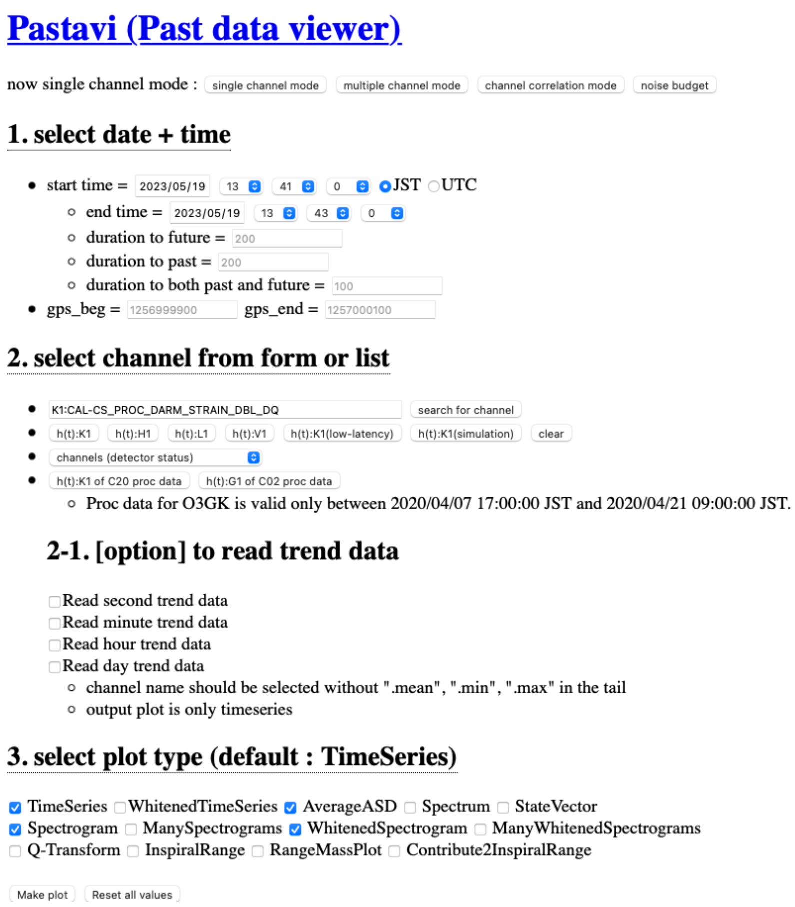

Figure 2: Top page of the web-based tool called Pastavi

Figure 2 shows the web page of Pastavi. The following three steps are required to make a plot. In step 1 (top of Fig. 2), the user selects the time and the date for reading the data in JST timezone, UTC timezone, or GPS time. In step 2 (middle of Fig. 2), the user selects the channel name to plot. The user can enter directly or search the full channel name by partial channel name. In step 3 (bottom of Fig. 2), the user selects the type of plot including time series, whitened time-series, the averaged amplitude spectrum density(ASD), time-frequency map (spectrogram), whitened time-frequency map (whitened spectrogram), calculation of detectable distance, and others. The plotting options required for typical plots, such as the axis scale selection, the plotting range selection, and the output of data in text format, are available. The web page is designed to be as simple, light, and user-friendly as much as possible.

We have made modifications and developed functions based on user requests and comments. Most recently, we have implemented the function to make the noise budget by combining the measured transfer function and the noise curve of the sensor.

2.3 DetChar cluster at KAGRA site

The new cluster computer has been built at the KAGRA site to enhance the online analysis resources for DetChar. HTcondor manages the compute jobs and was set up with the cooperation of NAOJ's astronomy data center (ADC). In addition to the summary page mentioned above, many analyses related to detchar are running at KAGRA site, such as the analysis to find transient glitches (called Omicron [12]), the coincidence analysis between such triggers (called Hveto [13]), the analysis to compute the coherence between multiple channels (called Bruco) and the data quality production (see Section 3.1). These analyses are running on the dedicated computers but will be integrated in the future so that they all run within the detchar cluster. This will allow for easier maintenance and the unification of the computing environment of these tools provided by IGWN computing.

3. Tools for event validation

3.1 Data Quality information

One of the most important roles of DetChar is to prevent the false detection of GWs [14]. GWs are very weak signals and are buried by various disturbances, such as vibration of the mirrors that constitute an interferometer and instability of the laser power and frequency. Such disturbances can also be detected as false GWs events. To separate GWs from such false events, it is necessary to understand the statistical behavior of the detector noise.

In GW searches, the observational data, which contains a lot of known disturbances, is tagged by Data Quality (DQ) flags and data category flags. Tagged data is removed from the input data for searching GWs to reduce the false event rate. For O3GK data, only the basic operating status of the interferometer was provided as an online process that is $O(10\text{s})$ and other information about noise behavior were provided as an offline process with $O(\text{month})$ delay. As one of DetChar's activities, we optimized criteria of DQ flags and updated the software to provide DQ flags with a shorter delay. The optimization of the criteria was conducted based on knowledge about the hardware problem, which was obviously during the hardware upgrade and the commissioning of the interferometer.

DQ flags contain disturbances due to the environmental noise transients coming from electrical glitches of instruments, and operational errors of human activities. The generated DQ flags are uploaded to the dedicated server and shared with data analysis members of LVK collaboration.

3.2 Data Quality Report

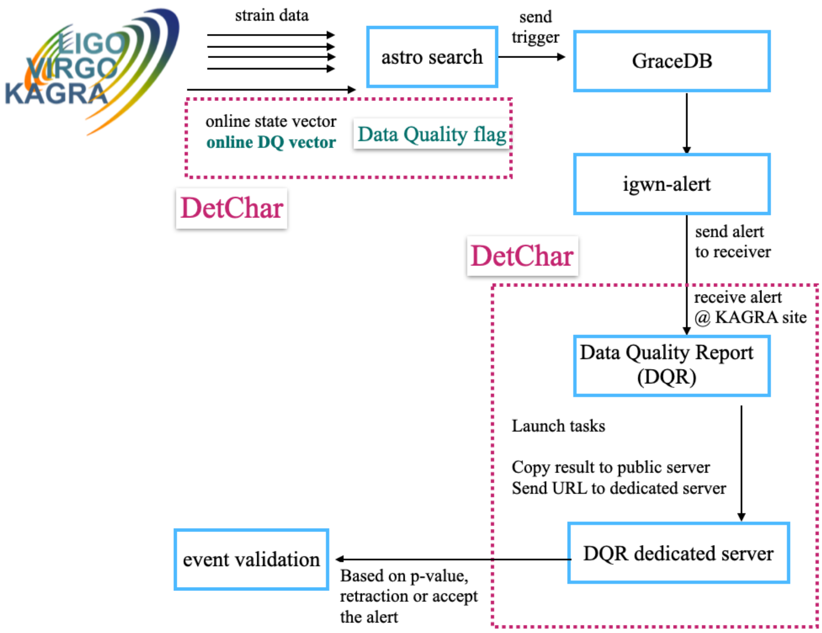

Figure 3: The schematic view of DQR processes. The all the data are collected in CIT and analyzed by low-latency pipelines. The found GW candidate (trigger) is send to the server called GraceDB and sent the alert to receivers vis *igwn-alert*. We receive the alert at KAGRA site and launch the tasks to provide the data quality around the trigger. The results will be sent to the DQR dedicated server. The event validation will be performed.

To access the physics related to the neutron star merger or the supernovae, it is important to perform follow-up observations by electromagnetic telescopes just after finding the GW candidate. One of the successful examples is GW170817 [15]. The data from GW observatories (LIGO, Virgo, and KAGRA) are collected to the cluster at California Institute of Technology (CIT). The low-latency search pipelines analyze the data set and provide the GW alert with a latency of a few seconds. The information, such as the mass of the binary star, the merger time, the estimated sky map, and the signal-to-noise ratio, are registered in the database (called GraceDB) to share with the collaborators.

The task of DetChar is to provide the data quality report (called DQR) of the data around the time of the GW candidate. In the past observation run (O3), the DQR was organized by LIGO and Virgo. The DQR played an important role in a number of retracted candidates and increased the confidence of candidates for astronomers of electromagnetic telescopes.

Toward the next observation run, LVK DetChar plans to provide the tool standardized across collaborations and to launch the DQR processes automatically triggered by the GW alert at each observatory site. Figure 3 shows the schematic view of DQR processes. We have participated in the development of the DQR tools and have contributed to the operational test with LIGO and Virgo DetChar members.

4. Summary

KAGRA is a cryogenic and underground gravitational wave detector consisting of a laser interferometer, located in Kamioka, Gifu, Japan. The O4 run has started from 25, May 2023. KAGRA has been in observation mode stably since 24 May with the sensitivity around 1.3Mpc. KAGRA resumed the commissioning from June 21, four weeks after the start of first half of O4 (called O4a), and will restart observation (O4b) in spring 2024. For the first detection of the GW by KAGRA, the detector characterization (DetChar) group for KAGRA have two tasks.

Firstly, imptovement of the sensitivity and the stability of the interferometer controls. We investigate the noise origin and the path contaminated the external noise by analyzing the multiple control signals and the witness sensors for noise hunting. To monitor the multiple sensors and control signals, we have provided the data monitoring tools, such as the summary page to check the long-term stability and the web-based tool to analyze the data easily.

Secondly, we provide the data quality information to prevent the false detection of GW in analyzing the data. In GW searches, the strain data containing known disturbances is tagged by Data Quality flags. Tagged data is removed from the input data for searching GWs to reduce the false event rate. For O3GK data, we have provided the basic operating status of the interferometer and other information about known noise issue. Toward the O4 run, we have developed the software to provide DQ flags with a shorter delay and the additional DQ flags. In addition, we started the project to provide the data quality report (DQR) for the GW candidate triggered by the low-latency search. The infra tools for DQR is standardized over the LVK collaboration.

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