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# Status of the underground gravitational wave detector KAGRA

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Gravitational-wave detector LIGO first detected the gravitational-wave signals in 2015, and then 90 compact binary coalescences were detected until March 2020. These detections provide new eyes to observe the universe and promote our understandings of the universe. For further promotions, precise localization of gravitational-wave sources is essential, which will be accomplished by observing the signals with more gravitational-wave detectors simultaneously. KAGRA is a kilometer-scale interferometric gravitational-wave detector located in Japan. There are two unique features in KAGRA: utilizing an underground site and cooling four main sapphire mirrors at cryogenic temperature. Underground site has a quite environment, which results in the reduction of seismic noise. Cryogenic mirrors reduce thermal noise of mirrors and their suspensions, which is one of the fundamental noise sources that limit the sensitivity of interferometric gravitational-wave detectors. These features are considered as the fundamental technologies for the next-generation gravitational-wave detectors to obtain further sensitivity; and therefore our experiences on utilizing the underground site and cryogenic mirrors can indicate the way for their development. KAGRA joined the fourth international observing run from 24 May to 21 June in 2023. During the observing run, we achieved higher sensitivity and stability compared with those in the previous international observing run on April 2020. In this presentation, the current status of KAGRA is reported.

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## 1. Introduction

The Laser Interferometric Gravitational-wave Observatory (LIGO) [1] first detected the gravitational waves (GWs) from a black hole binary coalescence in 2015 [2], and this great discovery enables us to observe the universe with a wholly new method. In 2017, LIGO had the second observing run (O2) and a gravitational-wave detector (GWD) Virgo [3] participated in the O2 from August of the year. Soon after Virgo joined the O2, LIGO and Virgo detected GWs from a binary black hole simultaneously [4], which enables precise localization of GW sources. Just three days after the success of three detector observations, they detected GWs from a binary neutron star [5], with which a short gamma-ray burst and electromagnetic afterglow followed. Many electromagnetic telescopes performed follow-up observations and confirmed a counterpart of the event [6]. This is the first successful follow-up observation and the beginning of multi-messenger astronomy with GWs. For its further promotion, it is essential to increase the number of GWDs that are operating simultaneously to determine the direction of GW sources precisely.

A Large-scale Cryogenic Gravitational-wave Telescope KAGRA [7] is an interferometric GWD constructed at Mt. Ikenoyama, Gifu, in Japan. KAGRA has two key features: one is constructed at the underground site and the other is utilizing cryogenic sapphire mirrors. The underground site provides a quiet environment that mitigates the effect of seismic motion. Cryogenic mirrors can reduce thermal noise, Brownian motion of atoms of mirrors and their suspensions. These two features are considered as key technologies for the next generation GWDs such as Einstein Telescope [8]; and therefore KAGRA can be a prototype of the next-generation GWDs.

KAGRA project formally started in 2010. Tunnel excavation started in 2012 and finished in 2014. After the excavation, facility construction started and finished in 2019. During the construction, KAGRA has two test operations: the 3-km Michelson interferometer with room-temperature mirrors and with a cryogenic mirror. After the construction, KAGRA conducted an international joint observing run, called O3GK, with GEO600 [9] in 2020. During the O3GK, the median of KAGRA sensitivity was 700 kpc and the duty cycle was 52% [10]. After the O3GK, several hardware updates were performed for 2.5 years and interferometer commissioning was followed. Then, KAGRA joined the fourth international observing run (O4) from May 24, 2023 for one month. During the O4, the median of KAGRA sensitivity was 1.3 Mpc and the duty cycle was 80% [11]. After one month of observing run, KAGRA restarted interferometer commissioning for further improvement of the sensitivity and plans to join the O4 again from the spring of 2024. In this paper, hardware updates and interferometer commissioning before the O4 are reported.

## 2. Hardware updates and interferometer commissioning

During the O3GK, KAGRA achieved a Power-Recycled Fabry-Pérot Michelson Interferometer (PRFPMI) with DC readout. We aim to achieve PRFPMI with a Resonant-Sideband Extraction (RSE) technique [12] in future; however PRFPMI configuration was also used in the O4 to increase the time for the noise hunting with the PRFPMI configuration, which was well characterized after the O3GK [13], before the O4. Figure 1 shows the schematic of the configuration during the O4. We worked on several hardware updates such as auxiliary laser systems and suspensions. Then, the interferometer was commissioned to achieve stabler operation with better sensitivity for the O4. Here, we briefly explain what we achieved before the O4.

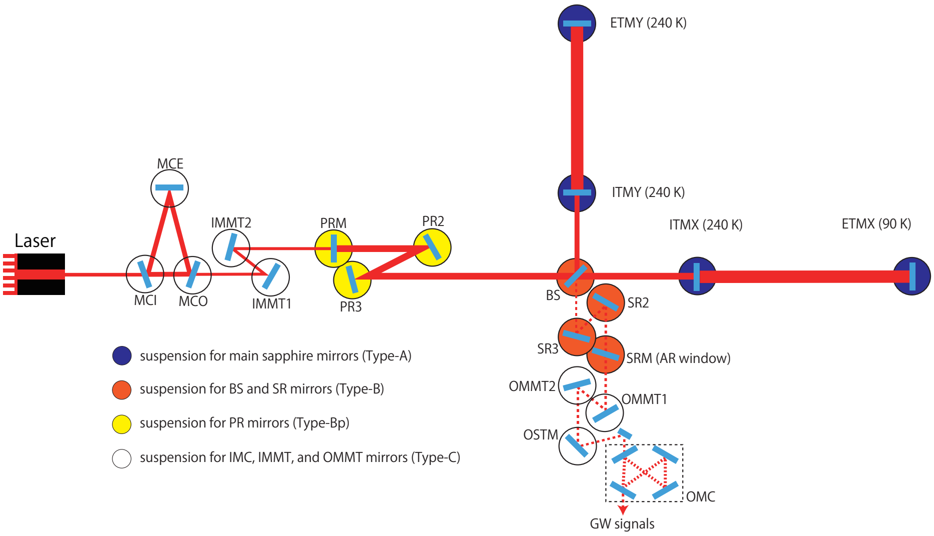


**Figure 1:** Schematic of interferometer configuration during O4 observing run. ETMX was cooled at 90 K and the other sapphire mirrors were at 240 K during the O4. SRM was replaced from 70% reflection mirror to AR coated window to increase GW signals with PRFPMI configuration.

### 2.1 Update of auxiliary laser system

KAGRA adopts Auxiliary Laser System (ALS) [14] for lock acquisition of PRFPMI as well as LIGO and Virgo. The ALS enables to relax the requirement of the residual motion of mirrors for the lock acquisition: resulting in robust lock acquisition. Laser beams for ALS are sent to the main interferometer with optical fibers, and fiber noise cancellation (FNC) system was introduced to reduce the phase noise induced from optical fibers. However, problematic phase noises were induced between optical fiber outputs and the interferometer, which cannot be canceled by the FNC, when seismic motion around 0.2 Hz band is loud. Therefore, we newly installed phase noise cancellation (PNC) system in the ALS.

The PNC system was achieved by picking off a part of injection and reflection beams, interfering them to obtain phase noise signals, and feeding it back to PZT actuators. Owing to the PNC, phase noise after optical fiber outputs is significantly suppressed, and lock acquisition of PRFPMI becomes successful with high seismic motion, which was difficult to be achieved during the O3GK [15].

### 2.2 Update of sapphire mirror suspensions and their commissioning

Main mirrors in KAGRA are suspended with a 9-stage pendulum called Type-A suspension, which consists of 5 room-temperature stages (Type-A tower) and 4 cryogenic stages (cryogenic payload) [16]. Type-A tower has Inverted Pendulum (IP) at the top and 5 Geometric Anti-Spring (GAS) filters. Both have Linear Variable Differential Transformers for sensing their positions and coil-magnet actuators for their actuation. In addition, IP has accelerometers and velocity meters for inertial damping control. Cryogenic payload has four stages called Platform, Marionette, Intermediate Mass, and Test Mass from the top. Photosensors, Optical levers, and length sensing optical sensors are used for sensing their positions. Cryogenic payload also has coil-magnet actuators as well as Type-A tower for their actuation.

During the O3GK, there were several failures in Type-A towers: some of the GAS filters didn't work properly and the noise performance of accelerometers was not good. Therefore, some of Type-A towers were disassembled and reconstructed, and new accelerometers were then installed. We also checked the healthiness of the suspensions after installation and vacuum evacuation not to repeat the hardware problems. After these works, repaired GAS filters are now working properly and inertial damping successfully reduced the vibration at 0.2 Hz by a factor of 5.

The cryogenic payload also has improvements after the O3GK: increasing the number of sensors, relocating sensors and actuators, and making actuators larger. Owing to these hardware improvements, we can achieve low-noise suspension damping controls and three-stage hierarchical controls of the suspensions, which could not be achieved during the O3GK.

### 2.3 Interferometer commissioning and noise hunting

After hardware updates and suspension commissioning, interferometer commissioning was started. We succeeded in locking Fabry-Pérot Michelson interferometer (FPMI) in August 2022 and PRFPMI with RF signals in January 2023. Then, PRFPMI with DC readout was successfully locked in February 2023. Figure 2 shows the sensitivity evolution from February to May in 2023.

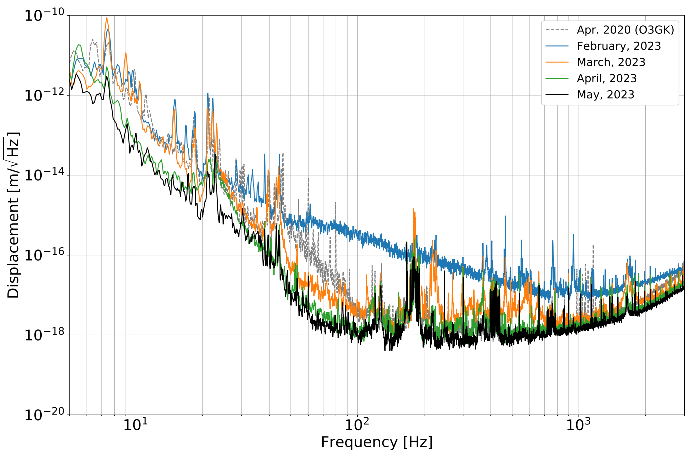


**Figure 2:** Sensitivity evolution of KAGRA after February 2023. Gray dashed lines show the reference sensitivity during the O3GK. Blue lines show the sensitivity when PRFPMI was first locked with DC readout after hardware updates. Orange lines show the sensitivity after reducing MICH, PRCL, and environmental noises. Green lines show the sensitivity with ADSs and WFSs. Black lines show after implementing all ASCs.

When PRFPMI with DC readout was first locked, the sensitivity was dominantly limited by noise coupling from controls of the other Degrees of Freedom (DoF) of the KAGRA interferometer such as Michelson DoF (MICH) and power-recycling DoF (PRCL). Therefore, MICH and PRCL control bandwidth were reduced as much as possible, and feed forward controls were implemented.

After the mitigation of noise coupling from the other DoF controls, environmental noise reduction was started. According to the experience during the O3GK, the interferometer would be sensitive to the vibration around output mode cleaner (OMC), so we turned off several devices around there and investigated their effects on the sensitivity.

After the reduction of environmental noises, we started to commission Alignment Sensing and Control (ASC) as much as possible. We successfully implemented ASC with Alignment Dither Systems (ADS) for IMMT2 and PRM, and Wave-Front Sensing (WFS) controls for BS, ETMX, ETMY, OMMT2, and OSTM. By utilizing ADSs and WFSs, all angular DoFs for PRFPMI alignment were controlled, which could not be achieved during the O3GK. In addition, we succeeded in implementing Beam Position Controls (BPC) on several mirrors: PR2, ETMX, and ETMY. Thanks to the BPCs, reproducibility of the interferometer alignment improved and enabled it to keep good sensitivity for a long time. Note that each mirror position can be seen in Fig. 1. Owing to ASCs, not only the sensitivity of PRFPMI but also the stability improved, and PRFPMI could be locked for more than 21 hours with the sensitivity greater than 1 Mpc during the O4.

## 3. Summary

KAGRA formally started in 2010 and finished construction in 2019. Utilizing the underground site and cryogenic mirrors are key features and advanced technologies, which would be used in the next-generation GWDs. KAGRA conducted hardware updates and commissioning after the O3GK on April 2020, and achieved improving sensitivity and stability, which led to join the O4 from May 2023.

We are now in commissioning and plan to join the O4 again from spring in 2024 with greater sensitivity of 3-10 Mpc. After the O4, we aim to improve the sensitivity further by introducing several upgrades: frequency dependent squeezing, high power laser, heavier mirrors, and so on [17]. Then, KAGRA will join the fifth observing run and contribute international GWD network and multi-messenger observation. In addition, KAGRA will contribute the development of the next-generation GWDs in future through our experiences of development and operation of KAGRA.

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