Observing the Universe from Underground Gravitational Wave Telescope KAGRA

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Abstract

The underground and cryogenic gravitational-wave telescope, KAGRA, had its first observation run in the spring of 2020. The KAGRA is based on a complex laser interferometer with a number of signal enhancement techniques and state-of-the-art noise reduction technologies to detect gravitational wave signals. The first formal observation was performed from February 25 to March 10, 2020, and its first joint observation with the gravitational-wave detector GEO600 was performed from April 7–21, 2020, which is called O3GK. This article reviews the status of the KAGRA detector in O3GK.

1 Introduction

Gravitational-wave (GW) astronomy commenced with the discovery of a binary black-hole merger detected by Advanced LIGO (aLIGO) in 2015 in their first scientific observation run, O1 [1]. In 2017, the Advanced VIRGO (aVIRGO) detector in Europe joined the second operation of aLIGO (O2), and the detector network discovered a neutron-star merger [2]. Using the three detectors (two aLIGO detectors and one aVIRGO detector), the angular resolution of the signal direction in the sky (sky localization) was sufficiently improved for other types of telescopes to observe and discover corresponding object [3]. This initiated multi-messenger astrophysics where various science cases have been developed [4]. The Kamioka Gravitational Wave Detector (KAGRA) is the first underground and cryogenic GW detector built in Gifu, Japan. Adding a fourth detector to the network can improve sky localization further and the duty factor to enhance discovery in fundamental physics and astrophysics [5]. In addition, KAGRA is a pioneer in detector technologies with unique underground and cryogenic features.

2 KAGRA Project

The KAGRA project is an international scientific collaboration for GW science and astrophysics. As of August 2020, it consists of 130 groups with more than 400 members from 14 regions. The co-host institutions are the University of Tokyo, National Astronomical Observatory of Japan, and High Energy Accelerator Research Organization. The KAGRA project started in 2010 with funds from the Japanese funding agency. The excavation of the KAGRA tunnel started in May 2012 in Ikenoyama Mountain,

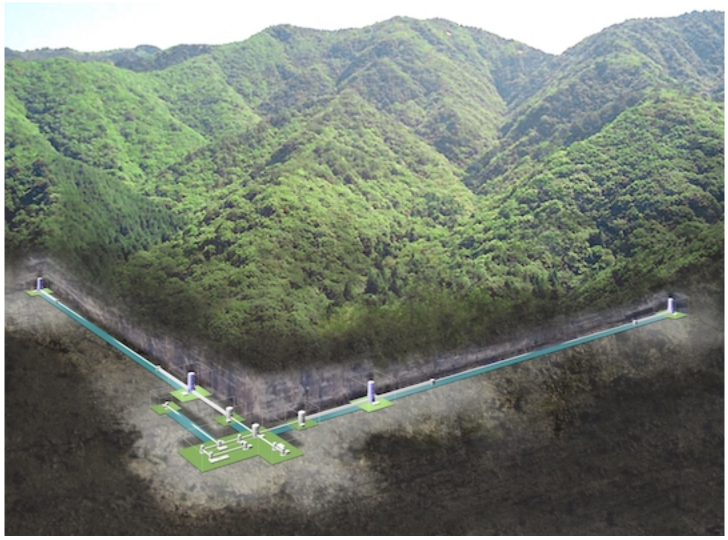

Figure 1: Image of the KAGRA underground site in Gifu prefecture, Japan. Although Ikenoyama Mountain was a heavy metal mining site, it is currently used for conducting several underground experiments related to fundamental physics. The KAGRA tunnels were newly excavated for the KAGRA experiment. Each tunnel has an L-shaped structure with a length of 3 km. Photo courtesy: KAGRA Observatory, ICRR, The University of Tokyo.

where underground experiment facilities, such as Super-Kamiokande, are located. After the completion of the excavation in early 2014, essential infrastructure such as power lines, network lines, clean booths, and vacuum enclosures were installed. While large-scale principal instruments, such as sapphire mirrors, large suspensions, and cryogenic instruments (see Sec. 3), were being installed and assembled in the tunnel, two engineering operations using temporary detector configurations were performed as project milestones in April 2016 (iKAGRA operation) [6] and April 2018 (bKAGRA phase-1 operation). In the bKAGRA phase-1 operation, cryogenic technology and the performance of the large vibration isolation systems of KAGRA were demonstrated [7]. In the summer of 2019, the major installation of the instruments was completed. Expeditiously, the commissioning of the detector was initiated. This continued until March 2020, when the first scientific operation began.

3 Detector

3.1 Optical Configuration

Similar to aLIGO and aVIRGO, KAGRA is a large-scale laser interferometer used to investigate subtle space-time displacements caused by the GWs. Fig. 2 shows the design of the interferometer configuration of the KAGRA detector. In addition to the 3 km Fabry-Perot arm cavities, the power-recycling mirrors (PRM, PR2, and PR3) constitute the power recycling cavity on the input side, and the signal-recycling mirrors (SRM, SR2, and SR3) constitute the signal recycling cavity on the output side. This optical configuration is a standard design in second-generation GW detectors (i.e., aLIGO, aVIRGO, and KAGRA), called the dual-recycled Fabry-Perot Michelson interferometer (DRFPMI). For the initial joint observation with GEO600 [9] (O3GK), owing to limited time and resources, the interferometer was operated in a simplified configuration without a signal recycling cavity. This configuration is called a power-recycled Fabry-Perot Michelson interferometer (PRFPMI) where the SRM is misaligned to prevent forming an optical cavity.

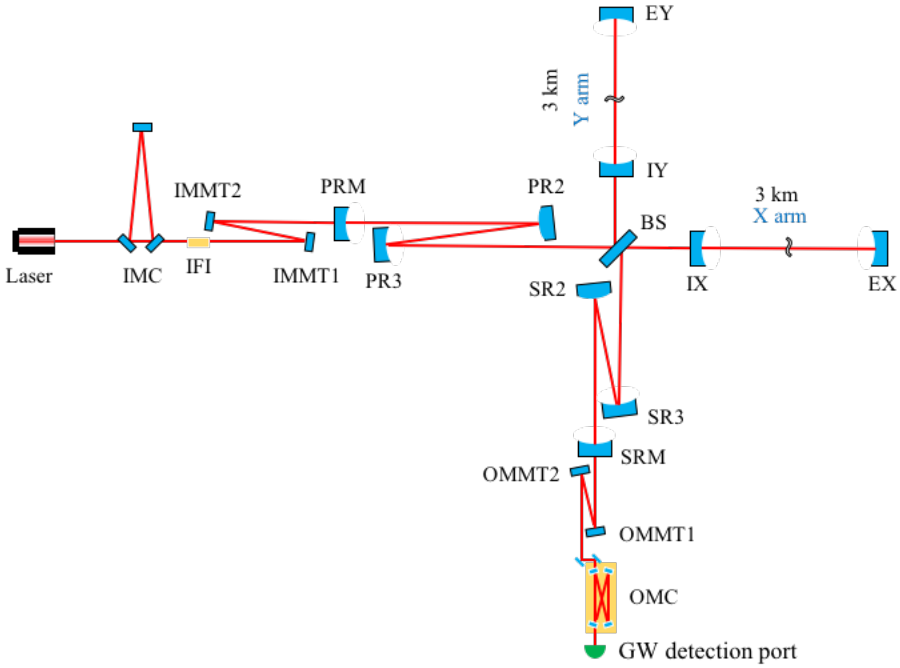

Figure 2: Conceptual optical configuration of the KAGRA interferometer. During an observation in the year 2020, one of the main mirrors, which is the signal recycling mirror and indicated as SRM, was not used for simplicity of interferometer controls. Abbreviations: Input mode cleaner (IMC), input Faraday isolator (IFI), input mode-matching telescope (IMMT), power-recycling mirror (PRM), beam splitter (BS), input test mass X (IX), input test mass Y (IY), end test mass X (EX), end test mass Y (EY), signal-recycling mirror (SRM), output mode-matching telescope (OMMT), and output mode cleaner (OMC).

To isolate the interferometer mirrors from seismic activities, the interferometer mirrors are held by vibration isolation systems that are significantly large suspensions. The test masses (EX, IX, EY, and IY mirrors forming the X and Y arm cavities) are made of sapphire [10] and suspended by the type-A suspensions (see Fig. 3). These are the largest among the KAGRA suspensions; they are at a height of 13.5 m and demonstrate the largest isolation performance for seismic motions. They consist of nine vibration isolation stages. The bottom four stages comprise the cryo-payload and are designed for operations at 20 K [11] to reduce thermal noise. During the observation run conducted in the year 2020, the test masses were preserved at room temperature because the sensitivity did not reach the thermal noise level.

The remaining suspensions are designed to be used at room temperature. The beam splitter and signal-recycling mirrors (SRM, SR2, and SR3) are suspended by type-B suspensions that have similar structures on the top part and have fewer vertical isolation stages in the middle compared to the type-A suspensions. The power-recycling mirrors (PRM, PR2, and PR3) are suspended by the type-Bp suspensions [8] that are adapted to smaller vacuum chambers. The three mirrors of the input mode cleaner (IMC), IMMT1, IMMT2, OMMT1, and OMMT2 shown in Fig. 2 are suspended by the simplest suspensions, which are the type-C suspensions. They are simple double pendulums for suspending small mirrors with ϕ=100 mm, whose design is based on the former GW project, TAMA300 [12].

For the laser source, the seed laser was a non-planar ring oscillator, Mephisto 500 NEFC (Coherent, Inc.) and the fiber-laser amplifier was a PSFA-10 mw-40 W-1064 (Coherent/Nufern, Inc.). The intensity and frequency of the laser were stabilized to prevent contamination of the GW sensitivity.

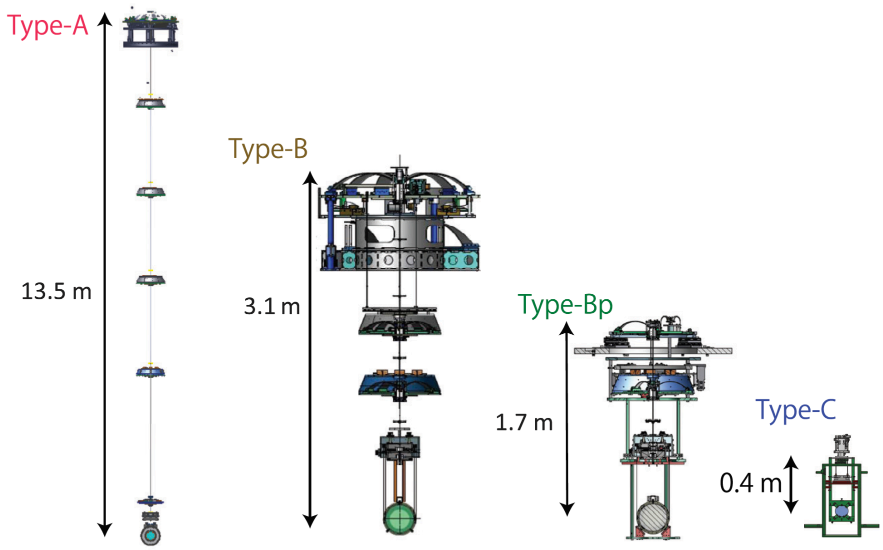

Figure 3: Types of KAGRA vibration isolation systems. This figure is acquired from Ref.[8]. The type-A large suspensions were used for the sapphire test masses, with the bottom four stages designed to be cryogenic. The type-B suspensions support the beam splitter and three signal-recycling mirrors. The type-Bp suspensions are meant for the three power-recycling mirrors. The other small ϕ=100 mm optics were held by the type-C suspensions.

The input mode cleaner (IMC) is a triangular cavity with a round-trip length of 53.3 m. The IMC rejects unwanted spatial higher-order modes and beam jitters from the input laser, and its length serves as a reference for the laser frequency [13]. A typical laser power injected into the main interferometer during O3GK was approximately 5 W.

The output mode cleaner (OMC) is a bow-tie cavity used to eliminate unwanted spatial higher-order modes and RF frequency sidebands used for interferometer controls that contaminate the GW detection port [14]. The final design of KAGRA OMC is semi-monolithic fused silica with four silica mirrors bonded on the silica breadboard. The OMC used for the KAGRA observation run in 2020 was a temporary design with a metal breadboard and four mirrors glued on metal mounts, bolted on the breadboard. The breadboard is suspended by three single-stage suspensions with blade springs for isolation of vertical seismic motion. The GW signals are extracted by the DC power readout of the OMC transmitting beam.

The data in the KAGRA tunnel, including the GW channel which is calibrated in rea-time, interferometer control signals and other auxiliary channels, e.g., environmental monitor channels, are transferred every 32 s to the main computer cluster system at the Institute for Cosmic Ray Research, Kashiwa, and Osaka City University. Data are also distributed from the Kashiwa computer system to the other KAGRA data tiers, that is, to Korea Institute of Science and Technology Information located in Korea and to Academia Sinica in Taiwan, with latencies of the order of several hours. GW searches and detector characterizations are performed there. The detecter sensitivities shown in this article use this real-time calibrated GW data.

For rapid GW searches, a chunk of data that is of duration 1 s is shared by the international detector networks. It is transmitted to Kashiwa and Osaka City University at a latency of approximately 3.5 s, then, transmitted to the computer centers at aLIGO (Caltech) at a latency of approximately 15 s. This low-latency pipeline contains only selected important channels.

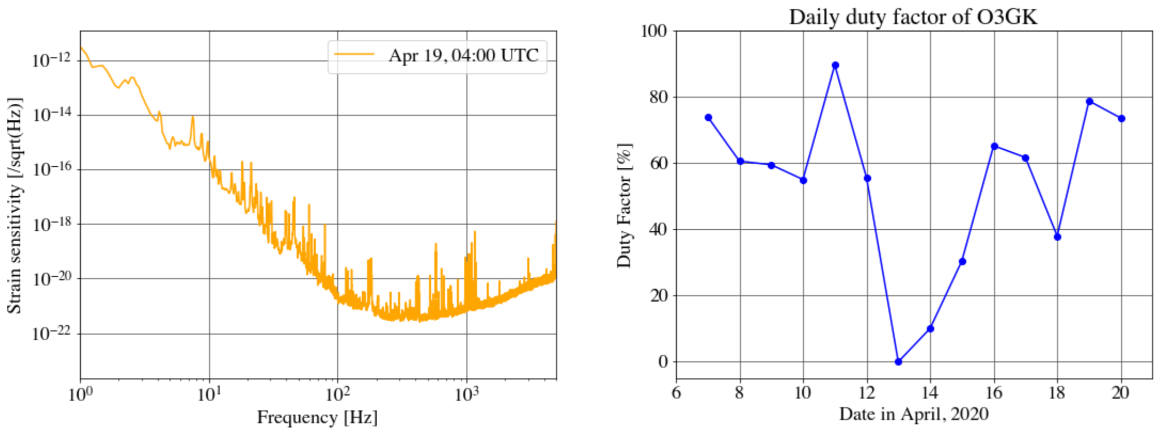

Figure 4: Left: Typical amplitude spectral density of the detector sensitivity in O3GK. Right: Daily duty factor of the KAGRA detector in O3GK. The mean duty factor of the period was 54%.

3.2 Interferometer Commissioning

As discussed, the large-scale interferometer is significantly complex. It requires considerable effort to integrate various instruments and parts until the interferometer can operate as a GW detector. First, the interferometer mirrors must be appropriately controlled for the complex optical cavities to resonate (or to be in anti-resonance) [15]. Without this, the interferometer will not respond to the GW signals. This is called as *lock acquisition*. Particularly, the first lock acquisition to establish the control and lock sequences persists for several months (this is why KAGRA operated in the simpler PRFPMI for this operation owing to limited time). Then, the complex procedures of the lock acquisition are automated. Once the interferometer is stably locked, every noise contaminating the detector sensitivity must be eliminated. This is called *noise hunting*. Based on the target sensitivity, noise hunting also requires several months or even years. This is why all large-scale interferometric GW detectors repeat the observation periods and offline periods to steadily upgrade the detector sensitivity in offline phases. The KAGRA sensitivity and limiting noise during O3GK are discussed in Sec. 4.2.

4 O3GK, the Joint Run with GEO600

4.1 Background

KAGRA's first joint observation with the GEO600 detector started at 08:00:00 UTC on April 7, 2020, UTC, and terminated at 00:00:00 on April 21, 2020, UTC. GEO600 is the GW detector in Germany with 600 m delay-line arm cavities [9]. Initially, KAGRA aimed to join the LIGO–VIRGO third observation (O3) once it achieves a certain sensitivity. However, owing to the COVID-19 pandemic, LIGO–VIRGO suspended O3 early on March 27, 2020, when KAGRA was still working for noise hunting. Furthermore, because GEO600, which had a sensitivity similar to that of KAGRA, was online when KAGRA began its observation in April, the GEO600-KAGRA joint observation was established.

4.2 Detector Sensitivity

The left panel of Fig. 4 shows a typical sensitivity of the KAGRA detector in strain [$/\sqrt{\mathrm{Hz}}$] in the frequency domain in O3GK. The high-frequency region above 400 Hz is limited by the shot noise, which is the photon-counting noise at the photodetector. The low-frequency region below 50 Hz is limited by the control noise from the resonance damping and controls of the type-A suspensions. Some spikes at approximately 180 Hz were from the suspension violin mode, which is a fundamental vibration mode of the suspension fibers that are thermally excited. Currently, the noise limiting the mid-frequency at approximately 100 Hz is unknown. Because the sensitivity of this region fluctuates significantly depending on the arm alignment, we assume that there are some noise coupling mechanisms related to the interferometer alignment. It can also arise from the scattered light as it is a typical non-stationary noise source. Details of the noise budget are being discussed and reports addressing this aspect are under preparation.

This sensitivity corresponds to a binary neutron-star (BNS) inspiral range of approximately 600 kpc. The BNS range is a figure of merit of GW detector we often use, describing how far (volume- and orientation-averaged) the single detector can detect the GW signals from a 1.4 $M_\odot$ neutron-star coalescence at a signal-to-noise ratio of 8 [16]. The BNS range in the 2-week O3GK is shown in the top panel of Fig. 5. The mean sensitivity in the science mode was 500 kpc, with a standard deviation of 170 kpc. The calibration error of this BNS range is assumed to be relatively large, possibly 30% or 40% because the real-time calibration pipeline does not include any optical gain alterations that are typically introduced by the alignment drifts. An offline analysis for more accurate calibration is in progress.

4.3 Duty Factor

The duty factor, which is the ratio between the period of the science mode (observation mode) and the total operation period, was 54%. The right panel in Fig. 4 shows the daily duty factor in O3GK. The duty factor on April 13 was zero because the interferometer was not operational owing to the so-called microseismic motion, i.e., the seismic motion between 0.1 Hz and 0.3 Hz, typically caused by ocean waves. The microseismic motion was significantly high owing to bad weather on April 13, as shown in the bottom panel in Fig. 5. It is band-filtered RMS seismometer data, filtered from 0.1 Hz and 0.3 Hz. The high microseismic motion continued until April 14, and the duty factor on that day was also degraded. The plot indicates that if the microseismic level was beyond approximately 1 [μm/s] RMS, the interferometer could not be operated. In future observations, suspension controls must be improved to isolate the seismic motion better, so that the interferometer locking can tolerate bad weather.

Compared with the performance of the aLIGO and aVIRGO detectors, the mean duty factor of 54% is low. A lock-loss occurred at hourly intervals because of the degradation of the global interferometer alignment. During the observation, no global active alignment control was implemented. Also, the large variations in the BNS range in the science mode are likely due to alignment drifts.

Furthermore, the lock-losses can be due to earthquakes. The middle plot in Fig. 5 shows the data from a seismometer at the EY station in the vertical direction to the ground. The data are band-filtered RMS, filtered from 30 mHz to 100 mHz, which is the typical frequency band of earthquakes. Compared to the top plot, some large spikes corresponding to earthquakes are coincident with some lock-loss times. A detector characterization study to investigate the relationship between the interferometer lock-losses and earthquakes is ongoing [17].

Data analysis of O3GK along with the GEO600 data for GW signal search is underway and will be presented in a future work.

5 Future Prospects of the Detector

KAGRA aims to join the next observation of LIGO–VIRGO (their fourth observation, O4). For KAGRA, the BNS sensitivity and duty factor must be significantly improved to contribute to GW astrophysics. The target sensitivity of KAGRA for O4 is 25 Mpc for BNS. To achieve the sensitivity, the

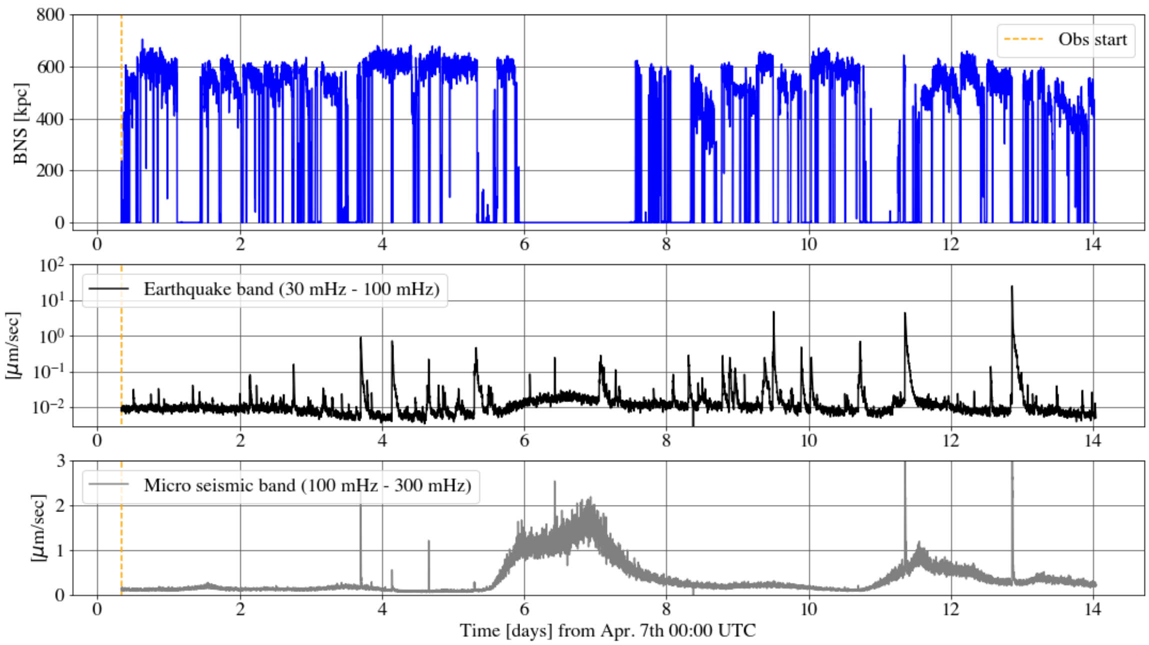

Figure 5: Top: BNS range in O3GK, April 7-21, 2020, UTC. The mean value of the sensitivity was 500 kpc. These data indicate a minute trend generated by the real-time calibration pipeline which have a relatively large calibration error. Middle: Seismic activity level at the earthquake frequency band (from 30 to 100 mHz). Note that the y-axis is on a log scale. Bottom: Seismic activity level at the microseismic frequency band (from 100 mHz to 300 mHz).

following hardware upgrades are planned: (i) Upgrading the interferometer configuration to DRFPMI. (ii) Improving the suspension damping and control schemes. (iii) Increasing the laser power to lower the shot noise. (iv) Improving the laser intensity and frequency stabilizations. (v) Reducing scattered light with more shrouds installed in vacuum.

6 Conclusions

The gravitational-wave detector, KAGRA, completed its first formal scientific observation in the spring of 2020. The last half of the observation was a joint observation with GEO600. Furthermore, KAGRA detector's mean BNS range was 500 kpc, with a duty factor of 54%. The obtained data are being analyzed for astrophysical searches. Currently, the KAGRA detector is offline for major upgrades to improve the sensitivity, thus aiming to join the next LIGO–VIRGO observation run.

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