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Excavation of an underground site for a km-scale laser interferometric gravitational-wave detector

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Abstract

KAGRA is a laser interferometric gravitational-wave detector with a 3 km arm length. It is to be constructed in the tunnels of the Kamioka mine in Hida, Gifu, Japan. The use of an underground site for small seismic motion is a key feature of KAGRA, as well as the use of a cryogenic technique to reduce any thermal noise. The KAGRA tunnels will have a total length of 7697 m and a total volume of 156 301 m^3. Tunnel excavation work began in May 2012, and continued until the end of March 2014. The construction of the experiment rooms in the tunnels is currently ongoing, and installation of the vacuum system was planned to begin in July 2014. KAGRA will then start observations in 2018.

Keywords: gravitational wave, laser interferometer, underground
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(Some figures may appear in colour only in the online journal)

1. Gravitational-wave detection and KAGRA

A gravitational wave (GW) is a physical phenomenon predicted in the general theory of relativity by Einstein in 1916. Non-spherical motion of masses generate GWs, which are ripples in the fabric of space-time. Since we can not produce any GW that is available for experimental study, GWs from the universe are targets for detection. The direct detection of GWs from the universe is a valuable achievement, because it will provide us with not only a validation of general relativity, but will also be a new investigation tool for astrophysics and cosmology.

Michelson interferometers using suspended mirrors as test masses are a kind of GW detector. An incident GW causes a displacement between the mirrors and the laser interferometer, which can be measured precisely. Physicists have already developed km-scale laser interferometric GW detectors, such as LIGO [1] with a 4 km arm length and VIRGO [2] with a 3 km arm length. Both detectors have been making observations for a few years with the current highest sensitivity. However, no GW signal has yet been observed. Detectors with a sensitivity that is one order better are thought to be needed to detect GWs during one year of observation. The sensitivity of detectors is limited by several fundamental noises, such as seismic noise, thermal noise and laser shot noise. Seismic noise involves a mirror displacement noise caused by seismic motion, which limits the sensitivity to below a few tens of a Hz.

KAGRA is a laser interferometric GW detector with a 3 km arm length, and was designed to be able to detect GW signals during one year of observation [3, 4]. The key differences between this and other km-class detectors in achieving a one order better sensitivity involve the use of an underground site for achieving small seismic noise, and a cryogenic technique for realizing small thermal noise. KAGRA is being constructed in the tunnels of the Kamioka mine (Kamioka, Hida, Gifu, Japan). Kamioka is 220 km north-west of Tokyo. The Kamioka mine was originally used for obtaining zinc, lead and silver, and has already completed its mining activities. There are already some laboratories in the Kamioka mine, such as Super-Kamiokande [5] and KamLAND [6], which involve the reuse of Kamiokande [7], XMASS [8] and the Cryogenic Laser Interferometer Observatory (CLIO) [9].

Figure 1 shows the amplitude of the seismic motion at CLIO in the Kamioka mine, as well as at a laboratory in a city area (the Institute for Cosmic Ray Research at Kashiwa, Chiba, Japan). As shown in figure 1, seismic motion in the underground site is more than 100 times smaller than that in the city area. This is the reason why we are constructing KAGRA in the Kamioka mine.

The first laser interferometric GW detector in an underground site was LISM, which has a 20 m arm length. Originally, LISM was developed in the National Astronomical Observatory of Japan, located at Mitaka, Tokyo, Japan. LISM was moved to the Kamioka mine in 1999, and reconstructed in order to verify any of the advantages of an underground site. The sensitivity achieved at Kamioka showed a significant improvement in the low-frequency region [10, 11]. Following the success of LISM, we developed a laser-interferometric GW detector, CLIO, in the Kamioka mine as a prototype of KAGRA, since 2002. The arm length of the CLIO interferometer is 100 m. The most important purpose of CLIO is to demonstrate a sensitivity improvement due to thermal-noise reduction using the cryogenic mirror technique. CLIO demonstrated a sensitivity improvement using monolithic sapphire test masses of under 20 K in March 2010 [12]. Following the success of CLIO, the KAGRA project started in June of 2010.

2. KAGRA underground site

Figure 2 shows a location map of the KAGRA tunnels. The tunnels were excavated in Mount Ikenoyama at the Kamioka mine, whose summit is at about 1300 m. There are two 3000 m arm tunnels connected perpendicularly. One arm tunnel in the north-east direction is called Xarm, and the other Yarm. The Yarm tunnel is rotated by 28.31 degrees from the north in a counter clockwise direction. The position of the connecting corner of the arm tunnels is at a latitude of 36.41 degrees north and a longitude of 137.31 degrees. The center area, the Xend area and the Yend area, where some of the experimental rooms exist, are located at the connecting corner of the arm tunnels and at the end of both arm tunnels, respectively. All of

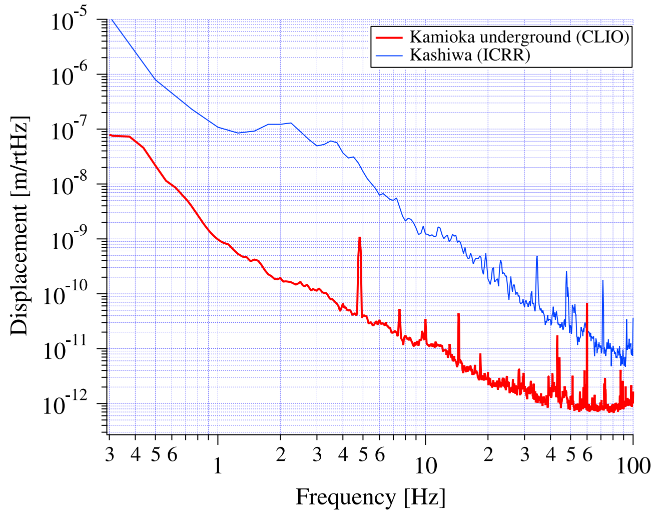

Figure 1. Seismic motion measured at an underground site (CLIO in the Kamioka mine) and a city area (the Institute for Cosmic Ray Research at Kashiwa, Chiba, Japan). The seismic motion at the underground site is more than 100 times smaller than that at the city area. The resonance peak near 5 Hz comes from the accelerometer itself.

these areas are inside, more than 200 m from the surface of the mountain, in order to obtain a quiet seismic motion environment, as expected from an underground site.

The KAGRA tunnels have two entrances: the new Atotsu entrance and the Mozumi entrance. The new Atotsu entrance was newly constructed for the KAGRA tunnels. Figure 3 shows the new Atotsu entrance, whose dimensions are a width of 4 m and a height of 4 m. The cross section of the new Atotsu entrance is the same as that of the standard cross section of the arm tunnels. The new Atotsu access tunnel of 459.4 m is located between the new Atotsu entrance and the center area. A bypass tunnel of 125.3 m between the Xarm tunnel and the new Atotsu access tunnel was added in 2014 in order to drain water. The Mozumi access tunnel of 315.4 m connects the Yend area and an existing tunnel connecting the Mozumi entrance.

Both arm tunnels are tilted by 1/300 for natural water drainage. The Xend area is at the highest altitude of about 382 m, and the Yend area is at the lowest altitude of about 362 m. The altitude of the center area is 372 m. Water drain ducts with a diameter of 400 mm are placed under the floor of both arm tunnels. Since much of the water flowing in the area of the experiment rooms should be avoided in order to maintain a quiet environment, the water drain paths must be carefully designed. Spring water in the Xend area and the Xarm tunnel must be drained through the bypass tunnel to the outside, and spring water in the center area and Yarm tunnel drained through a vertical hole to an existing tunnel that is 12 m below the Yarm tunnel.

Figure 4 shows a schematic view of the KAGRA tunnels, figure 5 a 3D model of the center area, and figure 6 a photograph of the center area. There is a parking area and a front room before the experiment rooms in order to prevent dust from getting into these rooms. The center experiment room A (width 15 m, height 9.5 m, and depth 40 m) is the largest experiment room in KAGRA. The beam splitter (BS) will be suspended in this room. Laser sources will be fixed on optical tables in a clean booth housed in an anti-sound room, which

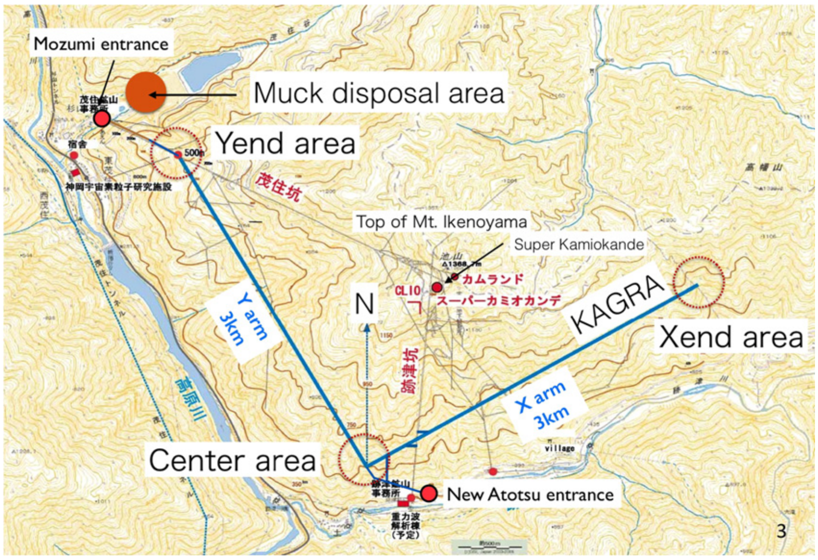

Figure 2. Location map of the KAGRA tunnels. The tunnels are in Mount Ikenoyama at the Kamioka mine, whose summit is at about 1300 m. There are two 3000 m arm tunnels connected perpendicularly. One arm tunnel in the north-east direction is called Xarm, and the other Yarm. The Yarm tunnel is rotated 28.31 degrees from the north in a counter clockwise direction. The position of the connecting corner of the arm tunnels is at a latitude of 36.41 degrees north and a longitude of 137.31 degrees. The center area, the Xend area and the Yend area contain some of the experiment rooms, which are located at the connecting corner of the arm tunnels and at the end of both arm tunnels, respectively. All of the areas are inside, more than 200 m from the surface of the mountain, to obtain the quiet seismic motion environment that we expect to be achieved at the underground site. Both arm tunnels are tilted by 1/300 for natural water drainage. The Xend area is at the highest altitude of about 382 m, and the Yend area is at the lowest altitude of about 362 m.The altitude of the center area is 372 m.

Figure 3. Photograph of the new Atotsu entrance. The dimensions of the entrance are a width of 4 m and a height of 4 m.

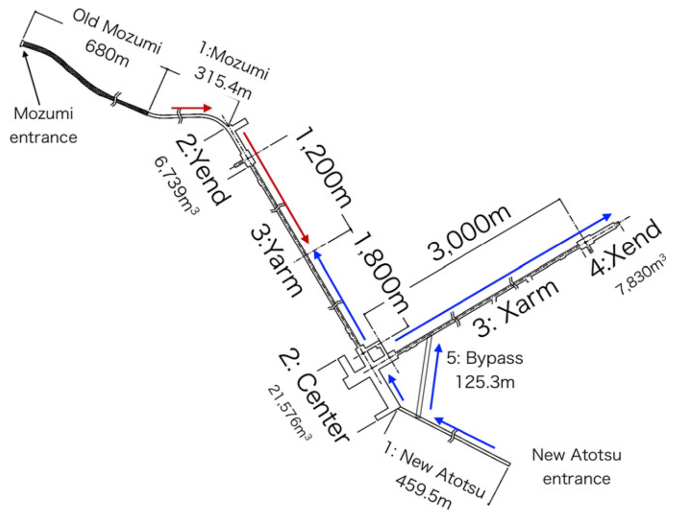

Figure 4. Schematic view of the KAGRA tunnels. Arrows indicate the progress direction of excavation. Excavation work has been performed at multi-working positions by multiple worker groups. A worker group entered from the Mozumi entrance and excavated the Mozumi access tunnel, the Yend area and the Yarm tunnel of 1200 m. Another group entered from the new Atotsu entrance and excavated the new Atotsu access tunnel and center area. After completing the first floor of the center area, excavation of Xarm and Yarm began. Excavation of the Xend area and the bypass tunnel was completed in the final period.

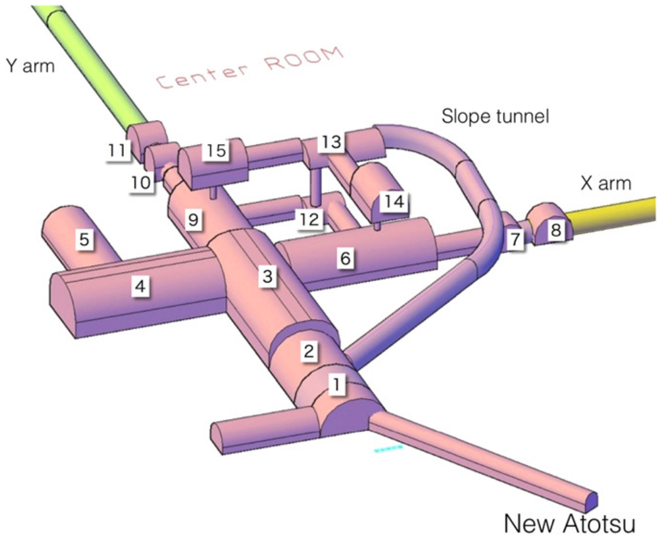

Figure 5. A 3D model of the center area. (1) parking; (2) front room; (3) center experiment room A; (4) center experiment room B; (5) center experiment room C; (6) Xfront cryogenic mirror room; (7) widening tunnel for the test mass at room temperature; (8) widening the tunnel for a gate valve; (9) Yfront cryogenic mirror room; (10) widening tunnel for the test mass at room temperature; (11) widening tunnel for a gate valve; (12) machine room; (13) vibration isolation preparation room; (14) Xfront vibration isolation room; and (15) Yfront vibration isolation room.

Figure 6. Photograph of the center area. The dimensions are a width of 15 m and a maximum height of 9.5 m.

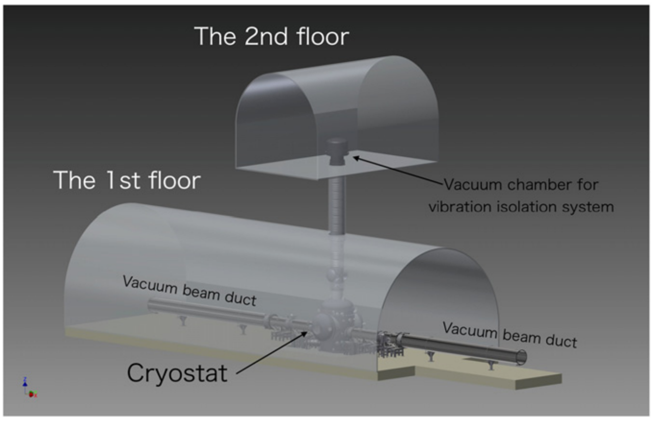

Figure 7. Schematic view of a test mass vacuum system. KAGRA uses a cryogenic mirror technique and test masses that are made of monolithic sapphire. They will be maintained at under 20 K so as to reduce thermal noise. The dimensions of the test mass are a diameter of 220 mm and a thickness of 150 mm. The test mass will be suspended by a vibration isolation system whose height is about 13 m. This vibration isolation system will be installed in a test-mass vacuum system whose height is about 15 m. The test-mass vacuum system will be installed in a cryogenic mirror room (first floor), a vibration isolation room (second floor), and a 5 m vertical hole connecting between the floors.

will be constructed at the end of the center experiment room B. Finally, more than 10 vacuum chambers for suspended optics will be placed in the center experiment rooms A, B and C.

There are Xfront and Yfront cryogenic mirror rooms next to the center experiment room A. Since KAGRA will employ a Fabry–Perot cavity in the each arm, the total number of test masses for GWs becomes four. Similar to CLIO, KAGRA uses a cryogenic mirror technique in which test masses made of monolithic sapphire will be maintained at under 20 K so as to

Figure 8. Photograph of the Yarm tunnel. The dimensions of the tunnel are a width of 4 m and a height of 4 m.

reduce any thermal noise. The dimensions of the test mass are a diameter of 220 mm and a thickness of 150 mm. The test mass will be suspended by a vibration isolation system whose height will be about 13 m. This vibration isolation system will be installed in a test mass vacuum system with a height of about 15 m. Figure 7 shows a schematic view of the test mass vacuum system. The test-mass vacuum system will be installed in a cryogenic mirror room (first floor), a vibration isolation room (second floor), and a 5 m vertical hole connecting between the floors. The diameter of the vertical hole is 1200 mm. The test-mass vacuum system consists of a cryostat, a vacuum duct, and a vacuum chamber for the base of the vibration isolation system. The cryostat will be placed on the floor of the cryogenic mirror room, and the vacuum chamber for the base of the vibration isolation system will be placed on the floor of the vibration isolation room on the second floor, which is supported by the 5 m thick hard rock of the Kamioka mine. The second floor has two access routes. One is a sloped tunnel 90 m long with a slope of about 14%, and the other is a spiral staircase. KAGRA will take two steps toward the final design. At the initial phase, other test masses will be used that are made of fused silica at room temperature instead of the cryogenic test masses. The fused-silica test mass will be suspended in a vacuum chamber placed in the widening tunnel for the test mass.

Figure 8 shows a photograph of the Yarm tunnel. The Xarm tunnel and Yarm tunnel connect the center area and the Xend or Yend area, respectively. The standard cross section of the arm tunnels are a width of 4 m and a height of 4 m. As mentioned above, the arm tunnels are tilted by 1/300 for natural water drainage. Two kinds of vacuum ducts will be placed in the arm tunnels. One vacuum duct is for the KAGRA laser beams (the diameter of the duct is 800 mm). Another vacuum duct will contain the laser beams used for interferometers (the geophysical interferometer), which will measure the strain of the ground for geophysics using a Michelson interferometer (the diameter of the ducts is 400 mm). The length of the geophysical interferometer is 1500 m, and there are widening tunnels in both arm tunnels at 500 m and 2000 m from the BS for vacuum chambers in which the optics for the geophysical interferometers will be fixed. Similar geophysical interferometers have already been operated since 2003 at the CLIO site [13]. The interferometers consist of two laser strain meters using

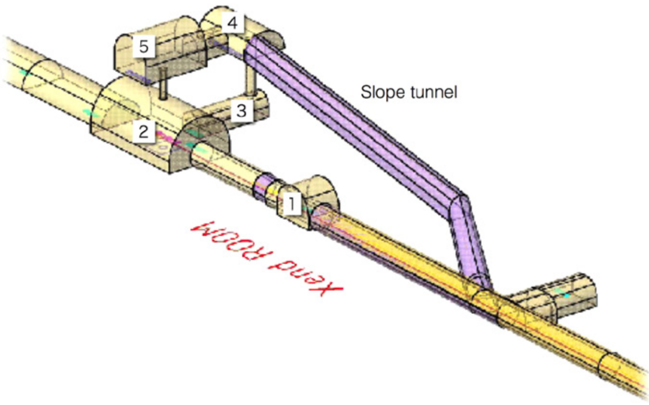

Figure 9. A 3D model of the Xend area. (1) The widening tunnel for a vacuum chamber for the test mass at room temperature and a gate valve, (2) the cryogenic mirror room, (3) the machine room, (4) the vibration isolation preparation room, and (5) the vibration isolation room.

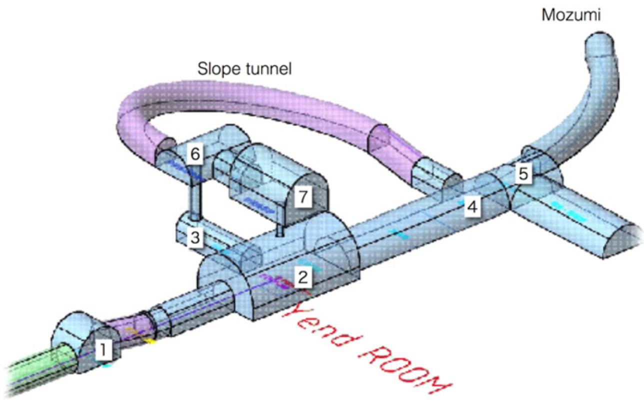

Figure 10. A 3D model of the Yend area. (1) The widening tunnel for a vacuum chamber for the test mass at room temperature and a gate valve, (2) the cryogenic mirror room, (3) the machine room, (4) the staff room, (5) parking, (6) the vibration isolation preparation room, and (7) the vibration isolation room.

Michelson interferometers [14] and one absolute length monitor using a Fabry–Perot cavity [15]. At least one laser strain meter at the KAGRA site will begin observations from 2015.

Figures 9 and 10 show 3D models of the Xend and Yend areas, respectively. Figure 11 shows a photograph of the Yend cryogenic mirror room. Since the test mass will be suspended at both the Xend area and the Yend area, the vibration isolation system for the test mass and the test mass vacuum system will be installed in a cryogenic mirror room on the first floor, a vibration isolation room on the second floor, and a vertical hole connecting the first and seconnd floors. The Yend area can be accessed from the Mozumi entrance through the old Mozumi mine road and the Mozumi access tunnel.

3. Tunnel excavation

Kajima Corporation (Japan) carried out KAGRA tunnel excavation work from 22 May 2012 to the end of March 2014. The total length and volume of the tunnels are 7697 m and 156 301 m^3, respectively. Kajima used the new Austrian tunneling method (NATM) by means of an explosive, ammonium nitrate fuel oil (ANFO). A key technology that Kajima used involved long hole blasts. Each normal blast excavated almost 1.5 m, but the long hole blast provided an excavation length of 4 m in the case of the KAGRA tunnel excavation work. Usually, four blasts per day at one working place were made. The total number of blasts was 2952 and the total amount of the explosive was 518 318 kg.

Excavation work using NATM consisted of the following processes: making holes, inserting ANFO explosives, blasting, taking away rocks and spraying concrete. Several heavy machines were needed in a cycle of the excavation work, and the heavy machines needed to be replaced for each process. The most important benefit of long hole blasting was to reduce any time loss caused by replacing the heavy machines. In addition to long hole blasting, Kajima used heavy machines as large as possible in the KAGRA tunnel in order to shorten the time for each process, and a high-capacity ventilation system to reduce the time necessary for ventilation after a blast. All efforts to shorten the work time were important to make it possible to complete the excavation work on schedule. The most significant progress was made in September 2013, during which the excavation length of the Xarm tunnel and the Yarm tunnel reached 359.4 m and 301.2 m, respectively, and the total excavation length was 660.6 m. The progress constructing the Xarm tunnel is thought to be the greatest on record of NATM in Japan.

Since the excavation work strongly depends on the condition of the excavated surface and walls, the tunnel often had to be excavated very slowly and at a shorter rate. Large amounts of spring water are the most frequent source of difficulties for the excavation work. More time was needed when water was present because any explosive in a hole might flow out. Also, the spraying of concrete was difficult to make sufficiently thick, and steel support structures or rock bolts were sometimes needed after blasts. The most difficult case was passing through faults, because the excavation work must pay attention to not only the spring water, but also any weak surfaces. An Ikenoyama fault crossing occurs in the Yarm tunnel at around 1800 m from the BS and a North 20th fault crossing occurs in the Xarm tunnel at around 2500 m in the KAGRA tunnel. Before excavation at the faults, Kajima Corp made bore holes into the faults in order to investigate the condition of the mountain and the positions of water springs. If Kajima found any serious weakness of the mountain, they improved the stiffness of the mountain by means of the all ground fasten (AGF) method, before conducting any excavation work.

Figure 4 shows how to conduct excavation work. It must be done at multi working positions by multiple worker groups. The first blast was conducted at the Mozumi access tunnel by a worker group that entered from the Mozumi entrance on 22 May 2012. This group proceeded with the excavation work of the Mozumi access tunnel, the Yend area and the Yarm tunnel, and stopped at the Ikenoyama fault because of spring water of about 180 L/min, which is the upper limit of the capacity of the turbid water treatment plant for the excavation work of the Yarm tunnel. The group then made bore holes into the Ikenoyama fault in order to drain water. All the Mozumi entrance work was completed on 27 April 2013. The remainder of the Yarm tunnel was excavated from the center area, and the Yarm tunnel was completed on 5 December 2013. Figure 12 shows a photograph taken at the moment of a blast to explode the final wall standing in the Yarm tunnel.

Figure 11. Photograph of the Yend cryogenic mirror room. Included are a pit for a cryostat and a vertical hole.

Figure 12. Photograph of the blast that opened the Yarm tunnel.

Another group started excavation of the new Atotsu access tunnel on 18 June 2012, and reached the center area on 1 October 2012. This group completed the first floor of the center area in 2012, and then started excavation of the Xarm tunnel and the Yarm tunnel on 24

December 2012 and 9 January 2013, respectively. As mentioned above, the Yarm tunnel was completed on 5 December 2013. The Xarm tunnel was completed on 1 March 2014. This means that Kajima excavated about 3000 m of tunnels during 14 months. The averaged excavation speed was 210 m/month. After completing the Xarm tunnel, excavation of the Xend area and the bypass tunnel started. All of the excavation work for the KAGRA tunnels was completed by the end of March 2014.

Appropriate dirt disposal and turbid water treatment is needed for the excavation work. Almost all of the dirt was carried by 10 t dump trucks, and disposed of at the area shown in figure 2. The total number of dump truck trips was almost 54,000. Dirt, including heavy metals, was selected out and taken to a different disposal area for appropriate treatment. The amount of dirt with heavy metals was 8% of the total. We used turbid water treatment plants and PH neutralizing plants before discharging water. The maximum capacities of the turbid water treatment plants and PH neutralizing plants were 300 ton/h and 500 ton/h, respectively.

4. Next steps

KAGRA is a laser interferometric GW detector that can be used in the tunnels of the Kamioka mine [3, 4]. All the excavation work, using NATM, was completed by the end of March 2014. Following completion, construction of the experiment rooms is currently underway. The installation of vacuum chambers and vacuum tubes will start in July 2014, and construction of the vacuum system will be completed by the end of March 2015. The preparation of a laser source and input optics will start in October 2014. The initial phase of the KAGRA interferometer, which uses test masses made of fused silica at room temperature, will start a test observation run by the end of 2015. Subsequently, we will exchange the fused silica test masses with sapphire test masses to reduce the thermal noise by means of the cryogenic mirror technique. Our plan is to start observations with a sensitivity that is expected to produce several GW detections in one year of observation until the end of March 2018.

Acknowledgments

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