

# REAL TIME CONTROL FOR KAGRA 3KM CRYOGENIC GRAVITATIONAL WAVE DETECTOR

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and KAGRA collaboration

## Abstract

KAGRA is a 3 km cryogenic interferometer for gravitational wave detection located underground Kamioka-mine in Japan. The next generation large scale interferometric gravitational wave detectors require very complicated control topologies for the optical path length between mirrors and very low noise feedback controls to measure the extremely tiny motion between mirrors excited by gravitational waves. In this paper, we report a current status of the KAGRA project and how to establish a real time control for such a complicated optical interferometer.

## GRAVITATIONAL WAVE DETECTION

Gravitational wave (GW) was predicted by Albert Einstein in his general theory of relativity. Hulse and Taylor observed an orbital period of PSR B1913+16 more than 25 years and found that the reduction of orbital period corresponded to emission of gravitational waves [1]. This is an evidence of the existence of gravitational waves but it is not thought as a direct measurement of gravitational waves. In the past 15 years, several hundred-meter (TAMA300 [2], GEO600 [3]) to kilo-meter scale (LIGO [4], VIRGO [5]) large gravitational wave detectors using interferometric optical cavities have been constructed and operated in several countries [6], but no detector has measured gravitational waves directly. LIGO and VIRGO are currently upgrading their configurations (Advanced LIGO[7], Advanced VIRGO [8]) to realize roughly 10 times more sensitivity. Direct detection of gravitational waves is being thought as a feasible project with recent technologies of lasers, optics, vibration isolations and controls.

## KAGRA PROJECT

KAGRA [9] is a Japanese project to construct a 3 km interferometric gravitational wave detector underground Kamioka-mine where is a famous site as Super-Kamiokande (see Fig. 1). One of the features of KAGRA is that low temperature mirrors will be used to reduce the thermal noise. This cryogenic technic is based on CLIO's experience [10]. CLIO is a prototype 100 m interferometer located in the same Kamioka mine for testing the advantage of underground site and reduction of thermal noise by cooling mirrors. With a successful result of reduction of thermal noise at CLIO, sensitivity of KAGRA will be comparable to Advanced LIGO and Advanced VIRGO. All three (or four since LIGO has two separate detectors) km scale detectors make a network of gravitational wave detectors

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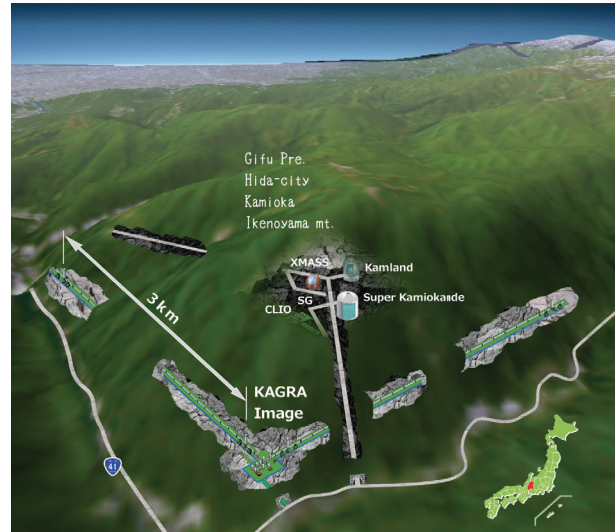


Figure 1: Image of KAGRA. KAGRA will be located in Kamioka mine underground Mt. Ikenoyama in Gifu prefecture, around center of Japan. The 3 km arms of Kagra will be placed as a L shape along the edge of mountain. Kamioka mine has been used as good experimental sites for several astronomical observatories, such as Super Kamiokande, XMASS, KAMLAND and CLIO.

to determine a direction of origin of gravitational waves by the difference of detection time.

Currently KAGRA is under construction to excavate tunnels. We spend two years for tunneling and another one year for facilities such as vacuum chambers and tubes or power/life lines, then start installation of optical components. KAGRA's optical configuration [11] at the final stage consists of a Michelson interferometer with two Fabry-Perot cavities (FPMI) on its arms, and other two mirrors are added to build a power recycling (PR) cavity and a signal recycling (SR) cavity (see Fig. 2). After the first installation/commissioning we will have a short observation by the FPMI configuration in a room temperature without the PR and SR cavities. Until the first observation, we call it initial KAGRA (iKAGRA). Then the second installation will start to have PR, SR. On the same time we will install sapphire mirrors to establish low temperature operation to reduce the thermal noise. This is called baseline KAGRA (bKAGRA). We will start observation for GW around 2018.

## CONTROLS FOR INTERFEROMETER

Using Pound-Drever-Hall (PDH) technique [13] is a quite standard method to extract and control a length of

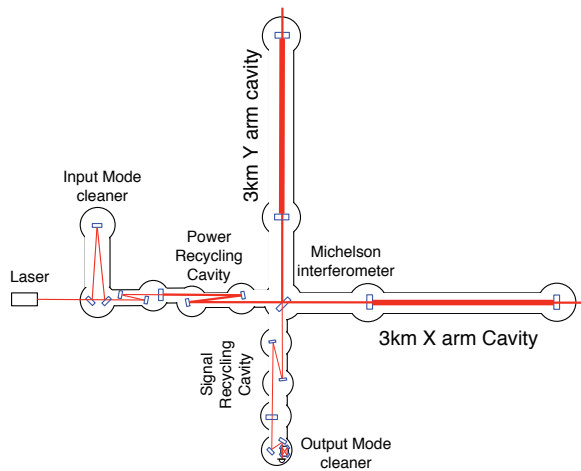


Figure 2: Optical configuration of KAGRA. The GW detector consists of Michelson interferometer and combined optical cavities. Main optics shown as blue rectangles here will be enclosed in vacuum chambers. More than 20 mirrors will be controlled in position and angle to keep the optical cavities resonant.

optical cavity. Control signals extracted from a photodetector is feedback to coil-magnet actuators attached on a mirror through some appropriate servo filters. Continuous feedback control is necessary in order to keep an optical resonance in the cavity. In other words, we need to lock the interferometer by controlling all the time during the observation of gravitational waves.

Control topology for the large scale interferometer is very complicated by complications of the optical configuration. In KAGRA, five degrees of freedom (DOFs) for length between seven main optics have to be controlled at a time in the main interferometer part, and input/output mode cleaner and laser frequency stabilization servo have also to be controlled. What each DOF is not independent makes the control much more difficult. Some of the DOFs are coupled to some of the DOFs. For example, length of the PR cavity is strongly coupled to common motion of two main arm cavities (CARM) since both DOFs are supposed to be a common mode length change. Other example is a coupling between the Michelson mode which is fed back to beam splitter (BS) and differential motion of arm cavities (DARM) since both DOFs are differential mode. Additionally alignment of mirrors for 20 DOFs and local motion of the vibration isolation system for 100 DOFs have to be controlled all the time for observations [12].

## CONTROL DESIGN

PDH technique is a process of modulation and demodulation. We have an electro-optical modulator (EOM) to modulate a carrier of laser at radio frequency (RF) band of  $\sim 10$  MHz at the frontal part of the interferometer. We have mixers to demodulate RF signals detected by a photo diode

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to extract control signals including information of the cavity length. If the number of DOF to be controlled is small and if their DOFs are not coupled, an implementation of feedback servo is quite simple. We need just a simple circuit with some simple feedback filters. We were using such analog electronic circuits to control the former 100 m scale interferometers in Japan. However the realistic large scale interferometer is a huge plant having many numbers and complications of coupled DOFs. We need a kind of sophisticated system to control such a huge plant to avoid human errors and reduce the noise hunting time to achieve our target sensitivity.

We are currently developing a real time control system using computers for KAGRA by collaborations with LIGO project [14]. Our system (see Fig. 1) consists of 20-30 real time front-end (RTFE) computers and 10-15 servers to manage RTFE computers. Each RTFE computer is connected to PCIe extension chassis which has 18 PCIe slots. Analog to digital converter (ADC) module with differential 32 channels or digital to analog converter (DAC) module with differential 16 channels or digital output (DO) module with 32 channels will be equipped into the PCIe chassis. Sampling frequency of this digital control system is 16384 Hz. The total number of signals for ADC will be  $\sim 2000$ , for DAC will be  $\sim 500$ , for DO will be  $\sim 2000$ .

All the RTFE computers are connected by four types of networks for the fast real time control and one standard TCP/IP network for the slow control using EPICS [15].

### Real time control

A reflective memory network is one of the most important networks for control to keep lock the interferometer. We have two types (for short/long distance) of reflective memory networks to transmit control signals. A typical unity gain frequency (UGF) that is equivalent to a band-width of a control loop will be several hundred Hz in this system. The UGF is not so high compared with the 16 kHz of sampling frequency, but it is not so easy to implement whole the real time control loops using multiple front-end computers connected through networks with this speed. The control network requires the smallest latency to have less phase delay for the control loop whereas the amount of transmitting data is not so large. We have selected GE-IP's reflective memory [16] as a long distance control network for the 3 km arms and Dolphin's reflective memory [17] as a short distance in the center room. Total time delay for a single control loop by connected computers would be  $\sim 100$   $\mu$ s that can have the UGF of  $\sim 200$  Hz.

To collect GW data and other important data from the interferometer, we have a data acquisition (DAQ) network. The DAQ network does not require so strict latency but the amount of data will be large as  $\sim 20$  MB/s for all the time during observation. However DAQ network requires that the latency has to be small to stamp the current time on GW frame data files to determine an arrival time of GW.

A GPS antenna is installed outside of the mine and the timing signal is provided through a timing network from

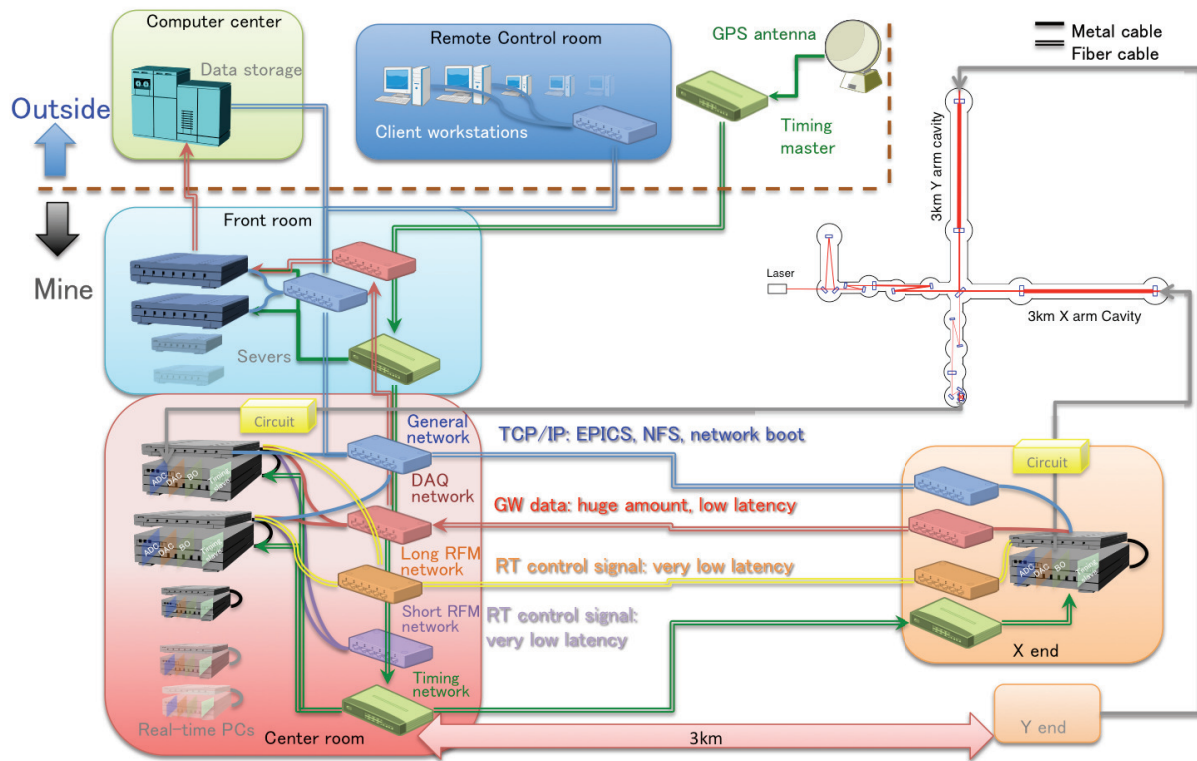


Figure 3: Control network design. There are four networks for fast control and one general TCP/IP network for slow EPICS control. Total ~30 real time front-end computers are connected and managed ~15 servers through the network. Timing signal is provided from outside of mine. Whole system is controlled by a outside remote room and gravitational wave data is transferred to data center located outside of mine through DAQ network.

the GPS antenna. This timing network synchronizes all the ADCs and DACs on the RTFE computers located many places in the mine. The timing system has a master-slave structure to have an automatic compensation for time delays caused by the distance among timing switches, so that it can minimize errors for the time stamp on frame files which would be recorded at different locations.

### Slow control

EPICS [15] database is used to implement slow controls. A slow control network will be used for many purposes except for the real time control explained above, such as slow signal monitors like a temperature variation as one of the environmental data, signal routing switches, filter gain setting or filter on/off switches and so on.

One of the most important roles of EPICS is to provide us with a good human interface. Graphical user interface (GUI) of EPICS that is called the Motif Editor and Display Manager (MEDM) has a simple and enough function to display the current status of interferometer. While EPICS can be controlled through the GUI, it can be also controlled by script a command from the terminal on client computers, so that the script which has several commands can make an automatic operation for the interferometer. This command operation can be used as a feedback servo by extracting a control signal on to EPICS and feeding back

to actuators through EPICS. The speed of EPICS feedback is not fast like ~0.1 Hz of UGF. This feedback control is used for an initial mirror alignment and so on.

EPICS system being used here is involved as a part of the whole real time control system. When the real time module is built, Input Output Controller (IOC) and channel database of EPICS are automatically built at the same time. We do not need to touch EPICS database file directly. All the channel names on real time module will be duplicated into similar EPICS channel names. The total number of EPICS channels will be easily ~100000.

### FEEDBACK NOISE

To detection GWs is the same as a series of long term fight with many kinds of instrumental noises of the interferometer. Principle noises of interferometer for GW detection are as follows; seismic noise, thermal noise, radiation pressure noise and shot noise. The radiation pressure noise and shot noise are coupled in the advanced large scale interferometer and they are called the quantum noise [18]. Noise floor of the mirror motion of interferometers will be less than  $10^{-19} \text{ m}/\sqrt{\text{Hz}}$ . We need a very careful design against the controls because controlling a plant can easily introduce a feedback noise into the plant if the noise level is very low. Typical ADC or DAC has much larger noise (~1000 times) than the noise of analog circuits. We

need to implement whitening/dewhitening filters to avoid ADC/DAC noise effectively in order to reach the target sensitivity. ADC or DAC has alias or image in principle when the signal is converted. We implemented anti-alias (AA) filters and anti-image (AI) filters to avoid the extra noises in cooperation with Hitachi-Zosen. Results of the AA/AI filters are reported in this proceedings.

### SUMMARY

KAGRA is a project to detect gravitational waves by constructing a 3 km scale interferometer in Kamioka mine in Japan. Construction for excavation of tunnels and facility will be done within the next several years. During construction, we are designing and developing subsystems such as a laser, mirrors, and seismic isolators and so on, including a control system. Controls for interferometer will be very complicated and it requires very careful design to minimize the feedback noise to measure the extremely small length of  $\sim 10^{-19}$  m. We employed computers with a real time operating system to control such a km scale interferometer connected by real time and slow control networks integrated by EPICS technology. KAGRA will start operation and observation in the near future. Control system will play a very important role not only for controls but also for monitors, data acquisitions, automatic operations and so on during all the time after installation, for commissioning, noise hunting and observation.

### ACKNOWLEDGMENT

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