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ENVIRONMENTAL MONITORING SYSTEM IN KAGRA

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Abstract. *The underground gravitational-wave detector, KAGRA, is controlled by many precision devices such as electric circuits and computers. Precision devices are placed on racks and these racks are widely distributed in the tunnel. The environment of the underground site is not easy to keep good condition for electronic devices due to high humidity, etc. If temperatures and humidities in the racks are continuously high, precision devices may be broken. Therefore, we developed a real-time monitoring system to control the environment of the precision devices. To acquire temperature and humidity data, we installed thermo-hygrometer in all the racks located at various places in the tunnel. The environment data is important also for data analysis to search for gravitational waves, since we use it for detector characterizations to evaluate data quality. We placed the thermo-hygrometers also outside of the racks. Once thermo-hygrometers acquire data, the monitoring system registers the data into Experimental Physics and Industrial Control System (EPICS) database in real time. So we can display the data of temperature and humidity in real time through the EPICS interface. If temperature or humidity exceeds critical values, this system sends alert emails to an administrator. Before/during the test observation of KAGRA, we operated the real-time monitoring system. This real-time monitoring system was found to be stable. Moreover, from the monitoring results of the data collected outside of the racks, we found that the humidities of some places seem to be correlated though the distance between the places is very far. It is considered to be related to the amount of the underground spring water.*

Keywords: Environmental monitoring system, Real-time display, Experimental physics and industrial control system

1. **Introduction.** Gravitational wave is one of the most important predictions of general relativity. Gravitational wave is propagating oscillations of the gravitational fields, just as light and radio waves are propagating oscillations of the electromagnetic fields. Whereas light and radio waves are emitted by accelerated electrically-charged particles, and gravitational wave is emitted by an accelerated mass. The existence of gravitational wave has long been verified 'indirectly' through the observations of Hulse and Taylor Pulsar (PSR B1913+16) [1]. Recently, the advanced LIGO detectors [2] 'directly' observed the gravitational wave signals from merging black holes with a high statistical significance [3]. The direct detection of gravitational waves is important not only because it will allow verifying general relativity and other theories in the presence of strong gravitational field, but also because it will help investigate various unsolved astronomical problems and find new objects that cannot be seen by other observational methods. To define gravitational wave astrophysics in the near future, it is well known that we need at least three or more gravitational wave detectors. Therefore, several laser interferometric gravitational-wave detectors have been designed and built all over the world. They include advanced LIGO [2] in the US, advanced VIRGO [4] in Europe, and KAGRA [5] in Japan. They will provide a global network which allows improved parameter estimations and sky localizations of gravitational wave sources from the astronomical objects.

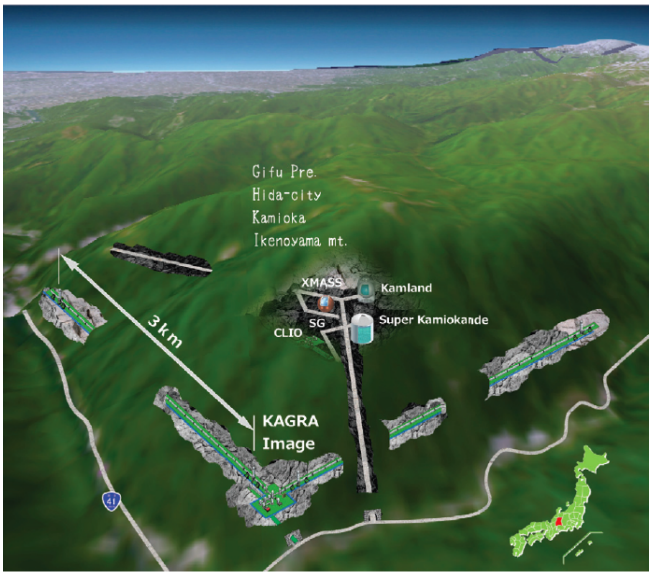


FIGURE 1. Schematic view of KAGRA. The 3-km arms of KAGRA are placed as an L shape along the edge of mountain. Kamioka mine has been used as a good experimental site for experimental facilities for particle physics and astronomical observations, such as Super-Kamiokande [6], XMASS [7], KamLAND [8] and CLIO [9].

KAGRA is a Japanese 3-km interferometric gravitational-wave detector, at an underground site which is a new excavated tunnel, in Kamioka mine, Gifu prefecture, Japan. The schematic view of KAGRA is shown in Figure 1. KAGRA has two outstanding features: cryogenic mirrors made of mono-crystalline sapphire to reduce thermal noises and the seismically quiet and stable environment of the underground site.

In order to control the interferometer, we use many precision devices such as electric circuits, and computers. Such devices are installed in racks located in very wide area of the underground site. However, the environment of the underground site is not easy to keep good condition for electronic devices due to high humidity, etc. Thus, the real-time monitoring of temperature and humidity is crucial for such devices. The alert mechanism is effective when the temperature or humidity goes beyond a critical value. In general, there are many applications of the real-time monitoring of temperature and humidity for server rooms, data centers, incubators of infants in hospitals, green houses, etc. (e.g., [10, 11, 12, 13]). In our case, we need to collect the environmental data from very wide areas of the underground site and check the status in the control room at the surface building about 7 km away from the underground site. The scalability of the system is important because the number of the observation points increases as the installation of the detector progresses. Moreover, the obtained environmental data are important also for data analysis to search for gravitational waves, since we use it for detector characterizations to evaluate data quality. Therefore, to refer collected environmental data in the future, they should be stored and accessible. These are challenging for us.

In KAGRA, Experimental Physics and Industrial Control System (EPICS) explained in Section 2.2 is introduced. About ten thousands types of data can be handled by using EPICS database. Moreover, if we can integrate the data from the various platforms of data logger on EPICS database, we do not have to handle different types of data formats, computer OS and so on. We can also save the data in the storage system without any independent data acquisition system. Therefore, we develop the environment monitoring system using EPICS database.

In this paper, we describe overview of the environment monitoring system in KAGRA. The paper is organized as follows. In Section 2, we review the developed environment monitoring system. In Section 3, we show our findings using the environment monitoring system. Section 4 is devoted to a summary.

2. **System.** The environment monitoring system mainly consists of four parts: wireless thermo-hygrometer equipments, Experimental Physics and Industrial Control System (EPICS), data flow network, and real-time display. We explain the details of each part.

2.1. **Thermo-hygrometer.** To acquire the data of temperature and humidity, we use the wireless thermo-hygrometer equipments (T&D Corp.) shown in Figure 2. Since the structure of the thermo-hygrometer equipments is simple and the scalability is high, we selected these equipments. The thermo-hygrometer equipments consist of data logger (RTR-507L), relay station (RTR-500C) and base station (RTR-500AW). This data logger uses the platinum resistance thermometer sensor and electrostatic capacitance type sensor. The measurement range of data logger is $-30 \sim 80$°C with precision ± 0.5°C for temperature and $0 \sim 99\%$ RH with precision $\pm 4\%$ RH for humidity. By wireless network (ARIB STD-T67 429 MHz), all devices can communicate within a 150 m distance. Base station has also IEEE 802.11b/g protocol and includes an alert system which can inform the alerts to users by e-mail. A relay station can connect 10 data loggers or relay stations and a base station can manage 10 relay stations or data loggers. In total, a base station can connect 100 data loggers to the network.

FIGURE 2. Wireless thermo-hygrometer equipments (T&D Corp.). Data logger (RTR-507L), relay station (RTR-500C) and base station (RTR-500AW). The data logger uses the platinum resistance thermometer sensor and electrostatic capacitance type sensor.

The software of the visualization for Windows OS is prepared by the vendor. However, the temperature and humidity can not be plotted in real time by this software. Detailed specification of the thermo-hygrometer equipments is found in [14].

2.2. **EPICS.** Experimental Physics and Industrial Control System (EPICS) [15] is an open source software tool, libraries and applications of real-time control systems for scientific instruments such as particle accelerators, telescopes, the advanced LIGO and other large scientific experiments. EPICS is designed for distributed control systems with a large number of independent devices. It sends and receives network messages through the infrastructures as well sequential logic programming information for the device control. In KAGRA, EPICS database is used to implement slow controls. A slow control network is used for many purposes, such as slow signal monitors like a temperature variation as one of the environmental data, signal routing switches, and filter gain setting or filter on/off switches. To monitor the environmental data in real time, we have to integrate the temperature and humidity data taken by the equipments described above, to the slow control network.

2.3. **Data flow network.** We show the schematic view of KAGRA underground site and architecture in Figure 3. The KAGRA site is mainly divided in four areas: the center area, X and Y end stations (3 km from the center area), and the control room (outside of the underground site), respectively. The racks housing of the precision devices are located near the various subsystems of KAGRA, such as vibration isolation systems and laser. One thermo-hygrometer data logger is placed in each rack. For evaluation of data quality, we place the thermo-hygrometer data logger also outside of the racks in each experimental area. Moreover, for the clean rooms, the data loggers were placed outside and inside of the room. In order to avoid connection losses between the data loggers and/or relay and base stations, we properly arranged the data loggers, relay and base stations. The number of data loggers, relay and base stations is summarized in Table 1. Figure 4 shows a data logger, relay and base stations at the deployment site.

The data flow diagram is shown in Figure 5. The observed values of each data logger are recorded at 1-minute intervals. From each data logger, the observation data is sent to a relay or base station by wireless devices. If the value of temperature or humidity is over a predetermined threshold value, the administrator receives alert e-mails from the base station. When data from all data loggers are received, the observation data is recorded in an XML format at the base station. Then, the XML files are sent to a FTP server at the control room through LAN. At the FTP server, the shell scripts developed by us

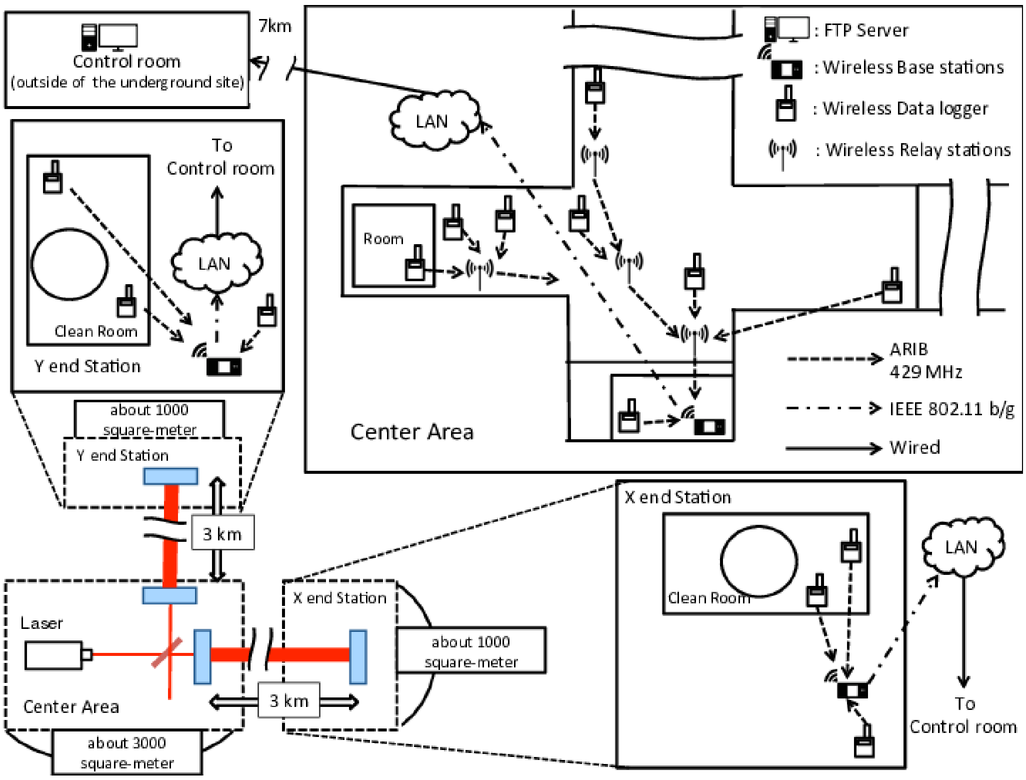


FIGURE 3. Schematic view of the underground site of KAGRA. The left bottom shows the 3-km L shape arms along the edge of mountain (see also Figure 1). The right upper panel shows the detailed description of center area. The left middle and right bottom panels show the detailed description of X and Y end stations, respectively. The left upper panel shows the control room (outside of the underground site). The architectures of each logger/station and network protocol are also shown.

Table 1. The number of data loggers, relay and base stations in each area

	Center Area	X end Station	Y end Station	Control Room	*Total*
Data Logger	Rack:4 Field:8	Rack:1 Field:2	Rack:1 Field:2	Rack:1 Field:0	19
Relay Station	5	0	0	0	5
Base Station	1	1	1	1	4

Figure 4. Data logger, relay and base stations at the deployment site

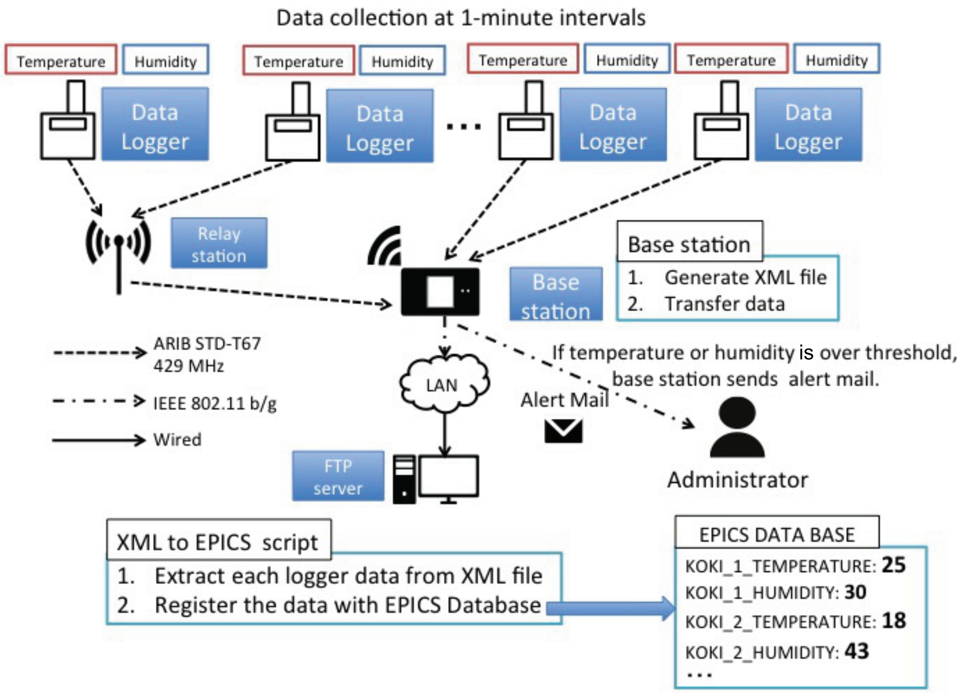


Figure 5. Data flow of the monitoring system

extract the data of each data logger from XML files and integrate the values on the EPICS database.

2.4. **Real-time display.** By using EPICS database and StripTool [16] in EPICS, we can plot the value of temperature and humidity in real time. This display is updated every minute. From the control room of outside of the underground site, we can access to all the data loggers/places in KAGRA.

Figure 6 shows an example of real-time display in the control room during the test observation of KAGRA, held in 3/15-3/31 and 4/11-4/25, 2016. Moreover, since the data of temperature and humidity is recorded in the EPICS database, we can use this information for evaluation of the interferometer data quality of offline.

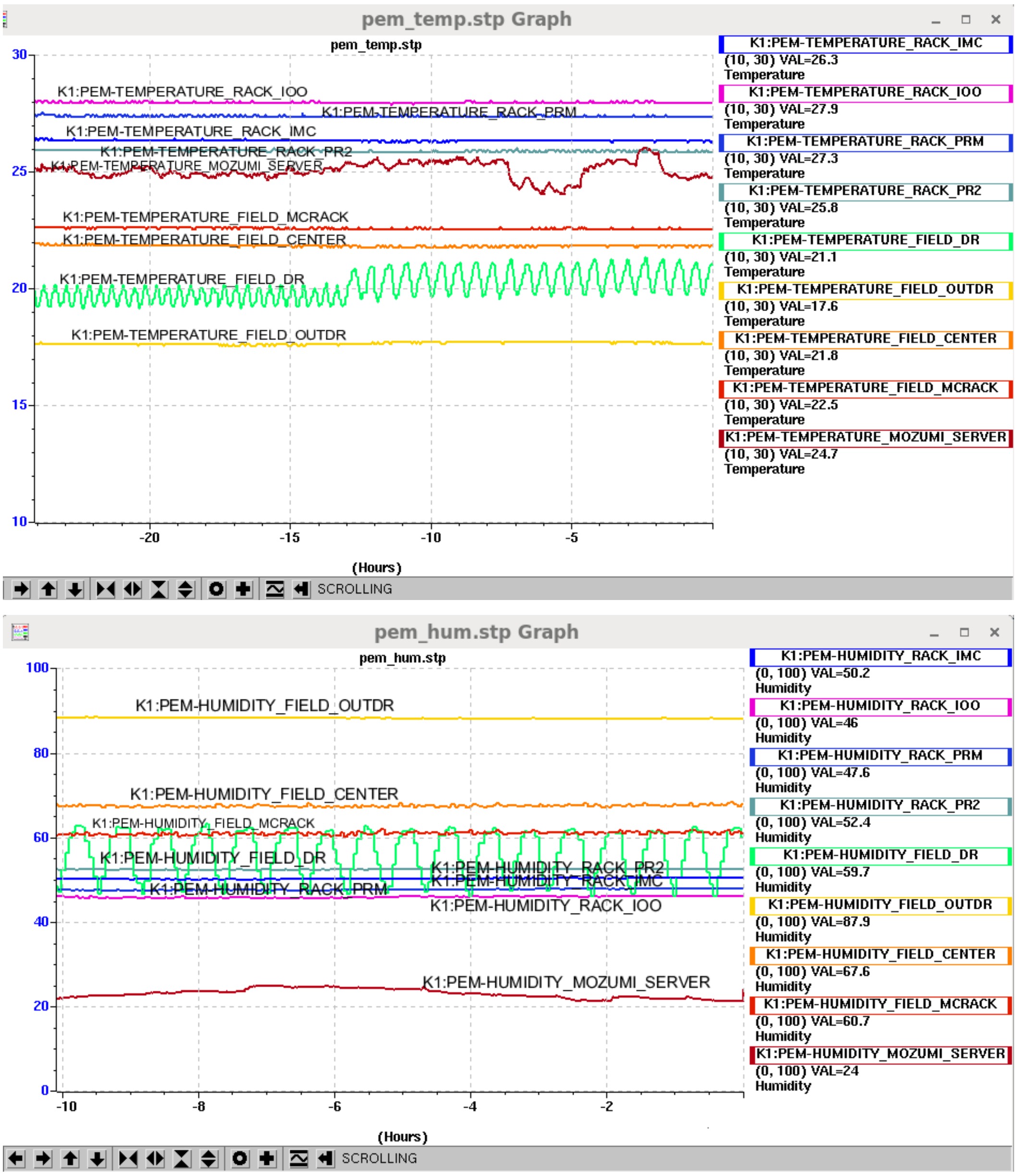
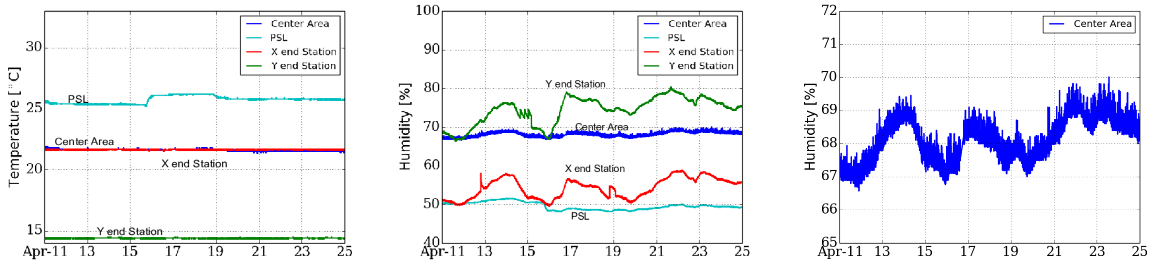


FIGURE 6. Example of real-time display in the control room. Upper and lower panels show the time series variation of temperature and humidity of several measurement places, respectively. Legend shows the place of data loggers (EPICS channels).

3. **Monitoring Results.** We plot the variation of the temperature and humidity during 4/11-4/25, 2016. Figures 7(a) and 7(b) show the results obtained by the loggers in the field of four areas: center area, X and Y end stations, and pre-stabilized laser (PSL) room which is the clean room located in the center area. Table 2 shows the average value, maximum and minimum of the the temperature and humidity for each area. The temperature of X end station is warm. This might be effect of the geothermal heat. The temperature of the center area is also warm because of a lot of electricity consumption. Since PSL room is warm due to the laser and other instruments, the temperature of PSL room is controlled by the air conditioner. In all areas, we find that there is no daily variation in the temperature, i.e., the temperature is stable.



(a) Temperature (b) Humidity (c) Enlargement of center area in Figure 7(b)

FIGURE 7. Variation of the temperature and humidity during the 4/11-4/25, 2016

TABLE 2. The average value, maximum and minimum of the temperature and humidity for each area. In each cell, the values of average (maximum/minimum) are shown.

	Center Area	X end Station	Y end Station	PSL Room
Temperature [°C]	21.6 (21.9/21.4)	21.6 (21.7/21.5)	14.4 (14.5/14.3)	25.7 (26.2/25.2)
Humidity [%]	68.1 (70.0/66.6)	54.3 (58.8/49.5)	74.3 (80.5/66.4)	49.6 (51.5/48.1)

The humidity of Y end station is high because of its low temperature whereas the humidity is more stable at the center area and in the PSL room. The humidities of X and Y end stations are not stable. The size of X and Y end stations is the same (see Figure 3) and the number of devices is almost the same. On the other hand, the distance between X and Y end stations is long (3 km $\times$ 3 km (see in Figure 3)). However, from Figure 7(b), the variation of the humidities of X and Y end stations seems to be correlated. Moreover, the size of center area is three times bigger than X and Y end stations (see Figure 3). In Figure 7(c), we show the enlargement of the variation of the humidity of center room in Figure 7(b). From Figures 7(b) and 7(c), the variation of the humidity of center area also seems to be correlated. Therefore, we assume that this behavior is related to the amount of the underground spring water of the mountain. We will investigate the exact reason.

4. **Summary.** In this paper, we introduced the real-time monitoring system of temperature and humidity in KAGRA. Before/during the test observation of KAGRA, which was held in 3/15-3/31 and 4/11-4/25, 2016, we operated the real-time monitoring system and took data. During the operation, alert e-mails also worked effectively. The operation was stable with no serious problems.

From the monitoring results of the data, we confirmed that the temperatures of each area are stable. As the interesting observation, we found that the humidities of X and Y end stations seem to be correlated, although the distance between X and Y end stations is very far. This correlation may be related to the amount of the underground spring water. However, we need to investigate the exact reason.

As future works, we plan to increase the observation points. We will also design the real-time display to comprehend the status better, based on observed data.

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