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1. Physical environmental monitors

1.1. Introduction

World gravitational wave(GW) interferometers have many history of the technical improvement for the noise reduction, because the gravitational wave signal is too small. The radiation pressure and shot noise which are come from the quantum uncertainty principle are the fundamental noise of the interferometer. Frequency and intensity laser noise should be included in the interferometer noise. Ground base interferometers have to take into account the ground motion, which are come from tidal, earthquake, waves and human activity. To overcome from ground motion, they are consist with various type of suspensions. KAGRA interferometer is constructed underground to reduce the effect of the ground motion. Underground environment is one of the unique feature of KAGRA interferometer. Thermal noise is also one of the fundamental noise. KAGRA interferometer has four cryogenic mirror to reduce the thermal noise. This cryogenic environment is also one of the unique feature of KAGRA interferometer.

Additional to fundamental interferometer noise, there are various kind of noises in KAGRA. For example, the beam jitter noise and scattered noise from the vibration of the optical table, beam duct and vacuum chambers. Interferometer control noise caused by length sensing and control(LSC) and alignment sensing and control(ASC) and DAQ, electric and circuit noise by ADC, DAC, coli driver circuit and so on. Following noises are called instrument noise. Also, to operate the interferometer, we need the vacuum pumps, air conditioner, fan, cooler, LED lights. They made the acoustic, magnetic, RF and vibration field.

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They are also included in the instrument noise. To monitor, investigate and reduce them, we need the physical environmental monitors(PEMs)

Three main purpose of the PEMs will be introduced. One is the understand, investigation and reducing the noise to improve the detector sensitivity. By performing the coherent analysis and PEM injection, which are written in Section. 1.4, we can understand the current dominant instrumental noise and noise path to gravitational wave channel. Second role is to distinguish between gravitational wave signal and instrumental noise. The detail will be described in DetChar section. Third role is R&D study for the third generation GW interferometer. As described below, KAGRA interferometer has two unique features, underground and cryogenic. And those features would be essential technique for the future GW interferometers. To understand the instrumental noise which is come from those features, it would be important message. To select the place of the Einstein Telescope, Virgo PEM team visited KAGRA observatory and share the information about underground interferometer.

Section. 1.2 shows the status of the KAGRA PEMs and its installation history. Section. 1.5 shows the some examples of the noise investigation using PEMs. And the future prospects are summarized in Section. 1.6

1.2. Installation polities of the KAGRA PEMs

KAGRA PEMs are installed with the following polities. The detail about the PEM place is summarized in the KAGRA PEM map web[1]. Fig. **??** showed the example of the KAGRA PEM map. Table. 1 summarized the sensor types, frequency range and sampling rate.

1.2.1. Monitors for the vibration, sound and voltage of the optical tables. There are many optical tables in the KAGRA detector, which are for the stabilizing and mode matching the laser, taking data for interferometer control, monitoring the transmittance lights from end test mass, controlling the photon calibrator and detecting GW signal. On the optical table, there are many optics, periscopes and photo-diode. They are directly affected the environmental noise. We decided to place at least one accelerometer, microphone and voltage monitor to each optical table. By monitoring them, we can investigate the stationary interferometer noise, narrow band frequency noise(line noise) and glitches which were caused by environmental noise.

1.2.2. Monitors for the ground motion in the underground facility. We placed the three large seismometers to the 2nd floor(center, Xend and Yend area) for monitor the ground motion. The important point is we placed them in the 2nd floor of the each area, because Type-A suspensions which consist the Fabry-perot cavity, were hanged from 2nd floor. They were used not only monitor the ground motion, but also the sensor correction. We installed three small seismometers at the first floor of the center area. (1) Input mode cleaner(IMC) area to monitor the local ground motion for the PSL room, IMC and input mode match telescope. (2) Beam splitter(BS) area to monitor the local ground motion for the power recycled mirror chambers, BS chambers and signal recycled mirror chambers. (3) Input test mass for the X arm cavity area to monitor the local ground motion for the Type-A suspension and compare the difference between 1st floor and 2nd floor.

[1] The PEM map is shown in https://www.icrr.u-tokyo.ac.jp/∼washimi/KAGRA/PEM/PEMmap/

1.2.3. Monitors for the magnetic field in the underground facility. We placed three magnetometers to the BS chamber, Xend cryochamber area and Yend cryochamber area to monitor the magnetic filed[2]. The monitor of the magnetic field is important to understand the identification and mitigation of narrow spectral artifacts, such as power line and magnetic field to/from suspensions and circuits. And magnetic filed transportation lightening effect,

1.2.4. Monitors for the temperature and humidity in the underground facility. Even the underground environment keep the temperature stably, KAGRA suspension is very sensitive for the temperature drift. There are many delicate circuits the monitor of the humidity is also important. Temperature and humidity varied with turning on and off of the instrument(Vacuum pumps, Fan, etc) We placed thermometers to all electric racks, booth, near the chamber, field and air conditioners.

1.2.5. Monitors for the weather condition outside of the tunnel. Weather station and lighting monitor[3] were set at the entrance of the KAGRA experiment area to monitor the environment at the KAGRA area.

Type	Sensor	Operating frequency	Number
Seismometer1	Trillimu120Q	10 mHz -150 Hz	3
Seismometer2	Trillium compact	10 mHz -150 Hz	3
Accelerometer1	TEAC710	20 mHz - 200 Hz	10
Accelerometer2	TEAC706	3 Hz - 14kHz	6
Accelerometer3	PCB M601A02	17 mHz - 10 kHz	4
Microphone1	B&K 4188-A-021	20 Hz - 12.5 kHz	3
Microphone2	ACO microphones	20(1) Hz - 20 kHz	XX
Microphone3	Audio-technica AT-VD6	60 Hz - 15 kHz	2
Magnetometer	Bartington Mag-13MCL100	DC - 3 kHz	3
Thermometer	RTR-507SL	5min	YY
Weather station	Vantage Pro2 #6152JP	ZZ min	1
Lightning monitor			1

Table 1 Summary of the KAGRA PEMs which were installed for O3GK observation.

1.3. Development of the KAGRA portable PEMs

Instead of the regular PEM channels as described in the Section. 1.2, we prepared so called "Portable PEMs" to access the unknown noise, characterization of the KAGRA instrument easily, and understanding the noise path which was detected by the regular PEM. Two types of the portable PEMs are prepared. One is the BNC type PEMs which use the BNC cable for data acquisition and constant current power supplying. Another one is the USB type

[2] https://arxiv.org/pdf/1801.07204.pdf later to add the reference
[3] https://www.icrr.u-tokyo.ac.jp/∼washimi/KAGRA/PEM/KamioKaminari/

PEMs which use the chromebook PC for the interface. Fig. 2 showed the block diagram for both PEM types.

The characterizations of the BNC type PEMs are followings; Merit : We can take data using KAGRA DAQ system, which can save data with other channel signals, can use KAGRA digital software and can prefer the coherent analysis with other channel signals. Demerit : We have to do the cabling, which means difficulty of the accessing to instrument which we have interested in. We need the AC or DC power supply for the constant current / signal amplifier interface(ACO TYP5006).

The characterizations of the USB type PEMs are followings; Merit : We can use google apps by Chromebook PC(10 inch, 890 g). There are many useful free softwares(Ex. spectrogram, signal recorder, generating signals). We don't need the complicated cabling. Demerit : The CPU power of the Chrombook is not so large. We need other machine for complicated analysis. Number of the USB type PEMs is small.

The detail information about the portable PEMs will be described in future paper.

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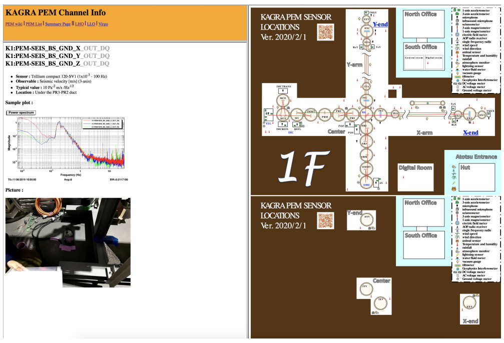

Fig. 1 KAGRA PEM map which is opened in the webpage.

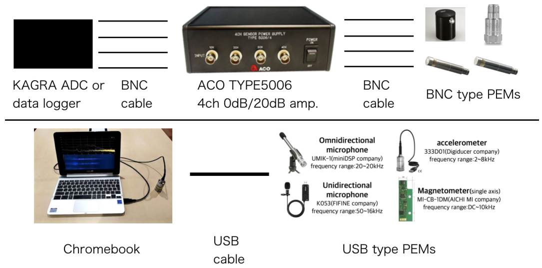

Fig. 2 The block diagram of the BNC type PEMs(top) and USB type PEMs(bottom)

1.4. *PEM injection*

PEM injection is one of the important measurement to evaluate the effect of the environment(sound, vibration, magnetic field, RF signal, etc) to the interferometer signals. By evaluate the coupling function($C(f)$) which can be described as

$$C(f) = \sqrt{\frac{x_{\mathrm{inj}}^2(f) - x^2(f)}{y_{\mathrm{inj}}^2(f) - y^2(f)}} \tag{1}$$

where $x_{\mathrm{inj}}(f)$ and $x(f)$ are the amplitude spectral density of the DARM displacement with and without PEM injection and $y_{\mathrm{inj}}(f)$ and $y(f)$ are the amplitude spectral density of the environmental monitors, we can evaluate the effect of the environmental noise to the DARM displacement.

1.5. *Noise hunting by PEMs*

We already succeeded to hunt the noise source which can affect to the DARM displacement. I will pick up the representative noise hunting.

- 17.2Hz noise hunting by installed PEMs
  The 17.2Hz noise was detected in the MICH control error signal. And there is large coherence with optical levers which were placed the center area. We found the Fan Filter Unit(FFU) for keep the clean room, generated the vibration and the resonance frequency of the framework vibrated the 17.2Hz. Now the FFUs were turned off.
- 44Hz noise hunting by portable PEMs
  The 44Hz noise was detected in the frequency noise of the green laser. When we evaluated the coherence with green laser frequency noise channel and PEM channels, we found that the accelerometers which were placed in the PSL room showed the large coherence. So, we entered the PSL room with USB type portable PEMs (accelerometer and microphone) and finally, we found the large 44Hz vibration from the 24V DC power supply which was used for the laser shutter. We replaced the position of the 24V AC power supply, this noise was disappeared.
- 280, 360Hz by PEM injection
  By applying the acoustic injection to KAGRA interferometer, the 280 Hz and 360 Hz peaks are turned out to come from the bellows at the IMC output. The acoustic field or vibration increased the vibration of the bellows and scattered light may be affected. The detail of this result will be appeared in the future PEM paper.

1.6. Future prospect

We are planning to evaluate the Newtonian noise for the future GW detector. The 3td generation GW detector, such as ET or cosmic explorer, will be placed underground. The Newtonian noise measurement in the KAGRA site will be the important information to select the placement of the next generation GW detectors.

Acknowledgment

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References

[1] J. P. Blaizot, and E. Iancu, Phys. Rep. **359**, 355 (2002).

A. Appendix head

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