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Investigation of the environmental noise at KAGRA detector

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KAGRA is the 2.5th generation gravitational wave detector in Japan. There are two unique features in KAGRA detector, one is the underground environment and the other is the cryogenics. Those two features would be the essential technique toward the next generation detector. Toward the observation, we installed various environmental monitors such as accelerometers, magnetometers, seismometers, microphones, temperature and humidity monitors, air pressure monitors, voltage monitors and so on. In addition to this, we established the portable environmental monitoring system for detector noise hunting. Those environmental monitors are also used for the R&D studies for the future gravitational wave detectors.. In this talk, we will present the investigation of the environmental noise at KAGRA detector and current status of the noise hunting using environmental monitors.

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1. Introduction

Gravitational wave (GW) astronomy is becoming a very exciting research field in physics and related disciplines. Since the first direct detection of GWs from a binary black hole merger [1], many GW signals have been detected using the LIGO [2] and Virgo [3] interferometers. The fourth observation run (Called the O4a run) started on 24th May 2023, with LIGO and KAGRA detectors, and Virgo will join soon. More exciting GW events will be detected in the future.

KAGRA [4] is a GW interferometer located in Japan. It is termed as a 2.5^{th}-generation GW interferometer since it is constructed underground [5] and operates at cryogenic temperatures (20K) [6]. By April of 2019, the installation work was mostly completed, and the first international observation run, called "O3GK," with the GEO600 [7] was performed in April 2020.

Since the typical amplitudes of GWs are extremely small, the vibrations from instruments, sound from outside the experimental area, etc can produce noise-source contamination that reduces the sensitivity. Major noise sources include environmental disturbances caused by earthquakes, the effects of magnetic and acoustic fields, temperature fluctuations, etc. To evaluate the environmental noise, we have installed more than 100 sensors in the KAGRA experimental site (including area outside tunnel). These are physical environmental monitors(PEMs) The detail of the KAGRA PEMs are given in [8]

2. Ground motion evaluation at KAGRA experimental area

Three tri-axial seismometers are placed at the center, X-end, and Y-end station, and one GIF was positioned along the X-arm to monitor the ground motions caused by Earth tides, earthquakes, ocean waves, and human activity near the experimental station. The Trillium 120QA seismometers were used. The seismometers were placed on the 2nd floor of each area; the four cryogenic mirrors that comprise the Fabry-Perot cavities, were hung from the 2nd floor. They are used not only for ground motions but also for sensor corrections, controlling the suspensions with multiple sensors. Fig. 1 shows a typical spectrum of ground motion in the KAGRA experimental area. The figure on the left shows a comparison of the inside and outside of the KAGRA experimental area and the TAMA area [9]. The ground motion inside the KAGRA experimental area was evaluated using one-year data as percentile, shown in the right figure.

2.1 Local Hurst exponent computation

Local computation of the Hurst exponent allows monitoring of this variability over time and its ingestigation in relation to other environmental sensors time series data. This could help investigate noise couplings that possibly affecting the detector sensitivity owing to changes in the spectral slope in the data. The details of the local Hurst exponent can be found in [10]. The Hurst exponent, H, can be expressed as $H = (\beta + 1)/2$, where the β is the spectral index ($P(f) \sim f^{-\beta}$). Fig. 2 shows the result when investigating of the KAGRA seismometer signals. As shown, the spectral characteristics between the X-and Y axes and the Z-axis are different, and Xend station is differs from the center and Y-end station. The next topic is the characterization of the time variance of the ground motion using Hurst exponent computation.

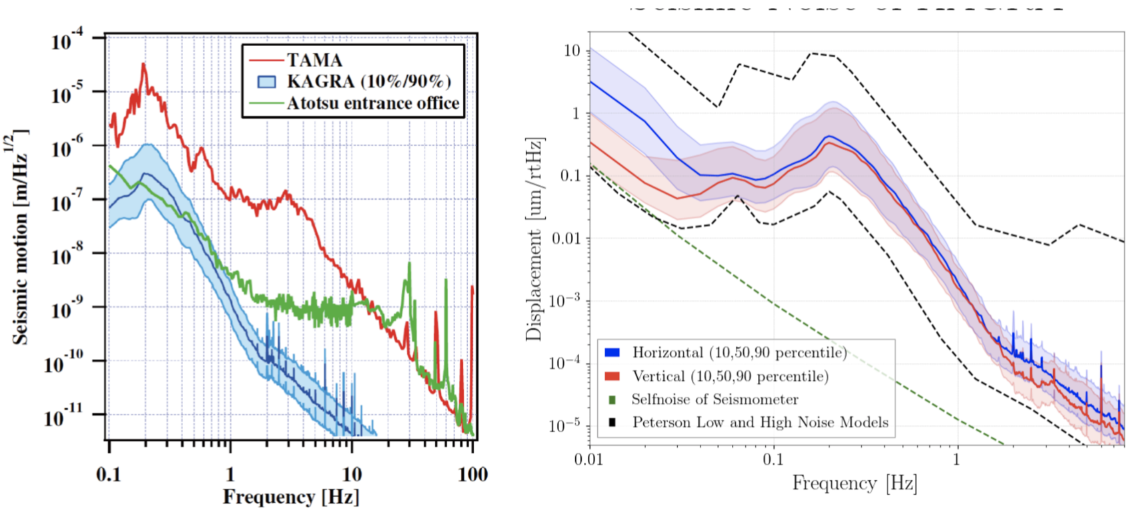

Figure 1: Percentail for KAGRA ground motion using 1 year seismometer data, and comparison the ground motion from outside and TAMA experimantal area.

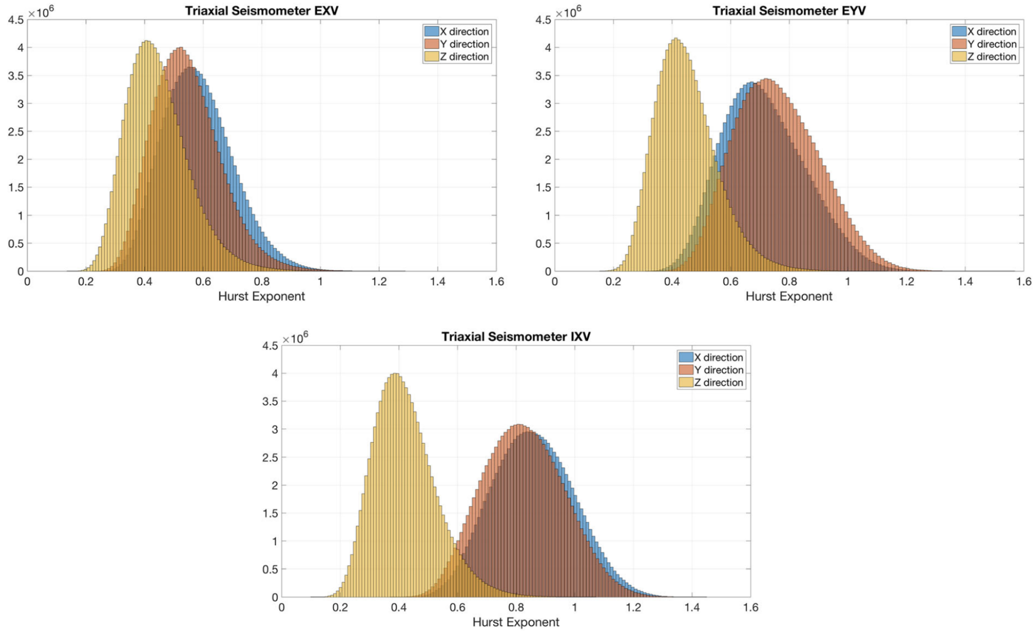

Figure 2: Histograms of the local Hurst exponent, computed over the whole analysed period using small overlapping scales of width n ¼ 500 and performing linear detrend in each window, for the three KAGRA seismometers

2.2 Evaluation of the microseismic motion at the KAGRA site based on the ocean wave data

Microseismic waves are ground motions excited by ocean waves. The frequency is approximately 0.1 Hz. Even at an underground site, microseismic motion cannot be ignored. During the O3GK, owning to the stormy days (large microseismic motion), maintaining the observation state was difficult for several days. Qualitatively, the effects of ocean waves on the KAGRA site are known, which would be quantified by creating simple approximation equations for ocean waves and ground velocity at the KAGRA. In addition, we evaluated the characteristics of ocean waves around the KAGRA site. Ocean wave data were published by the Nationwide Ocean Wave information network for Ports and HArbourS (NOWPHAS). The correlation analysis for the ocean wave data in each bay can be categorized into threeparts, Sea of Japan, Pacific East area, and Pacific South area. From the 12 ocean wave datasets of the near bay, we performed the principal component analysis to extract the typical ocean wave data for the upper three areas and then fitted the results with a non-linear function. Finally, we succeeded in explaining the ground motion from ocean wave data with high precision. Fig. 3 shows a comparison of the microseismic motion at the KAGRA site and predictions from the ocean waves. By inputting wave forecast data into the established model, we can forecast future microseismic motions. Fig. 4 shows an example of the microseismic forecast graph. This contributes to the commissioning work at the KAGRA observatory, particularly for scheduling. The detail can be found in [11].

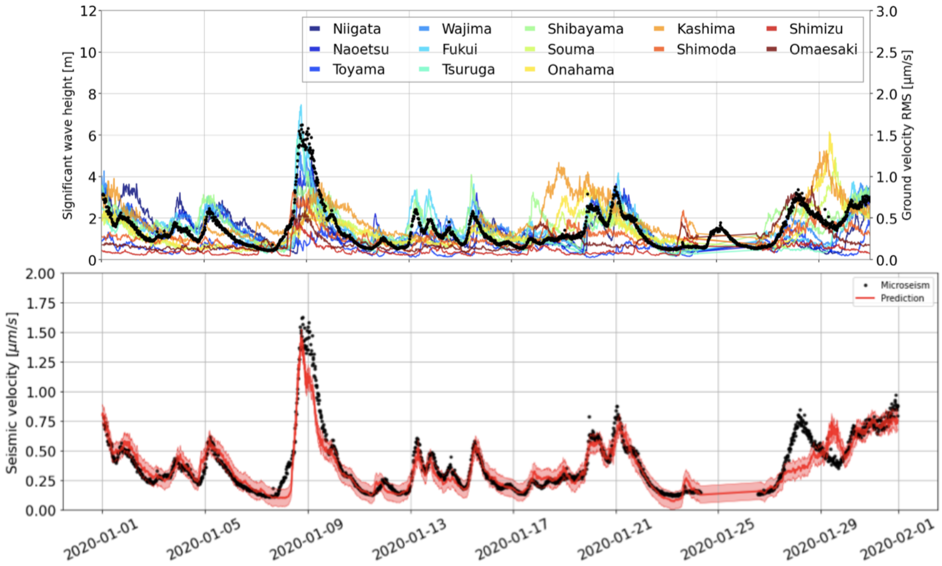

Figure 3: Comparison of the microseismic motion at the KAGRA site, between the observed data (black) and the prediction from the ocean waves (red, with the 1σ error band). The typhoon period (gray hatched) is not used for the prediction. The SWH and the microseismic motion at January 2020

3. Newtonian noise evaluation at KAGRA experimental area

Newtonian noise(NN) is associated with density fluctuations in the surrounding geology. NN may limit the sensitivity of these advanced detectors in the low-frequency band (up to 10 Hz) and is

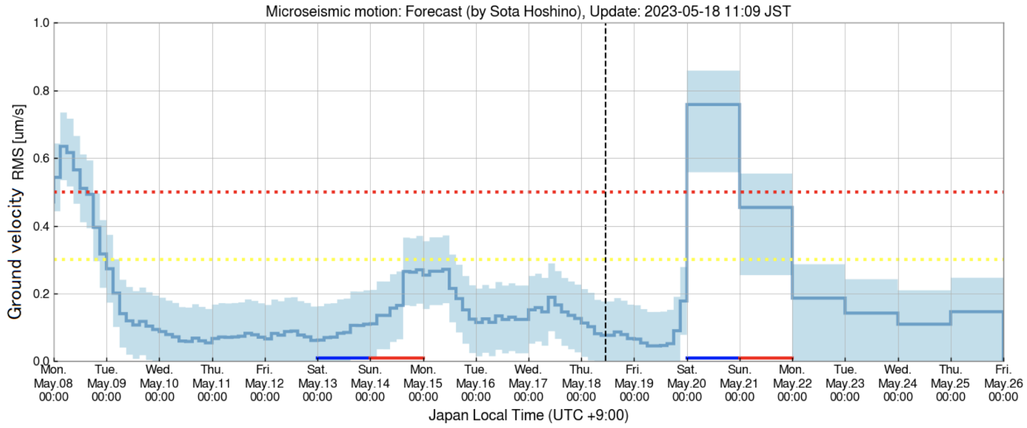

Figure 4: An example of the microseismic forecast graph. The black line shows the current date, in this case, 2023-05-18 11:09 (JST). The right and left sides of it are the future and past, respectively. The horizontal dotted lines (red and yellow) correspond to the benchmark microseismic level , red is 0.5um/s, and yellow is 0.3um/s.

certainly a limiting noise source for ‘third generation’ detectors that are currently in the conceptual design phase. Underground sites promise a significantly reduced contribution of the environment to detector noise, thereby opening the possibility to extend the observation band to frequencies well below 10 Hz. For this reason, the proposed next-generation infrastructure Einstein Telescope in Europe can be realized underground aiming for an observation band that extends from 3 Hz to several kHz.

3.1 NN estimation from surface Rayleigh waves, body waves and the acoustic field

Ambient noise in the low-frequency band of 10–20 Hz at the current surface sites of the Virgo and LIGO detectors is predominantly produced by the detector infrastructure. Avoiding compromise with the quality of an underground site with noisy infrastructure is essential at least at frequencies where this noise can became a detector sensitivity limitation. We characterized the KAGRA underground site to determine the impact of its infrastructure on the environmental fields. We observed excess seismic noise and, its contribution to the important band below 20 Hz was minor preserving the full potential of this site to realize a low-frequency GW detector. Moreover, we estimated the NN spectra of surface and underground seismic waves and the acoustic field inside the caverns. Accordingly, these will likely make a minor contribution to the KAGRA’s instrument noise in the foreseeable future as shown in Fig. 5.

3.2 NN evaluation from water fluid system

A water pipes was placed near a sapphire mirror. Therefore, we must evaluate the effects of the NN in the water flow system. To continuously measure the water flow, we placed the water flow measurement system at the end of the Y-end station. In addition, with the use of the results of the water flow measurement system, we investigated the NN using 3D simulation and theoretical calculations. We used FLOW3D software for the water flow simulation. According to the theoretical calculations, the the surface microstructure largely affects NN. Both evaluate the NN with straight

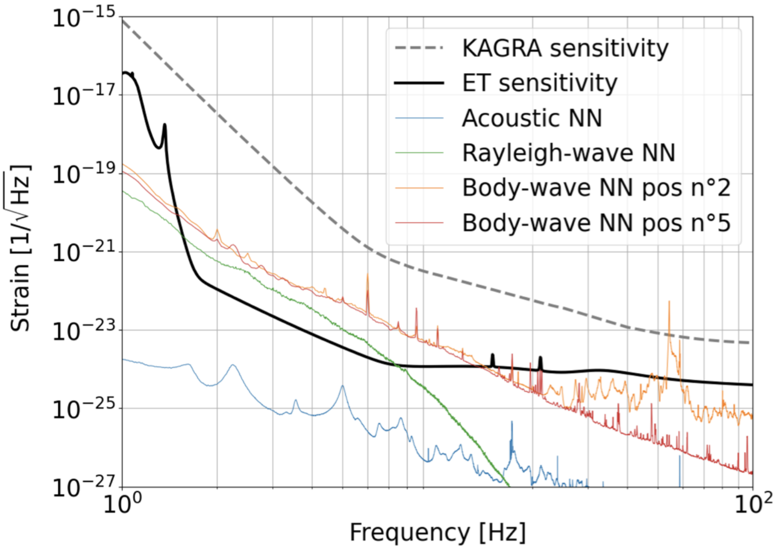

Figure 5: Modeled acoustic and seismic NN spectra (90th percentiles). The KAGRA sensitivity curve represents an optimistic scenario (130 Mpc horizon for neutron-star binaries). The seismic spectrum used for the pos 5 NN spectrum is not representative of conditions during observing runs. It is only shown to illustrate what effect infrastructure might potentially have on NN.pos n2 and n5 is the seismometer position, corner station and Y-arm station, respectively.

and realistic KAGRA pipe shapes with various water flows. Although the NN was concluded to be under the KAGRA design sensitivity, it appears in the Einstein Telescope design sensitivity. This result is interesting for future detectors.

4. Signals from Tonga volcano eruption on January 15th, 2022

On January 15, 2022, the undersea volcano of the Hunga Tonga-Funga Ha'apai erupted. Global seismic wave, shock waves, and electromagnetic waves generated by a recent eruption in Tonga reached the KAGRA experimental area, which is more than 8,000 km away, and their signals were clearly visible in various environmental monitors and a geophysics interferometer. Unfortunately, the KAGRA interferometer has been upgraded. Two papers were published, one focused on the evaluaton of the KAGRA Facility[12]. and the other was the result of the geophysics interferometer[13]. This volcanic eruption induced multiple lightning strikes and emitted electromagnetic waves. These lightning strikes excited Schumann resonance. A twice larger magnetic field around the 7.5 Hz frequency region was detected soon after the Tonga volcano. Several tens of minutes after the Tonga Volcano, the p- and s-wave ground motions were detected by seismometers located in the KAGRA experimental area. After approximately seven hours after the eruption, the air pressure signal and ground motion induced by air pressure were detected using a seismometer, infrasound microphone, and barometers. Using a combination of these detectors, we characterized the facility of the KAGRA experimental area, for example, transfer function of the air pressure from outside area to inside area, and the ground motion between the corner station and each end-station.

5. Noise hunting using the portable environmantal monitoring system

To achieve better sensitivity, noise hunting would be an essential issue. To evaluate the noise from the environment, the following procedure was established: (1) Tapping test to determine critical points roughly. (2) Shaker/acoustic injection over a wide area without a witness sensor. Swept sine injection was performed to investigate the non-linear coupling. (3) Narrow bands shaker/acoustic injection with multiple witness sensors. We evaluated the noise budget by calculating the response function. The details of the evaluation of the detector noise by response function can be found in [14].

One of the critical points that was found by performing the tapping test during the commissioning for the O4a run was the leg at the vacuum chamber for the output mode cleaner(OMC). Out of the six legs in the OMC chamber, three legs are for the vacuum chamber itself, and the other three legs are for the optical table inside the OMC vacuum chamber. Fig. 6 illustrates the process of the vibration level by turning off several instruments. Compared to the vibration level during the O3GK period, although a larger vibration level was detected at a frequency of approximately 700 Hz, it is notably not sensitive to the noise in this frequency. By turning off unnecessary vacuum pumps, air coolers and filter fan units (FFUs), we could reduce the vibration level, and as confirmed, this vibration did not limit the KAGRA detector sensitivity curve at this time.

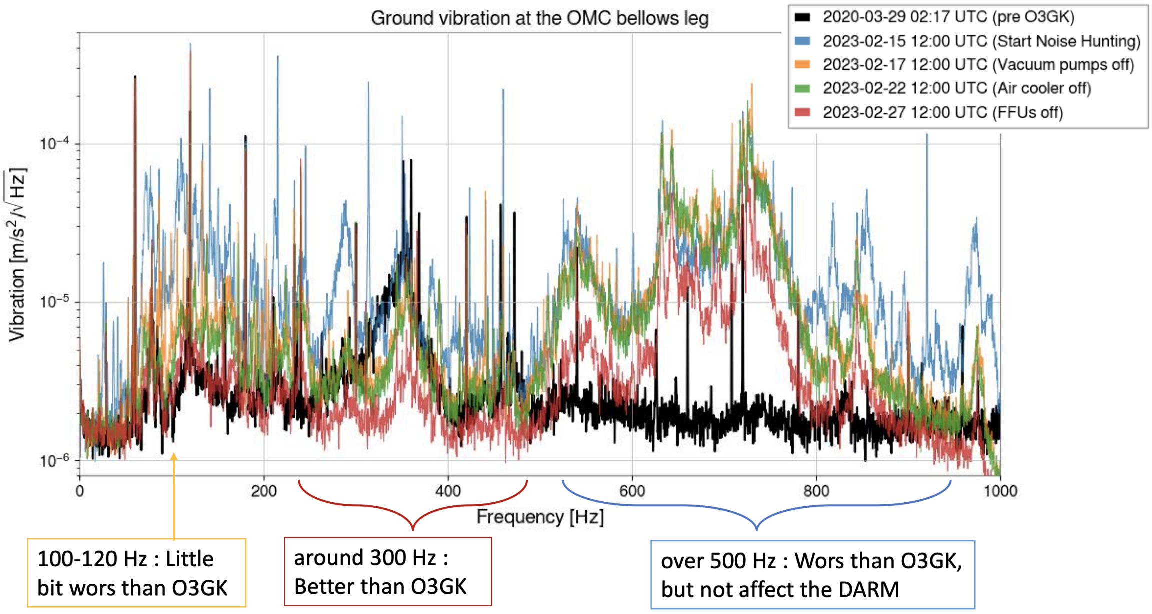

Figure 6: OMC leg

6. Conclusion

KAGRA is a GW interferometer located in Japan. There are two unique features, one is the underground environment, and the other is the cryogenic environment. This proceeding was focused on the ground motion and related noise. Ground motion can be reduced to install the detector at the underground site. The unique analysis method, Hurst exponent computation showed the characteristics of ground motion at each experimental area to be different. NN evaluation is also important, particularly for next-generation detectors, since the noise reduction below 10 Hz is critical for the GW detection range. We evaluated the NN from ground motion, acoustic, and water fluid. Not only the ground motion but also other environmental noises affect the sensitivity of the KAGRA. PEM would significantly support noise hunting.

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