# 論文の内容の要旨

# Development of input optics for the gravitational wave detector KAGRA
# (大型重力波検出器KAGRAにおける入射光学系の開発)

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A gravitational wave (GW) is a wave of the space-time distortions traveling at the speed of light. The GW was not directly detected for 100 years after the prediction of its existence by Einstein in the general theory of relativity in 1916, and many scientists have been tried to detect the GW. In such situation, in September 2015, the first direct detection of the GW was achieved by Advanced LIGO (aLIGO), in the U.S. aLIGO detected the GW from a coalescence of binary black holes. It was surprising for many physicists since most of the physicists predicted that the first detected GW would be from a coalescence of binary neutron stars. According to the analysis, this GW source is the binary black holes located about 410 Mpc away from the earth and their masses were $36M_{\odot}$ and $29M_{\odot}$, respectively. This observation gave us an important suggestion on the event rate of coalescences of binary black holes, namely, 9-240 events per year within the range of 1 Gpc, which is far more than the predicted value of 0.1-1 events per year. It was also a surprise that their masses were about $30M_{\odot}$, since the mass of a celestial compact object that had been a candidate for a black hole by the X-ray observations so far was approximately $10M_{\odot}$. Since the first observation, the GW signals from three coalescences of binary black holes have been observed by two detectors of Advanced LIGO. In August 2017, Advanced Virgo (AdV) in Italy participated in the observation, and GW signals from a coalescence of the binary black holes and a coalescence of the binary neutron stars were detected simultaneously by the three detectors of aLIGO and AdV. In the event of the binary neutron stars coalescence, the short $gamma$-ray burst(GRB) was observed 1.7 seconds after detection of the GW. The $\gamma$-ray intensity was lower than those emitted from any other short GRBs ever observed. It is an open question whether such dark short GRBs have just been overlooked or the GRB in this event is special. In any case, if similar GRBs are observed with multi-messenger observations with GWs, it is expected that they will provide new knowledge on astrophysics. Like this, GW signals provide a new brunch of astronomy different from the current astronomy using electromagnetic waves.

In such a situation, a GW detector called KAGRA is under construction in Japan. KAGRA is a GW detector with arm length of 3 km under construction in the mine of Kamioka, Hida City, Gifu Prefecture, Japan. iLIGO and Virgo is called the first generation detectors, and aLIGO and AdV are called the second generation detectors. On the other hand, KAGRA is called the 2.5th generation detector. This is because the KAGRA incorporates several more advanced features as follows: the quantum noise reduction by using the RSE interferometer, the thermal noise reduction by cryogenic mirrors, the seismic noise reduction by the 13 .5 m large suspension built underground. Using these techniques, KAGRA has design sensitivity

that can detect GW generated by a coalescence of the pair of 1.4 solar mass neutron stars 140 Mpc away from the earth. In 2016, the test run with a simple Michelson interferometer were conducted, and stable operation was achieved.

KAGRA has the several significances in the worldwide GW detector network. The design sensitivity of the three GW detectors are shown in Fig.**??**. As shown in the figure, the sensitivity of KAGRA below 10 Hz is the best among three detectors. The predicted GW signal of the known spinning pulsars are shown in Fig. 2. As shown in Fig. 2, the frequencies of many of the GWs from the pulsars are below 10 Hz, where only KAGRA has the sensitivity for the GW signal, and actually only KAGRA can detect the GW signals from some of such pulsars with the designed sensitivity. Second significance is the improvement of the duty cycle of the GW detector network. If KAGRA join to the detector network as the fourth detector, the duty cycle, when more than three detectors are in operation, is approximately 80 %. Also, KAGRA will improve the ability to localize the GW sources. By using the Monte Carlo simulation, the sky localization accuracy with three detectors as well as with four detectors are calculated. According to this calculation, the sky localization accuracy improves to 9.5 $\text{deg}^2$ from 30.25 $\text{deg}^2$.

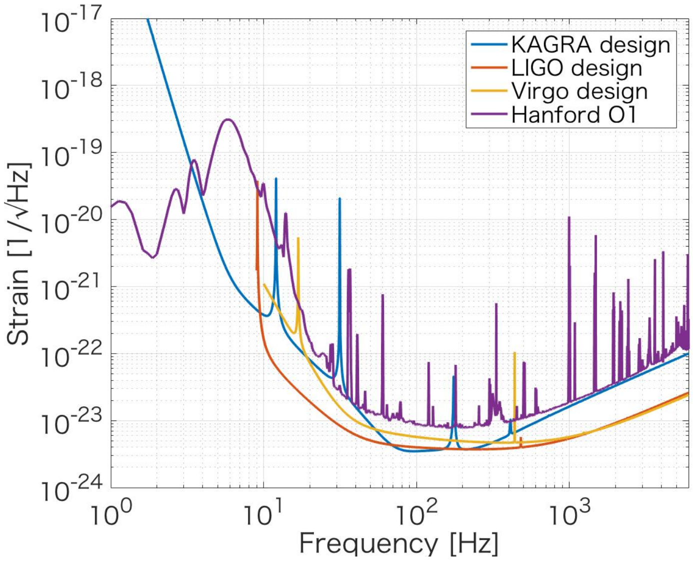


Figure 1: Sensitivity curves of each detector. The designed sensitivity curves of KAGRA (blue), LIGO (red), and Virgo (yellow) are shown, together with the measured sensitivity of the Hanford site (magenta) in the first observation run (O1) of aLIGO in 2015.

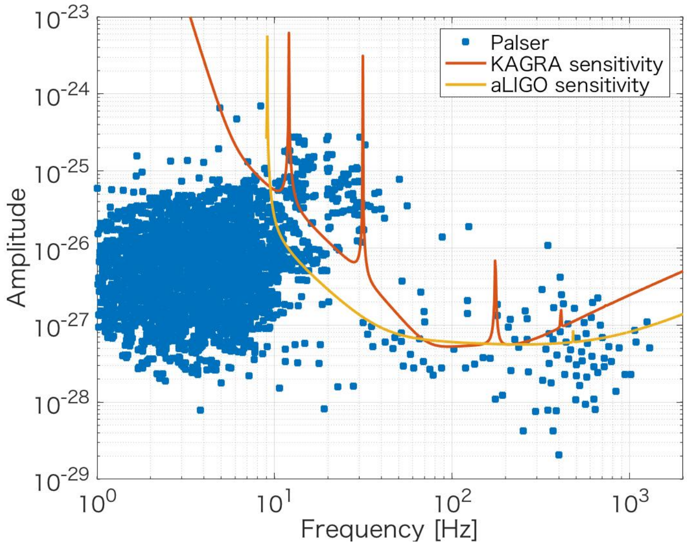


Figure 2: Predicted GW signals from pulsars with the KAGRA and aLIGO designed sensitivities with 1 year observation.

The participation of KAGRA in the GW detector network is an urgent matter in the development of the GW astronomy. Currently, the intention of KAGRA to participate in the third observation of aLIGO and AdV (O3) scheduled in 2019 was announced. Each subgroup is in the process of developing a system that can achieve the required sensitivity for O3 participation.

We have developed one of such a subgroup, the input optics. The input optics aims to provide stable light to the main interferometer. Frequency and intensity fluctuations of the laser light can be noise which limits the sensitivity of the detector. Therefore, the laser light needs to be stabilized, and the input optics performs the laser intensity stabilization, the laser frequency stabilization, the beam jitter reduction and spatial mode cleaning.

The input optics consists of the following optical components: the pre-mode cleaner (PMC), the reference cavity (RC), the modulation system, the input mode cleaner (IMC), the input Faraday isolator (IFI) and the input mode matching telescope (IMMT). The PMC is a bow-tie shaped rigid optical cavity which is responsible for spatial mode cleaning of the laser beam, the intensity noise reduction in the radio frequency (RF) band, and the reduction of the beam jitter. The RC is a rigid linear cavity used for the frequency stabilization as the laser frequency reference. The control signal of the main interferometer is obtained using the PDH method. The PMC, the RC, and the modulation system are on a single optical table placed in the air, and this table is called the pre-stabilized laser (PSL) table. The light emitted from the PSL table is incident on the IMC. The IMC is a large triangular cavity with a round trip length of 50 m. It is not only responsible for cleaning the laser spatial mode but also used as a frequency reference more stable than the RC. The light emitted from the IMC enters the main interferometer via the IFI that isolates light entering into and reflected from the main interferometer. The IMMT matches the laser spatial mode to the eigen-mode of the main interferometer.

The author is responsible for the design, the installation, the investigation, and the integration of the PSL and the IMC. The PSL and the IMC are the main part of the input optics, and almost all stabilization is done with the PSL and the IMC. The theme of this thesis is the installation and the investigation of the frequency stabilization system (FSS), which is one of the most important systems in the input optics. The FSS has two requirements; one is the requirement for the duty cycle of 95%, and the other is the requirement for the frequency noise of 1 Hz/$\sqrt{\text{Hz}}$ at 100 Hz. The frequency noise needs to have a smaller contribution to the GW sensitivity than other fundamental noises such as the quantum noise, the thermal noise, and the seismic noise. The control of the FSS is automated, and it is possible for the FSS to keep locked for approximately a week. Furthermore, even once the lock gets lost, the FSS can return to the locked state within 1 minute. Therefore, the FSS of KAGRA satisfies the requirement for the duty cycle.

Each actuator of the FSS is calibrated by using several transfer function measurements, and a model of the FSS is constructed. The noise budget has been made based on the model, and the noises which limit the frequency stability in almost all bands are identified. The noises included in this noise budget are as follows: the frequency noise of the laser source, the shot noise, the electronics noises in the photodetectors and the control servos, the length fluctuations of the cavities used as the frequency references, the phase noise of the voltage-controlled oscillator(VCO) used as the driver for the acousto-optic modulator(AOM), and the residual amplitude modulation (RAM) noise. We simulate the optimization of the control configuration with the model of the FSS. From this simulation, it is shown that the IMC length fluctuation by the seismic motion is dominant at the frequencies below 100 Hz, and that the RAM noise and the VCO phase noise at the higher frequencies than 100 Hz. Furthermore, the RAM noise and the VCO phase noise don′t satisfy the requirement at the higher frequencies than 2 kHz. However, the noises can meet the requirement in the frequency band below 1 kHz where the GW signals are expected. The estimated frequency noise is shown in Fig.3. Moreover, by installation of the pre-mode cleaner (PMC), using the phase noise improved VCO, and adding the faster actuator such as the electro-optic modulator (EOM) to the second loop, those noises can be improved and satisfy the requirement in the whole frequency band.

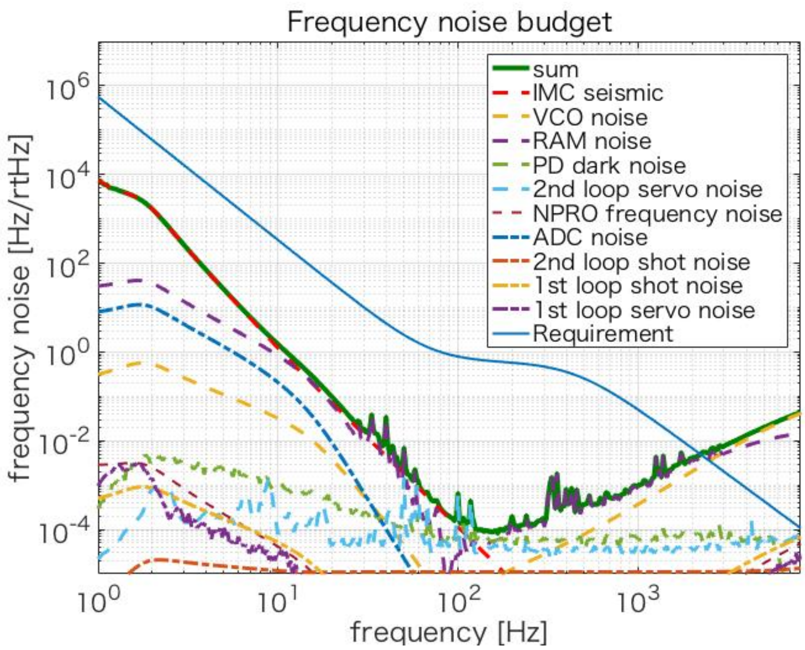


Figure 3: Noise budget of the frequency noise. The IMC seismic noise and the RAM noise are dominant at the frequencies below 100 Hz. In contrast, above 100 Hz, the RAM noise and the VCO noise are dominant, and they meet requirement below 2kHz, where GW signals are expected from compact objects. The seismic noise of the RC and the residual gas noise of the RC are not included in this plot because those noises are much lower than other noises.