PROCEEDINGS OF SCIENCE

Study of Newtonian noise from the KAGRA cooling system

Rishabh Bajpai,[a,*] **Takayuki Tomaru,**[a,b,c] **Toshikazu Suzuki,**[c] **Kazuhiro Yamamoto,**[d] **Takafumi Ushiba**[e] **and Tohru Honda**[c]

[a] *National Astronomical Observatory of Japan,*
2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

[b] *Department of Astronomy, Graduate School of Science, The University of Tokyo*
2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

[c] *High Energy Accelerator Research Organisation,*
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

[d] *Department of Physics, University of Toyama,*
Toyama, Toyama, 930-8555, Japan

[e] *The University of Tokyo Institute for Cosmic Ray Research Kamioka Observatory,*
Higashimozumi 238, Kamioka, Hida, Gifu 506-1205, Japan

E-mail: rishabh.bajpai@nao.ac.jp

Large-scale Cryogenic Gravitational-Wave Telescope, KAGRA, is a second-generation gravitational-wave detector (GWD) in Japan. The features distinguishing KAGRA from other GWDs are its underground location and the cryogenic operation of the four main mirrors. The underground location provides a quiet site with low seismic noise, while the cryogenic operation cools the mirrors down to 20 K, reducing the thermal noises. However, as cooling system components are relatively heavy and in close proximity to the test masses, oscillation of gravity force induced by their vibration, so-called Newtonian noise, could contaminate the detector sensitivity. Therefore, we used the results from the vibration analysis of the KAGRA cryostat at 12K to estimate cooling system Newtonian noise in the 1-100 Hz frequency band.

In this talk, we present methods, considerations, calculations and results of Newtonian noise estimation. Since cryogenics will be a key technology employed in third-generation detectors like Einstein Telescope, the findings can guide the design of the cryogenic infrastructure of these third-generation detectors.

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1. Introduction

KAGRA [1, 2] is a second-generation interferometeric Gravitational wave detector (GWD) located in Gifu, Japan. The optcial confirguration of the detector is a dual-recycled Fabry Perot Michelson, like other second-generation GWDs. However, features of KAGRA that distinguish it from LIGO [3] and Virgo [4] are it's underground location and use of cryogenics to cool the sapphire test masses (TM) down to 20 K. The underground location provides a site with low seismic vibration and Newtonian noise, while cooling the TM reduces the thermal noise. KAGRA is also called a 2.5 generation detector, since the underground site and cryogenics are key features for thrid-generation detector like Einstein Telescope (ET) [5].

While the background seismic motion at KAGRA site is relatively small, TM still need to be suspended to achieve sufficient isolation. The four sapphire TMs is KAGRA are suspended from 13.5 m, nine-stage vibration isolation system called the Type-A suspension [6]. The top five stages of the suspension are kept at room temperature and isolate the cryogenics part from seismic motion. The bottom four stages (including the mirror) are called the cryogenic payload and cooled down to 20 K. The key challenge for KAGRA was to cool the cryogenic payload without injecting external vibrations. This was made possible with the development of KAGRA cryostat [7]. The KAGRA cryostat is a double-radiation shield cryosat cooled down by four low-vibration pulse tube cryocooler [8] as shown in fig. 1. The cryogenic payload is cooled down to 100 K via thermal radiation and to 20 K through conduction cooling via thin 6N (99.9999% pure) aluminum heat-links.

In 2021, vibration analysis of KAGRA cryostat [9] was conducted. We observed that the vibration of the cooling infrastructure was 2-3 orders of magnitude larger than the seismic motion. Furthermore, The coupling of this vibration to the cryogenic payload via heat-links was found to be well attenuated below the current design sensitivity [9]. However, we suspected that Newtonian noise (NN) coupling of this vibration could be a noise source.

Newtonian noise is caused by fluctuation of local gravitational fields around the TM due to fluctuating mass distributions. Some sources of Newtonian noise are the seismic waves, vibrating objects and atmospheric fields [10–13]. As the cooling system (CS) components are relatively heavy and in close proximity to the mirror, NN induced by their vibration could contaminate the detector sensitivity. Therefore, we evaluated the NN of KAGRA cooling system. Here, we present the results of our calculation and discuss the impact of this NN on KAGRA sensitivity.

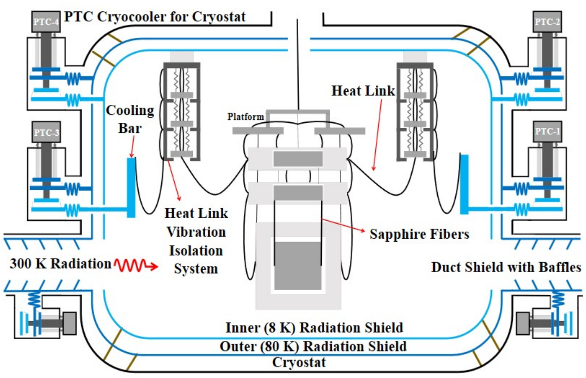


Figure 1: Schematic of KAGRA cooling system.

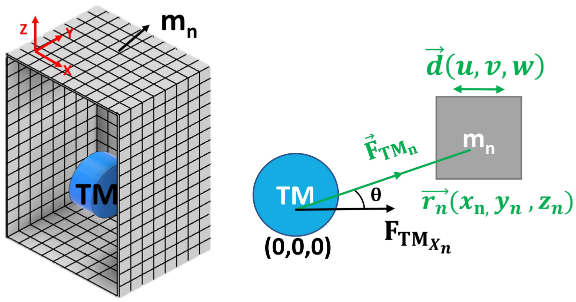


Figure 2: A simple hollow cuboid cooling system used to formulate the Newtonian noise expression.

2. Derivation of Newtonian Noise Expression

To derive the NN expression, we consider a simple hollow cuboid cooling system with the TM (of mass M) at origin, substituted as a point-mass as shown in fig. 2. The cooling system is then split into an N element mesh where each element is substituted as a point mass weighing m_n. Now, the gravitational force on TM along X-axis (optical) due to a mesh point mass at $\vec{r_n}(x_n, y_n, z_n)$ is:

$$F_{\mathrm{TM_{X_n}}} = GMm_n \frac{x_n}{(x_n^2 + y_n^2 + z_n^2)^{\frac{3}{2}}} \tag{1}$$

If mass m_n moves/vibrates with $\vec{d}\,(= u(t)\hat{i} + v(t)\hat{j} + w(t)\hat{k})$, the fluctuation in $F_{\mathrm{TM_{X_n}}}$ will be;

$$\nabla F_{\mathrm{TM_{X_n}}} = F_{\mathrm{TM_{X_n}}} \cdot \vec{d} \tag{2}$$

A detailed derivation of cooling system NN expression can be found in [14]. By adding up the contribution of force fluctuation due to each element of the mesh we get the force fluctuation due to the entire cooling system in time-domain, from which the amplitude spectral density (ASD) of force fluctuation is calculated. Multiplying the ASD with the constant, $\frac{\sqrt{4}}{M\omega^2 L}$ gives us the Cooling System Newtonian noise strain as,

$$\sqrt{S_h(\omega)} = \frac{\sqrt{4}G}{\omega^2 L}\sqrt{A^2 S_u(\omega) + B^2 S_v(\omega) + C^2 S_w(\omega)} \tag{3}$$

where, G is gravitational constant, L is the arm-length, ω is the angular frequency, $S_u(\omega)$, $S_v(\omega)$, and $S_w(\omega)$ are power spectral densities of the cooling system vibration along X, Y and Z axis and it is assumed they have no correlation between them and A, B and C are constant depending on the geometry with values; $A = \sum_{n=1}^{N} m_n \left[\frac{-2x_n^2+y_n^2+z_n^2}{(x_n^2+y_n^2+z_n^2)^{\frac{5}{2}}}\right]$, $B = \sum_{n=1}^{N} m_n \left[\frac{-3x_n y_n}{(x_n^2+y_n^2+z_n^2)^{\frac{5}{2}}}\right]$ and $C = \sum_{n=1}^{N} m_n \left[\frac{-3z_n x_n}{(x_n^2+y_n^2+z_n^2)^{\frac{5}{2}}}\right]$, respectively. Since, similar vibration coupling with no correlation for all four test masses is expected, a factor of $\sqrt{4}$ is multiplied.

3. Newtonian Noise of KAGRA Cooling System

3.1 Calculation

Figure 3 shows the cross section of KAGRA cryostat with the components whose NN was evaluated. To calculate the NN these components were meshed in Ansys and the values of A, B

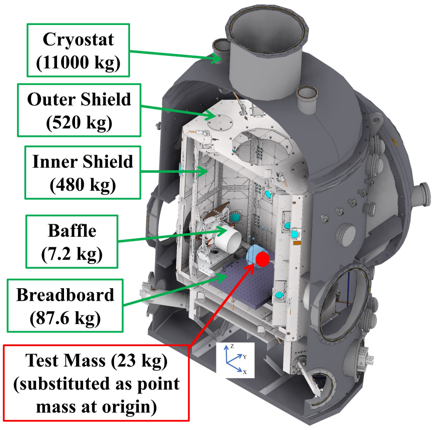


Figure 3: Cross-section of KAGRA cryostat showing the components considered for Newtonian noise calculation.

and C were calculated using an APDL (Ansys Parametric Design Language) code. The calculated values can be found in Table I of citation [14]. It was found that the values of $A \gg B$ or C. Therefore, only vibration along X-axis was considered to evaluate the NN of KAGRA cooling system. Then eq. (3) is reduced to;

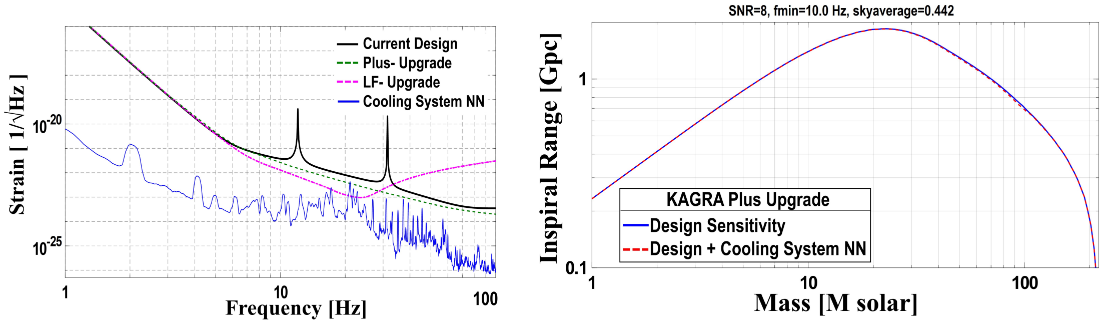
$$H_{\mathrm{NN}} = \frac{\sqrt{4}G}{\omega^2 L} \times \sqrt{S_u(\omega)} \times A \tag{4}$$

where, H_{NN} and $\sqrt{S_u(\omega)}$ are the NN strain (in $1/\sqrt{\mathrm{Hz}}$) and vibration spectral density along X-axis (in $\mathrm{m}/\sqrt{\mathrm{Hz}}$) of the component under consideration, respectively. The largest contribution to NN comes from breadboard followed by radiation shields, cryostat and baffle. The details of the components meshes, vibration spectra and other assumptions are described in [14].

3.2 Impact

Cooling system NN is evaluated as the sum of NN from individual components and is plotted as solid blue spectrum in fig. 4(a). Furthermore, the cooling system NN is below the current design sensitivity of KAGRA (black spectrum). Therefore, it does not limit the current inspiral range of the detector as shown in fig. 10 (a) in [14].

Different future upgrades have been proposed for KAGRA in [16]. Figure 4(a) also shows the sensitivity curve for two such upgrades KAGRA LF and Plus for low and broadband frequency sensitivity improvement, respectively. Comparing the upgraded design sensitivities with the cooling system NN, it can be seen that some of the peak around 16-30 Hz are larger then the upgraded sensitivities. The most probable upgrade scenario is KAGRA Plus which introduces high power laser, 100 Kg test mass and frequency dependent squeezing. To evaluate the impact of cooling system NN, the inspiral range of KAGRA Plus with and without the NN noise is plotted in fig. 4(b) using the code in [15]. This comparison shows that no science is lost due to cooling system NN as it has minimal impact on the Plus inspiral range. Note that even for KAGRA LF and Plus NN calculations TM is assumed to be a point mass and the geometrical size effect of 100 kg TM is not considered.



(a) (b)

Figure 4: (a) Comparison of current and upgraded KAGRA design sensitivity with calculated Cooling System Newtonian Noise. (b) Comparison of KAGRA Plus inspiral range with and without cooling system Newtonian noise. Note that the X-axis represents mass of a component object, assuming equal mass binaries.

4. Conclusion and Future Work

From the vibration analysis of the KAGRA cryostat a 2-3 orders of magnitude increase in the radiation shield vibration at cryogenic temperature was observed. Since the cooling system components are heavy and in relatively close proximity to the mirror we evaluated the Newtonian noise injected by the KAGRA cryostat. Our calculations show the cooling system NN has negligible impact on current KAGRA sensitivity and only minimal impact KAGRA upgrade (plus) sensitivity. An important point to note is that the current model does not take into account the size effect of TM. This is because in the current ANSYS model the TM is not meshed but substituted as a point mass. Therefore, the calculated NN is underestimated. We are improving the model to include the test mass mesh to include the TM size effect. While the cooling system NN is not an issue for KAGRA it could limit the sensitivity of third-generation GWDs like ET. Therefore, it will be important for detectors like ET to suppress the vibration of their cooling system and consider the distance between cooling infrastructure and TM during the design phase.

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