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Stray-light control in the interferometric gravitational-wave telescope KAGRA

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In this presentation, we introduce stray-light mitigation in the KAGRA gravitational-wave (GW) telescope. Since the third observation run (O3) in 2020, we have completed overhaul of the interferometer system to improve the observable distance for various gravitational-wave sources by reducing unwanted noises in the signal output. Among such noise sources, stray light dominated mid-range frequency in the interferometer's output like the other GW telescopes. Some optical baffles against the stray light had been located in the arm cavities of the interferometer before O3, so this time we focused on treatment of the vertex area where the GW signals are extracted due to interference of two light beams from the arm cavities with each other. We performed ray trace simulation, designed new optical baffles, and installed them for the obvservation run in May-June 2023.

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1. Introduction

In most optical systems, stray light is one of the last-standing problems that would reduce their performance of them without proper treatments. The situation is the same for KAGRA [1], the gravitational-wave (GW) telescope in Japan. Like the other GW telescopes such as LIGO and Virgo, KAGRA is also a laser interferometer, in which the tiny ripples of space time, the gravitational waves, will be converted to phase fluctuations of the laser light.

After the third observation run (O3GK) in 2020, we analyzed the output noise from KAGRA. The analysis showed that at the mid frequency range, which should be the best sensitive range, seemed dominated by stray-light noise [2].

Since before starting O3GK, several types of optical baffles have been incorporated into the KAGRA interferometer. They are mainly installed in the two arm cavities, each of which is a Fabry-Perot resonator having a length of 3 km [7]. Because the arm cavities are the most sensitive transducers from the GWs to light phase modulation, the stray light measures were thoroughly done at that time.

The central part of the interferometer, however, has not been sufficiently done regarding the stray light countermeasure. The main optical component of the central part is a beam splitter (BS), at which the light beams coming back from the two arm cavities are interfere with each other, and the phase difference in the light beams would be remained to make a signal light and then brought into the light detection part (antisymmetric port).

In addition to the BS, there are six important mirrors in the central part. Among them, PRM, PR2, and PR3 are to form a power-recycling optical cavity, with which the input power can be recused to increase the GW sensitivity. SRM, SR2, and SR3 are to form a signal-recycling optical cavity, with which the sensitive frequency range can be optimized. Now the KAGRA interferometer becomes so sensitive that stray light within these central components would affect the performance.

To overcome this problem, we performed ray trace simulation in the interferometer. Using the results, we designed new optical baffles dedicated for those mirrors, and installed them before starting the latest observation run (O4a).

2. Non-sequential ray trace

Unwanted light beams, or ghost beams, are generated at each mirror, which has a high-reflectivity (HR) surface and a anti-reflection (AR) suface. Although its high reflectivity, a fraction of light power transmits though the HR surface and reaches the opposite surface, or the AR surface. Then this transmission of light becomes a ghost beam. Again, although the AR surface has a small reflectivity, a fraction of the light power reaching at the AR surface would be reflected off to become additional unwanted light beams. They are also ghost beams.

Accordingly, each optic would generate infinite number of ghost beams in theory. An infinite is not suitable for computer simulation such as ray trace. If possible, we should determine a threshold of light power (or a ratio with respect to that of the main beam) of the ghost beam so that we can truncate the series of them under consideration. It is, however, difficult to determine the threshould clearly. The stray-light noise is proportional to a product of (a) light power recombined to the main beam and (b) the secondary (or higher-order) scatterers' movement. When the movement is larger

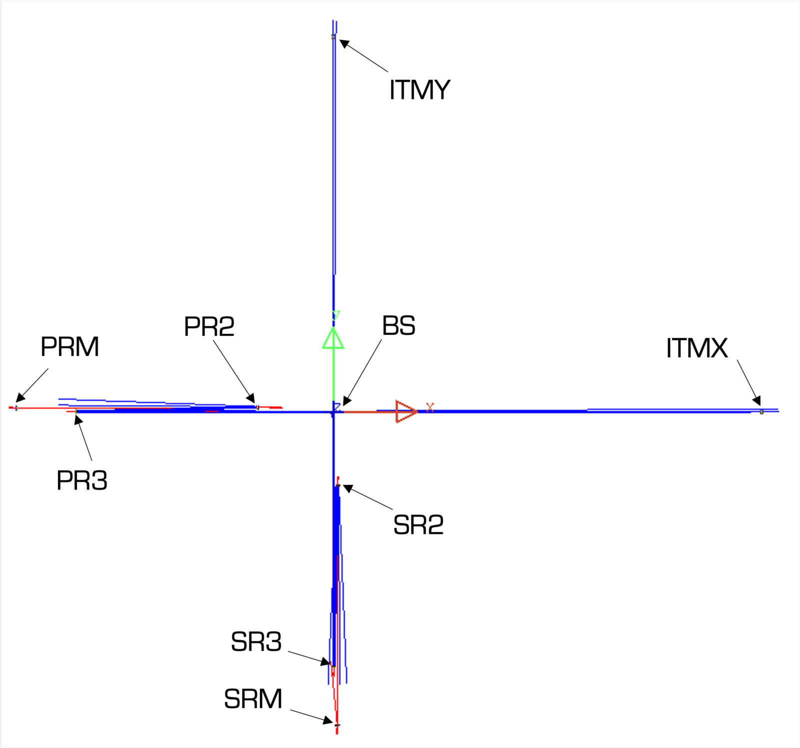

Figure 1: Overview of the central part of the KAGRA interferometer with the main (drawn in red) and ghost beams (in blue). The abbreviations of the mirrors are explained in the main text.

than the light wavelength, which is 1064 nm for our case, the contribution of the movement in effect should be folded by a sine function.

We started with setting *working* threshoulds for the ghost beams to be traced. In the ideal case, this is a ratio of 1 ppm with respect to the main beam concerned, but sometimes it is mitigated to around 10 ppm to take a balance of the ideal design and the real world. Fig. 1 shows an overview of the result of the ray trace in the central area of the KAGRA interferometer[1]. The main beam is drawn in red, while the ghost beams in blue. ITMX and ITMY are names of the mirrors at the entrance end of each arm cavity; the expanded names are input test mass in the X direction and in the Y direction, respectively.

For example, the detail of the rays around the SR2 mirror is shown in Fig. 2, where “MB” stands for the main beams, while the other names are to identify each ghost beam one by one. An obstacle left above SR2 is a virtual optical stop used only for the simulation. In the end, an actual optical baffle will be located here. In the same manner, the detailed analysis was performed for the other mirrors shown in Fig. 1.

Our usage of the ray trace here is unique. In the usual cases, to identify which parts are illuminated by the ghost beams, an array of rays would be launced from the first scatterer in the simulation, and then, for example, the resultant illuminance (sometimes even a wavefront) on the other surfaces would be reconstructed. Our light source is, however, a coherent laser source, and evolves in the fundermental Gaussian (or TEM00) mode. There is a method to do ray-trace

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[1] The ray trace was done with *LightTools* by Synopsis.

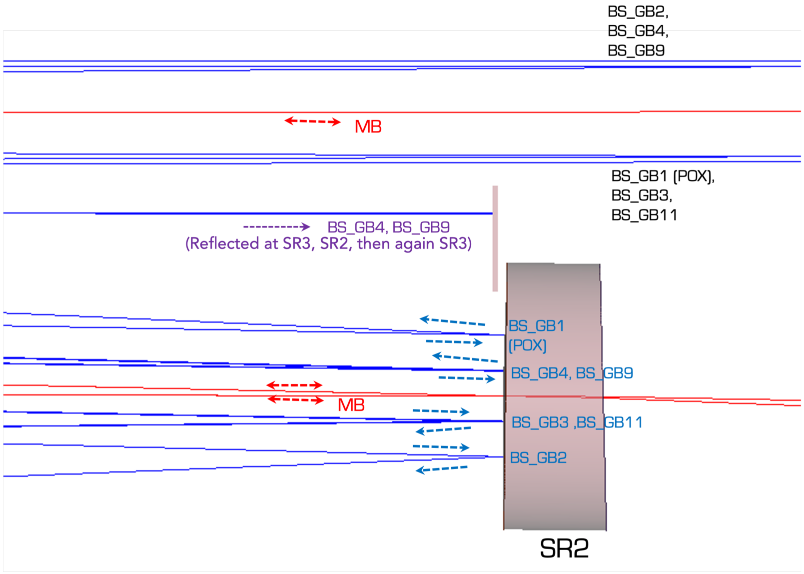

Figure 2: Detailed situation around SR2. MB in red shows a central axis of the main beam. The other names are to identify each ghost beam one by one.

simulation even for TEM00 beams by using a set of rays [4, 5], but we avoided to adopt it. There are several reasons for this avoidance, and a practical one is that the number of rays to be managed becomes too much. If there would be a software package including a function of the non-sequential ray trace with such sophisticated methods, it would be helpful for this kinds of design. Alternatively, Each traced ray in Fig. 1 is mere the central axis of each light beam. Even with this situation, as shown in Fig. 2, still many rays have to be concerned.

Giving up the automatic assignment of “width” information to these main and ghost beams with such sophisticated methods, we manually attached the width to each of the beams afterwards by passing all the beam axes information to the mechanical CAD. In this situation, the width is the usual 3σ of the Gaussian distrubution at the location, and calculated from the TEM00 evolution by hands. Using the information, new optical baffles were designed.

3. Design of the optical baffles

The conceptual design of the new optical baffles is to reflect the ghost beams off the main optical plain. The light beams in the interferometer around in Fig. 1 are s-polarized, and so it corresponds to a p-polarized light with respect to the vertically tilted optical baffles. Fig. 3 shows such a typical case for PR2, for example [6]. Here the black tilted screen is the optical baffle, which is located in front of the HR surface of the PR2 mirror. In fact, there is another optical baffle at the AR side of PR2 as well.

To pass the main beams through, some of the baffles require appropriate apertures. The minimum aperture size depends on the mirror, because the main beam widths on the mirrors are desparate with each other. On the other hand, if the aperture becomes too large, unwanted ghost beams cannot be shut. Considering these conditions, we determined the aperture sizes by typically

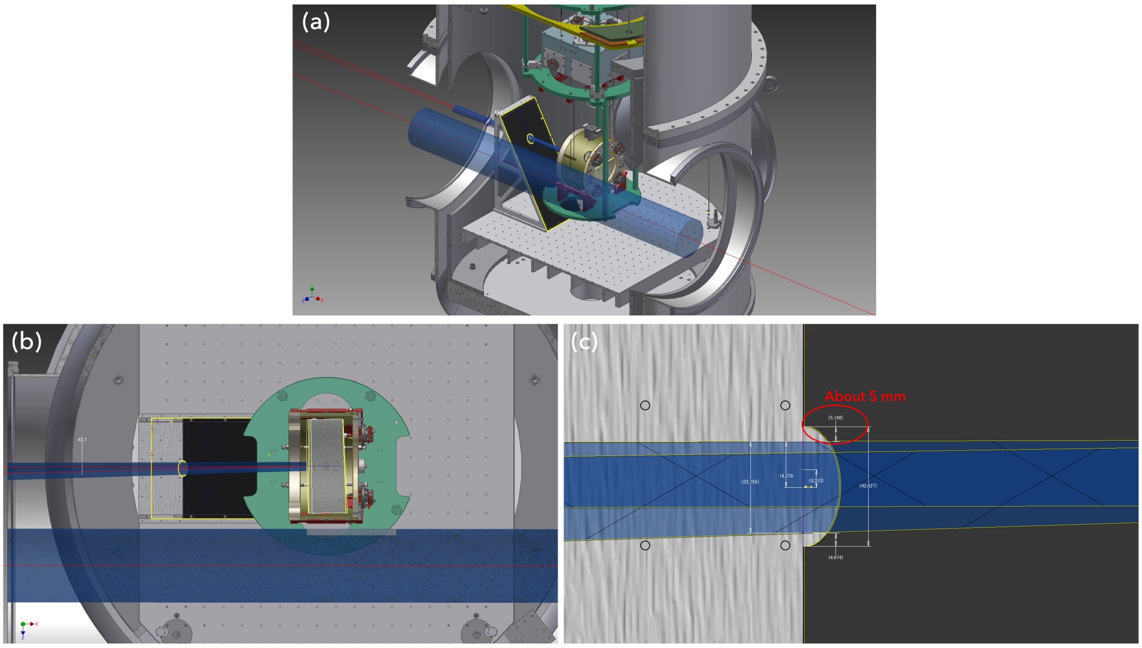

Figure 3: (a) Relative positions of the PR2 mirror, the optical baffle for the HR surface, and the other mechanics surrounding them. (b) Cross sectional top view of (a). (c) Close view of (b) around the aperture. Not shown in this figure, but there is an additional baffle located at the AR side of PR2.

setting only a few millimeter gaps around the main beam widths. For example, as shown in Fig. 3 (c), the gap is about 5 mm for the PR2 HR-side baffle. The narrower gaps would increase the difficulty of their installation, so we also considered the feasibility of the installation procedure at the same time when tuning the gaps in design.

As already discussed, the motion of the secondary scatterers, which is in this particular case the PR2 HR-side baffle, also contributes to the noise due to the stray light. To reduce the motion, the baffles are fixed on relevant suspended tables. This table can be also seen in Fig. 3.

The surface finishing of the baffles is with *Solblack* reported in the paper [7]. Not only the screen plates, but also the structure frames and screws for assembly are all coated with this black material. The examples of the products are found in Fig. 4. This figure shows that the assembled optical baffles are stocked on a table in a clean room at Advanced Technology Center of National Astronomical Observatory of Japan. Finishing test assemblies there, we once disassembled them, and packed into dedicated guard boxes. Then they were shipped to the KAGRA site afterwards.

4. Installation

As already discussed, due to the small gap of the aperture around the light beam passing, the installation of the baffles needs relevant accuracy. To make a visible and reproducable mapping of the beam spot on the free space, we prepared serveral kinds of jigs. Newly designed beam target plates were fabricated and often used. The target plates have mechanical interfaces useful for reproductive positioning of them with respect to the suspended mirrors. Referring the target plates,

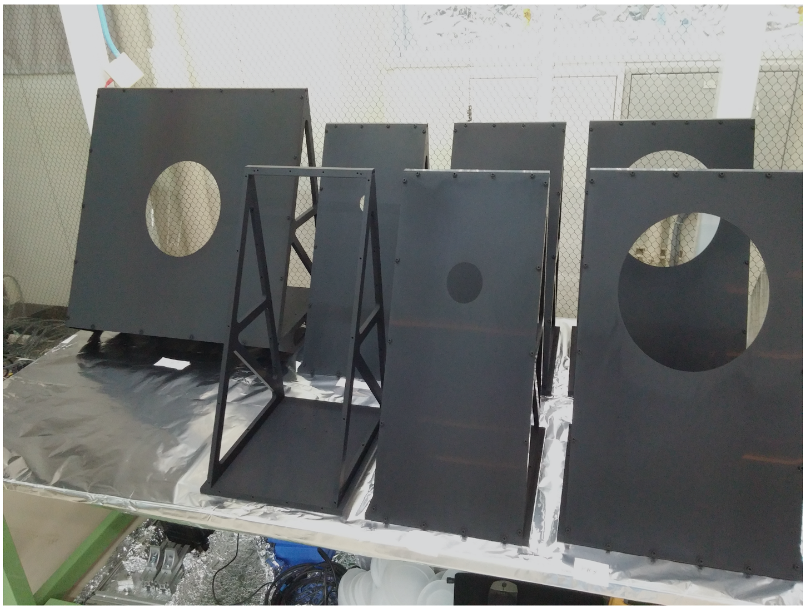

Figure 4: Various kinds of the newly-designed baffles stored in a clean room at Advanced Technology Center of National Astronomical Observatory of Japan.

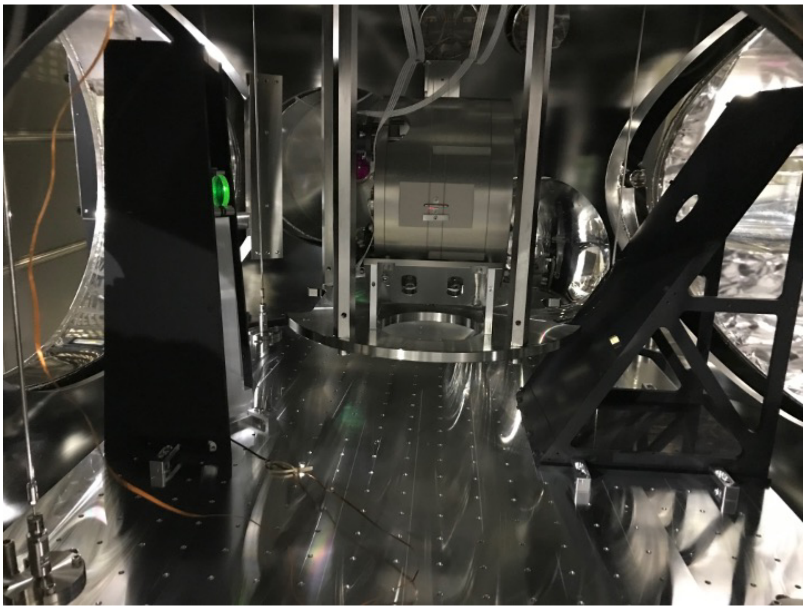

Figure 5: The baffles installed on a suspended table both at the HR and AR sides of the PR2 mirror. There seems a steering mirror (shining in green as illuminated by the green laser light) installed on the same suspended table.

and using laser levels, we were able to align the main beams and then the baffles as well within a sufficient, a few millimeter accuracy.

As shown in Fig. 5 (but not yet shown in Fig. 3), there is a steering mirrors standing on the same suspended table on which the baffles are located. The steering mirrors are for main beams, so their alignment should not be affected due to the additionally installed baffles. This is a difficult work. To do so, the required balance or ballast weights were calculated, and prepared in advance. The lengths of the wires suspending the table were properly tuned. The steering mirror in Fig. 5, which is shining in green as it is illuminated by auxiliary green laser beams. This steering mirror is to align the green beam to the 3-km end, so the balance of the suspended table has to be particularly cared.

The sufrace finishing of the baffles, Solblack, is so fragile [7]. We should not touch the important surface, or the screen plates, as much as possible. For precise alignment of the baffles, some handling jigs were also prepared.

All the planned baffles have been installed before starting the latest observation run, O4a. A detailed analysis of the baffle effects are not yet done, but the noise level at the relevant frequency range got better in the lates observation run (O4a) than that of O3GK (to be reported in other talks). Not all of this improvement would be due to those baffles, but it can be true that the baffles do not reduce the sensitvity of the interferometer.

5. Conclusions

We learned that the mid-frequency range of the KAGRA interferometer output would be contaminated by stray-light noise during O3GK. We prepared new baffles to be installed in the central area of the interferometer for the improvement of the the noise level. These baffles have been installed as planned. In the latest observation run, O4a, the sensitvity at the relevant frequency range seems improved.

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