PROCEEDINGS OF SCIENCE

Stray light noise simulations for the Einstein Telescope and Virgo and the use of instrumented baffles

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We present an estimation of the noise induced by scattered light inside the main arms of the Einstein Telescope (ET) gravitational wave detector. Both ET configurations for high- and low-frequency interferometers are considered. As is already the case in the existing experiments, such as LIGO and Virgo, optically coated baffles are used to mitigate and suppress the noise inside the vacuum tubes. We propose baffle layouts for ET and compute the remaining scattered light noise contribution to ET sensitivity. Virgo has introduced the novel concept of instrumented baffles, with the aim to implement active monitoring of the stray light distribution close to the main mirrors. We present the technology and the comparison of the data with simulations, and show their potential to monitor the performance of the mirrors, the presence of defects and point absorbers in the mirror substrates, and to assist in the pre-alignment of the arms.

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1. Introduction

Scattered light is one of the sources of noise for gravitational wave interferometers. Proper ways to mitigate it have been needed in LIGO, Virgo and KAGRA, but still further studies are carried out in order to better understand this phenomenon. For the case of Virgo, numerical simulations and an instrumented baffle around the input mode cleaner (IMC) have been used to this end [1–4]. Similarly, new instrumented baffles are planned to be installed around the end test masses (ETM) of the Fabry-Pérot (FP) cavities of Virgo before O5 [5]. Since this problem is also expected to affect third-generation detectors, like the Einstein Telescope (ET), a thorough study must be made to ensure that it does not compromise the expected sensitivity [6].

In this proceeding, we review the instrumented baffle installed around the IMC in Sec. 2, we present the latest simulations carried out to the assess the merit of the ETM instrumented baffles in Sec. 3 and we present a first estimation of scattered light noise in the main arms of ET in Sec. 4.

2. Review of the IMC instrumented baffle

In Spring of 2021, an instrumented baffle was installed around the end test mass of the IMC cavity of Virgo [3]. This instrumented baffle has been taking data since then, allowing for an analysis of the scattered light.

Simulations of the expected field inside the cavity were performed in order to compare them with the data taken by the instrumented baffle. These simulations, first presented in Ref. [1], performed with the fast Fourier transfrom (FFT) code called static interferometer simulations (SIS) [7], include the effect of the measured mirror maps of the three mirrors that form the IMC cavity. These simulations, when compared to the real data measurements, display very good agreement. This comparison is shown in Fig. 1.

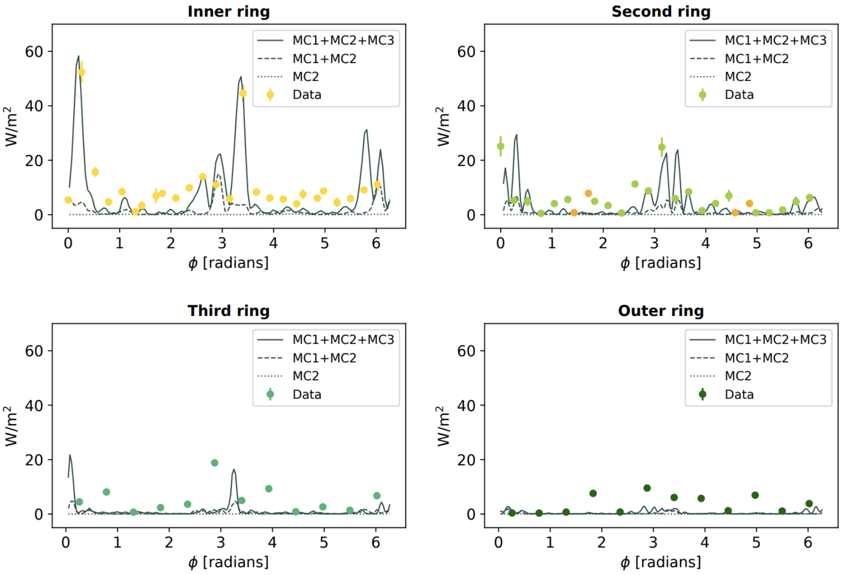

Figure 1: Comparison between the data measured by the instrumented baffle of the IMC and the simulations. Image extracted from Ref. [3].

Especially for the baffle inner ring of photodiodes, the positions of the peaks are well predicted by simulations. It also points out that there is a strong effect on the scattered light field depending on the mirror maps added, as the noninclusion of one of them leads to very different distributions of light, none of which is compatible with the measured one. This comparison between data and simulations allows also to validate the code and the hypothesis performed by the numerical tools.

At the same time, another important point is to make sure that the presence of the baffle does not degrade the performance of the cavity. The long-term behavior displays that the temperature measured by the sensors of the baffle stabilize rapidly after the laser is turned on. Figure 2 shows the temperature evolution of some sensors over a period of four months, indicating this long-term stable behavior needed for an instrument of this kind.

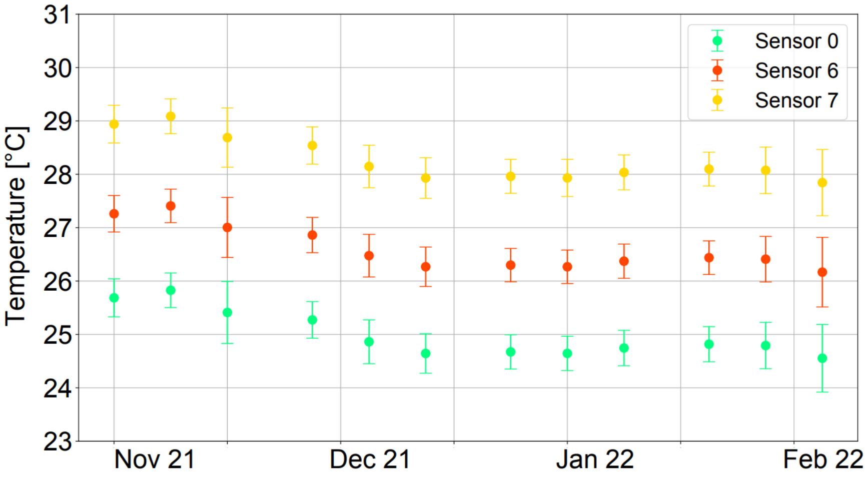

Figure 2: Evolution of the temperature of three representative sensors over the span of four months. Sensor 7 is the one closest to the controller and, therefore, the one dissipating the highest heat. Image extracted from Ref. [4].

For further details regarding the mechanics, the sensors, the electronics, the optical and vacuum compatibility tests, the data acquisition system, the calibration of the photdiodes and the installation of the baffle, the reader is referred to Ref. [4].

3. Simulations for the ETM instrumented baffles

Between O4 and O5, Virgo has planned major improvements to the interferometer. One of such is to extend the technology presented and demonstrated in the IMC towards the ETM of the FP cavities. Since the upgrades will include also a change in other parameters of the cavity, detailed numerical simulations are needed in order to assess the merit of installing the baffles around the ETM as well as to aid in the design. A correct prediction of the level of light to which the various sensors will be exposed to can help in the decision of the model to be employed and the region where they have to be calibrated.

These simulations, also performed with SIS, show that the nominal configuration distribution is the one shown in Figure 3. The first four layers of sensors are expected to receive a power in the range of 1 – 100 μW, while the last layer experiments a sharp drop in power and would measure around 1 nW. This effect is caused by a cryobaffle in front of the ETM that clips the field.

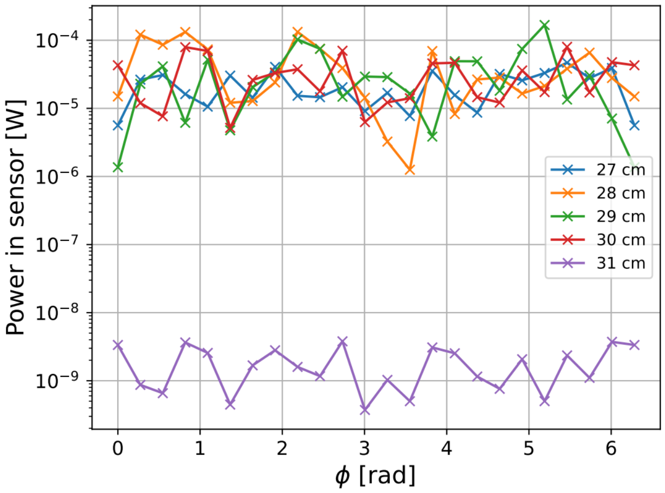

Figure 3: Power measured in each photodiode of the instrumented baffle around the ETM planned for O5 in nominal configuration as predicted by the simulation. Image extracted from Ref. [5].

This baffle can also be used to detect non-ideal conditions of the cavity. For example, if there is a given misalignment inside the cavity, the power reaching the sensors will be different. It can be also simulated using the SIS code and the results for a misalignment of the laser of 8×10^{-7} rad along the x direction is shown in Figure 4.

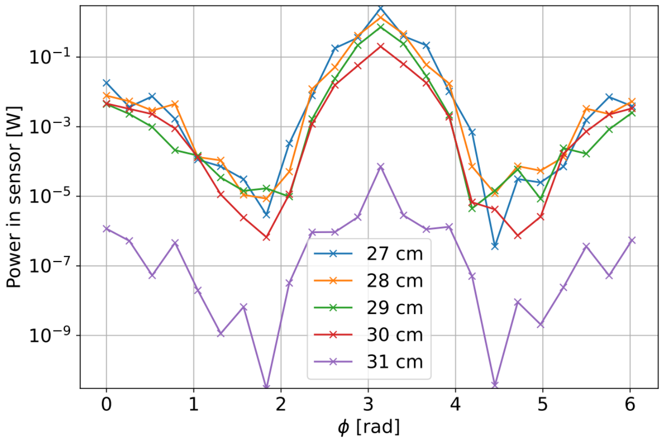

Figure 4: Power measured in each photodiode of the instrumented baffle around the ETM planned for O5 with a misalignment of the laser of 8×10^{-7} rad along the x direction as predicted by the simulation. Image extracted from Ref. [5].

These results show that the distribution of power reaching the instrumented baffles is significantly different from the one in nominal configuration, allowing for the detection of the degradation of the cavity. At the same time, as shown in Ref. [5], this distribution changes with the amount of misalignment and its direction, and it also differs if there is a point absorber present in either mirror.

Therefore, installing an instrumented baffle around the ETM can be used to monitor the scattered light in different conditions. It can also be used for pre-alignment tasks, as the power measured by the sensors is highly dependent on the cavity conditions.

4. Baffle design for ET

Following with all the knowledge acquired during the design and operation of LIGO, Virgo and KAGRA, the design of the baffles for the main arms of ET can be made. The idea to decide the position of each baffle is that of shielding all possible tube surfaces from the mirrors. Therefore, all photons scattered by the mirrors should impact a baffle instead of any other surface. This reasoning produces a recurrent formula to obtain the position of the baffles inside the main arms, as argued in Ref. [6].

Using this argument with the baseline configuration parameters, the number of baffles per FP cavity is of 244 for the high frequency (ET-HF) configuration and of 222 for the low frequency (ET-LF) one [6]. Once the position of these baffles has been set, the noise generated by them can be computed. There are mainly two contributions to the stray light noise: the backscattering and diffraction generated by the baffles. The first of them refers to the process of photons reaching back any of the mirrors after having scattered in the baffles. The latter refers to the noise created by the finite aperture of the baffles that clips the field and generates a diffraction pattern that can pile up and limit the sensitivity.

Both noises can be modeled and quantified to obtain an estimate of the noise. Using SIS simulations, the backscattering can be computed using the procedure described in Ref. [6]. Similarly, the diffraction can be computed analytically taking into account the serration of the inner edges of the baffles, something done to destroy the coherence among them.

Two important assumptions need to be made in order to obtain these estimations. The first is that regarding the quality of the mirrors expected for ET. Since there is currently no information available on the polishing and coating that the mirrors will have, the assumption that has been made is that the quality expected for the mirrors of Virgo in O5 will be maintained for ET. If this quality can be improved for ET, the estimations here shown can be regarded as conservative. The second one is that regarding the movement of the baffles. Scattered light noise depends on the spectrum of displacement of the baffles. This information is yet unavailable as there is no information of the transfer function between the ground and the baffles. Therefore, the seismic noise measured in the two candidate sites (Sardegna and the Euregio Rhein-Maas) are used. In both cases, though, the phase-wrapping effect is taken into account as in Ref. [2].

The results using the parameters defined in Ref. [6] are displayed in Fig. 5. They show that the diffraction noise is more relevant than the backscattering one in all configurations and proposed sites, but the total noise is still below the safety margin of one order of magnitude less than the expected sensitivity. This implies that the scattered light is expected to be subdominant at all frequencies provided that the recommendations presented in Ref. [6] are met.

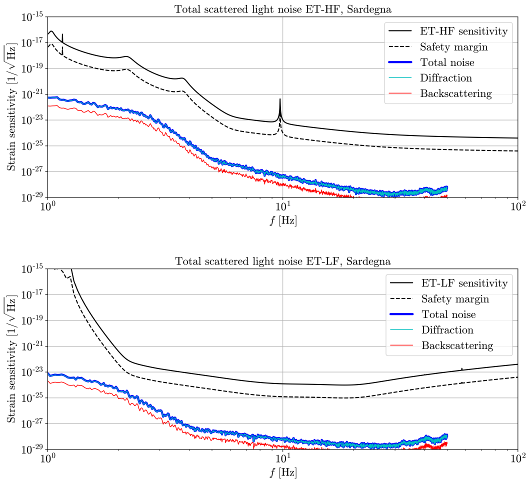

Figure 5: Stray light noise due to diffraction effects (cyan lines), backscattering effects (red lines), and the total noise (blue lines) as a function of frequency compared to the anticipated (top) ET-HF and (bottom) ET-LF sensitivity curves (black lines) and the corresponding 1/10 safety margin (dashed lines). The results are computed using the seismic noise data from (left) the Sardegna site and (right) the Euregio site. Images extracted from Ref. [6].

5. Conclusions

In this proceeding we have reviewed the IMC instrumented baffle, proving its use and its long term stability. Furthermore, the data that this baffle has taken is in agreement with the numerical simulations performed with an FFT based code. Then, the simulations for the O5 configuration of Virgo have shown that instrumenting the baffle surrounding the ETM can measure the scattered light distribution in nominal conditions while being also sensitive to the presence of a misalignment. Finally, a preliminary estimation of the stray light noise of ET has been shown. The results show that provided some recommendations are met, the levels of noise do not compromise the projected sensitivity.

References

[1] A. Romero-Rodríguez et al., *Determination of the light exposure on the photodiodes of a new instrumented baffle for the Virgo input mode cleaner end-mirror*, *Class. Quantum Grav.* **38** (2021) 045002.

[2] A. Romero-Rodríguez et al., *Determination of the Stray Light-Induced Noise from the Baffle in the Cryogenic Trapping Area of Advanced Virgo in O5*, *Galaxies* **10** (2022) 86.

[3] O. Ballester et al., *Measurement of the stray light in the Advanced Virgo input mode cleaner cavity using an instrumented baffle*, *Class. Quantum Grav.* **39** (2022) 115011.

[4] M. Andrés-Carcasona et al., *Instrumented baffle for the Advanced Virgo input mode cleaner end mirror*, *Phys. Rev. D* **107** (2023) 062001.

[5] A. Macquet et al., *Simulations of light distribution on new instrumented baffles surrounding Virgo end mirrors*, *Class. Quantum Grav.* **40** (2023) 077001.

[6] M. Andrés-Carcasona et al., *Study of scattered light in the main arms of the Einstein Telescope gravitational wave detector*, *arXiv:2307.14104 [gr-qc]* (2023) .

[7] A. Romero and H. Yamamoto, *SIS20-Overview*, Tech. Rep. LIGO-T2000311-v2, LIGO (2021).