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The challenge of low frequency sensitivity in ground-based GW detectors

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Abstract. This paper describes the current performances of the ground based interferometric gravitational wave (GW) detectors in the low frequency region (from 10 Hz to 100 Hz). The detectors' design sensitivity, where only fundamental noises contribute, is currently not achieved by any of them, which are instead limited by control noise. In the following, the current status of these detectors is described, together with the status of the research aimed to improve the low frequency limit in view of the next generation detectors.

1 Introduction

Within the context of Gravitational Waves (GW) detection, interferometric GW detectors have revolutionized astrophysics over the past decade, allowing the detection of relevant cosmic events that were previously unobservable. These instruments are based on the principle of the Michelson interferometer with the addition of resonant Fabry-Pérot cavities, in which the main optical components (i.e. test masses, TM) are suspended as free-falling bodies, which also helps to isolate them from the seismic disturbances. In order to be able to detect the weak signal of a gravitational wave, it is necessary that such optical components are positioned in the so-called working point, in which the mirrors are kept steady with respect to each other with enough accuracy in terms of residual motion, e.g. deviation from the operating point along the optical axis. Such requirements are typically of the order of $10^{-12} \div 10^{-16}$ m for longitudinal degrees of freedom (DOFs), and 10^{-9} rad for angular ones [1]. Since the free motion of the suspended elements is orders of magnitude larger, specific feedback control systems are necessary to sense and keep the elements in the correct operating point. As a consequence of the implementation of such feedback systems, control noise becomes one of the main offenders spoiling the detector sensitivity at low frequency, below 40 Hz. By addressing control noise, we aim to significantly improve the sensitivity of gravitational wave detectors at low frequencies, thereby enhancing our capability to detect and analyze gravitational waves from a wider range of astrophysical sources, especially in view of third-generation detectors, which aim to further improve these noise limits. This work provides an overview of the current status of low-frequency noise for the second-generation detectors, noise reduction techniques,

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and future perspectives in overcoming control noise challenges to improve gravitational wave astronomy.

2 Present status: Advanced LIGO and Advanced Virgo

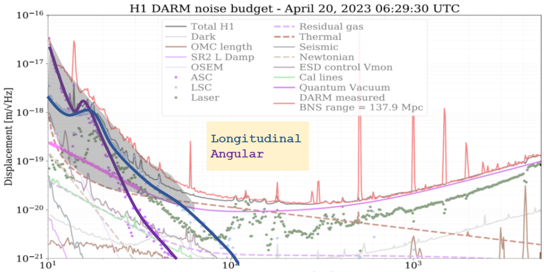

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Figure 1. Example of a noise budget for the current ground based detector Advanced LIGO. The gray shadow highlights the contribution of control noises. Cyan and violet lines correspond to longitudinal and angular control noise respectively.

Reaching an optimal sensitivity at low frequency is very important in order to be able to detect new gravitational signal sources, such as continuous waves emitted from isolated neutron stars or binary systems long before merging, and obtaining better parameter estimation of binary systems during the inspiral phase.

The low frequency design sensitivity is fundamentally limited by a variety of noise sources such as seismic/newtonian, suspension thermal and radiation pressure [2], but none of the present detectors in operation, like Advanced Virgo and Advanced LIGO [3, 4], has ever reached the design sensitivity, being limited by control noise, see Figure 1 [5].

In the following subsections, a brief description of the currently limiting control noises is given, explaining how they couple to the main GW signal.

2.1 Longitudinal and angular Control noises

The detector shows its best sensitivity only if the main optical components are kept in precise microscopic positions, defined as auxiliary DOFs, that are: the resonance of the long arm cavities for the fundamental mode of the carrier field, the resonance of the Power Recycling cavity, the anti-resonance of the Signal Recycling cavity, the MICHelson DOF in destructive interference and the mirrors aligned with respect to the main beam.

The mirrors usually move orders of magnitude more than the required residual motion of the suspensions; this forces us to implement feed-back control loops to reduce the mirror motion and to hold them in the designated working point. This leads to the inevitable reintroduction of control noise in the detection band. The auxiliary longitudinal control DOFs couple to the main GW signal due to the presence of opto-mechanical couplings [6].

To cope with the longitudinal control noise one can act in a number of ways: reducing the optical defects to improve the couplings of the auxiliary DOFs; improving the photodiode sensing noise (by designing better electronics or increasing the impinging power to enhance

the sensor signal to noise ratio); improving the controller roll-off in the detection band [1]; implementing feed-forward techniques [7, 8]; implementing online diagonalization between auxiliary DOFs [9].
For the angular DOFs, the coupling is indirect, since their control noise couples into the longitudinal DOFs through the beam/mirror decentering with respect to the actuation center, generated by the residual angular displacement. The actual recipe to minimize angular control noise, apart from the one already mentioned for longitudinal control, is to minimize the longitudinal coupling by means of the dithering technique [10] or by implementing the angle/length feed-forward technique [11].

2.2 Non-linear Control noise

As described in the previous section 2.1, the contribution of the linear noises can in principle be nulled by implementing a subtraction technique, which is not the case for non-linear noises.
The non-linear behavior of this type of noise is due to the fact that the coupling of the various auxiliary DOFs can be modulated at low frequency due to oscillations in the working point, which are generally due to alignment fluctuations. These noise contributions cannot be suppressed using standard feed-forward techniques, which act in the linear regime, but they can be mitigated by improving the accuracy in the modulating DOFs, or by using noise regression methods that predict the noise through witness channels. This method can be used to determine complex non-linear noise couplings in the detector signals [12]. Studies are on-going to implement a non-linear noise suppression in the GW signal [13, 14].
In complex optical systems such as GW detectors, stray light is usually one of the main sources of non-linear noise. Not only for direct coupling to the sensitivity, but also through auxiliary DOFs, an example is visible in [15]. This noise can be mitigated by optimizing the optical system, i.e. by reducing the reintroduction of the stray light into the main beam either by reducing the displacement noise of the scattering surface, or by implementing non-linear noise subtractions.

3 Future perspectives

For the next generation detectors, such as the Einstein Telescope [16, 17] and the Cosmic Explorer [18] detectors, the low frequency sensitivity is extremely challenging and several orders of magnitude of improvement in that region are required.
First of all the fundamental noises have to be reduced:

- *The seismic noise* has to be better suppressed at lower frequencies with respect to the performance of the current detectors [19].
- *The suspension thermal noise* has to be reduced, for example by operating in cryogenic conditions.
- *The gravity gradient noise* has to be reduced, for example by installing the detector underground [20].

However, as it has been described in the previous sections, the future detectors will be unlikely limited by fundamental noises, as the control noise re-introduction will be still the major offender. The solution for this problem is to have a larger suppression of the seismic motion at low frequency, to strongly reduce the control bandwidths. In order to achieve this,

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[1] These actions are valid also to reduce the angular control noise.

several R&Ds are on-going, covering several aspects.
One of the main lines of research is focused on the pre-isolation of the suspensions to reduce the residual motion of the optical components that have to be controlled [21, 22]. The inter-lock of platforms can indeed reduce the longitudinal residual motion by 3 orders of magnitude, and the residual angular motion to 1 nrad/$\sqrt{\text{Hz}}$ at 100 mHz.
Moreover, studies are on-going about implementing the use of very large test masses to reduce the radiation pressure noise and the angular control noise [23] [2].
As it has been described before, also the non-linear noises have to be addressed such as the stray light noise [25]. Last but not least, the magnetic noise has to be mitigated to reach the target sensitivity by designing the detector to be magnetic noise free, implementing better grounding of the electronics, avoiding noisy electronic devices close to the main optical components and implementing passive magnetic shields [26].

4 Conclusions

In this paper the state of the art of the techniques implemented in the present detectors to improve the low frequency limit in the sensitivity is described, as well as the on-going research for the future detectors. The main offenders have been identified as the control noise, due to both longitudinal and angular controls, and the non-linear noise (stray light and non-linear couplings of auxiliary DOFs).
The mitigation of these noise contributions will be even more challenging for the next generation of gravitational wave detectors, but the strong R&D efforts from the entire GW community bring great hope for overcoming the low-frequency barrier.

References

[1] “The longitudinal control for the Advanced Virgo Plus gravitational wave detector” (PhD Thesis, Università di Trento, December 2022) M. Valentini https://tds.virgo-gw.eu/ql/?c=18934

[2] The Virgo Collaboration, "Advanced Virgo Plus Phase I Design Report", Virgo-Technical DocumentatSion System, Report No. VIR-0596A-19 (2019) https://tds.virgo-gw.eu/ql/?c=14430

[3] EPJ Web of Conferences 280, 08005 (2023) https://doi.org/10.1051/epjconf/202328008005

[4] Aasi, J. et al., 2015, ”Advanced LIGO”, Class. and Quant. Gravity 32(7), 074001, doi:10.1088/ 0264-9381/32/7/074001

[5] E. Capote LHO logbook entry n38869 https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=68869

[6] E N Tapia San Martín et al 2023 Class. Quantum Grav. 40 185008 DOI 10.1088/1361-6382/aceb4e

[7] B. Swinkels, E. Campagna, G. Vajente, L. Barsotti and M. Evans "Longitudinal noise subtraction: the alpha-, beta- and gamma-technique" Virgo note VIR-0050A-08 https://tds.virgo-gw.eu/ql/?c=2055

[8] Virgo logbook entry https://logbook.virgo-gw.eu/virgo/?r=60841

[9] van Dael et al 2024 Class. Quantum Grav. https://doi.org/10.1088/1361-6382/ad7cb9

[10] A.Allocca, et. al. “Interferometer Sensing and Control for the Advanced Virgo Experiment in the O3 Scientific Run”, Galaxies , vol.8, n.4, https://doi.org/10.3390/galaxies8040085

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[2] The high moment of inertia of the test masses reduces the Sidles/Sigg mode frequency, i.e. the radiation pressure effect [24]. Lower angular mode frequencies imply the need of a lower angular control bandwidth.

[11] J. Driggers “Controls Issues in Advanced LIGO”, GWADW 2019 https://agenda.infn.it/event/15928/timetable/?view=standard#73-control-issues-in-advanced

[12] C. F. Da Silva Costa et al 2018 Class. Quantum Grav. 35 055008. https://doi.org/10.1088/1361-6382/aaa536

[13] Yu, Hang, e Rana X. Adhikari. 2022. «Nonlinear Noise Cleaning in Gravitational-Wave Detectors With Convolutional Neural Networks». Frontiers in Artificial Intelligence 5: Art. No. 811563.

[14] G. Vajente, Y. Huang, M. Isi, J.C. Driggers, J.S. Kissel, M.J. Szczepańczyk, and S. Vitale Phys. Rev. D 101, 042003 – Published 18 February 2020

[15] Virgo logbook entry https://logbook.virgo-gw.eu/virgo/?r=63491

[16] M. Punturo et al., Class. Quantum Grav. 27, 194002 (2010)

[17] ET steering committee, ET design report update 2020, (ET Technical Documentation System), ET-0007B-20https://apps.et-gw.eu/tds/ql/?c=15418

[18] E. D. Hall et al., “Gravitational-wave physics with Cosmic Explorer: Limits to low-frequency sensitivity”, Phys. Rev. D 103, 122004 (2021)

[19] F. Fidecaro et. al. "A novel concept for seismic attenuation systems in gravitational wave detectors" GWADW 2023. https://agenda.infn.it/event/32907/timetable/?view=standard_inline_minutes#115-a-novel-concept-for-seismi

[20] J F J van den Brand et al 2010 J. Phys.: Conf. Ser. 203 012076. https://doi.org/10.1088/1742-6596/203/1/012076

[21] "Active platform stabilization with a 6D seismometer” Appl. Phys. Lett. 121, 174101 (2022)

[22] S. M. Koehlenbeck, et. al. ”A study on motion reduction for suspended platforms used in gravitational wave detectors.” Sci Rep 13, 2388 (2023). https://doi.org/10.1038/s41598-023-29418-x

[23] B. Lantz "100 kg optic with upgraded suspension for LIGO A#” GWADW 2023. https://agenda.infn.it/event/32907/timetable/?view=standard_inline_minutes#132-heavy-suspension-designs-f

[24] A.Sidles, D.Siggs, "Optical Torques in Suspended Fabry-Perot Interferometers", Physical Review Letters, vol.354, no.3, pp.167-172, 2006.

[25] “Stray light noise simulations for the Einstein Telescope and Virgo and the use of instrumented baffles” https://doi.org/10.22323/1.449.0551

[26] Site-selection criteria for the Einstein Telescope. Rev. Sci. Instrum. 91, 094504 (2020). https://doi.org/10.1063/5.0018414