GR24-AMALDI16 IOP Publishing
Journal of Physics: Conference Series **3177** (2026) 012089 doi:10.1088/1742-6596/3177/1/012089

Methodological approach to evaluate control requirements for gravitational wave detectors

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Abstract. The assessment of the requirements for the maximum allowable displacement of optics (both in RMS and within the detection band) is a crucial aspect of designing a new gravitational wave detector. Since these requirements must be defined in order to ensure an optimal performance of a detector, they should account not only for the residual motion of the optics but also for potential defects that could degrade the overall detector response. This study plays a fundamental role in the design of suspension, sensors and thermal compensation systems. In this work, we present a methodological approach for computing these requirements, which can serve as a guiding principle for the design of all gravitational wave detectors.

1 Introduction

The Advanced Virgo+ detector is planned to undergo an upgrade in the coming years to the so-called *for O5 configuration* [1], implementing stable recycling cavities to mitigate sensitivity to optical aberrations. This upgrade will entail substantial modifications to the interferometer's optical configuration and, consequently, to its sensing and control architecture.

A sophisticated control system is required to maintain the main optical components at the optimal working point, both in longitudinal and angular directions, in order to satisfy the resonance conditions of the various optical cavities. Meeting these conditions is essential to achieve the detector target sensitivity and to maximize the duty cycle for data taking.

In the control scheme design process, a fundamental parameter is the maximum allowable deviation of each controlled degree of freedom (dof) from its working point, herein referred as the *control accuracy requirement.*

For the longitudinal dofs, the control accuracy requirement is conventionally derived from the linewidth of the respective cavities to be stabilized [2]. The maximum allowable displacement of the corresponding mirrors is typically set to a small fraction of the linewidth, on the order of 0.1%. For the angular dofs, the requirements are defined such that the beam–mirror decentering induced by mirror misalignment does not exceed 0.1 mm, thereby ensuring optimal overlap between the cavity optical axis and the incoming beam.

CARM		**PRCL**		**MICH**		**SRCL**	
1×10^{-8} m		5×10^{-12} m		3×10^{-10} m		2×10^{-9} m	
IB tilt		**IB shift**		**PRM$_1$**	**PRM$_2$**	**PRM$_3$**	
2 nrad		10 μm		100 nrad	100 nrad	30 nrad	
BS	**SRM$_1$**	**SRM$_2$**	**SRM$_3$**	**DIFF(+)**	**COMM(+)**	**DIFF(-)**	**COMM(-)**
50 nrad	100 nrad	100 nrad	100 nrad	2 nrad	2 nrad	100 nrad	100 nrad

Table 1: Standard accuracy requirements for the longitudinal and angular degrees of freedom. The description of the various dofs are shown in [5]

In Table 1 the standard requirements are shown [2] [3]. The longitudinal degrees of freedom, shown in the first line, are: CARM (Common Arm length), PRCL (Power Recycling cavity length), MICH (central interferometer differential length) and SRCL (Signal Recycling cavity length). The angular degrees of freedom are shown in the second and third lines, as: IB tilt and shift (tilt and shift of the Input Beam), PRM$_x$ (the x-mirror in the Power Recycling cavity), SRM$_x$ (the x-mirror in the Signal Recycling cavity), DIFF(+)/(-) (the *hard* and *soft* [4] differential modes of the Arm cavities) and COMM(+)/(-) (the *hard* and *soft* common modes of the Arm cavities) [5].
These requirements are largely arbitrary, with no quantitative assessment of the actual impact of a mistuned operating point on the detector's performance. In this work, we propose an alternative methodology for defining accuracy requirements, based on evaluating the performance degradation induced by deviations from the optimal operating point.

2 New principles to set the accuracy requirements

A deviation from the optimal operating point induces variations in the overall detector response, specifically in the open-loop transfer function (OLTF) of the main gravitational-wave channel (DARM), which degrades the detector's performance [6]. Furthermore, such mistuning can increase the coupling of auxiliary degrees of freedom into the sensitivity. The accuracy requirements are therefore defined to satisfy the following criteria:

Longitudinal degrees of freedom

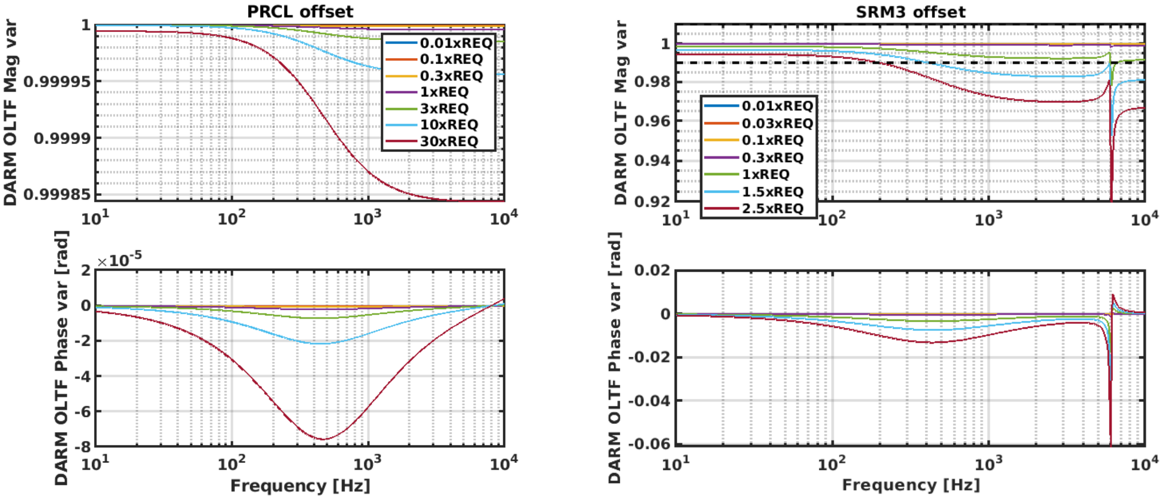
- The variation in the DARM OLTF must remain below 1%, consistent with the typical calibration error.
- The increase in auxiliary dofs-to-DARM coupling must remain below 0.2% in the 10–40 Hz band, where subtraction techniques are effective [7].
- The increase in coupling must remain below a factor of 2 above 50 Hz, ensuring that the incoherent sum of the five longitudinal dofs noise contribution remains below the target sensitivity. This assumes the design provides a safety margin of 10.
- The coupling requirement is relaxed linearly with frequency above 10× the unity gain frequency (UGF) of each loop, as the loop roll-off suppresses noise reintroduction in this regime. The UGFs expected for each longitudinal control loop, based on the Advanced Virgo+ Phase I experience, are reported in [8].

Angular degrees of freedom

- The variation in the DARM OLTF must remain below 1%.

3 Results and conclusions

The study of the effect of the mistuning of the working point has been carried out in Finesse3 [9], by adding a DC offset, proportional to the standard requirement on the locking signals of the longitudinal degrees of freedom or on the angular position of the optics, see Table 2, and evaluating the detector response (DARM OLTF) and the couplings to the sensitivity.



(a) Detector response variation, with respect to the optimal working point, for several PRCL offsets. The requirement used in this case (REQ) is 5×10^{-12} m. It is visible in this case that the 1% threshold is not reached even if the mistuning of the PRCL working point is increased of a factor 30. This means that the PRCL requirement could be safely relaxed of a factor 10, if all the other points listed in section 2 are fulfilled.

(b) Detector response variation for several SRM_3 misalignment. The requirement used in this case (REQ) is 100 $nrad$. It is visible in this case that the 1% threshold is crossed already for a factor 1.5 of the initial requirement meaning that the standard requirement is reliable. The notch feature at 6 kHz is still under investigation.

Figure 1: Example of DARM OLTF for PRCL and SRM_3 working point mistuning.

CARM		**PRCL**		**MICH**		**SRCL**	
$1{\times}10^{-7}$ m		5×10^{-11} m		3×10^{-9} m		6×10^{-9} m	
IB tilt		**IB shift**		**PRM_1**	**PRM_2**	**PRM_3**	
2 nrad		20 μm		200 nrad	200 nrad	60 nrad	
BS	**SRM_1**	**SRM_2**	**SRM_3**	**DIFF(+)**	**COMM(+)**	**DIFF(-)**	**COMM(-)**
50 nrad	200 nrad	200 nrad	100 nrad	4 nrad	4 nrad	100 nrad	100 nrad

Table 2: New requirements obtained evaluating the detector response.

Figure 1 presents an example of the DARM OLTF variation, relative to the optimal response, for PRCL mistuning and SRM_3 misalignment. The results indicate that the PRCL accuracy requirement can be relaxed without significantly degrading the detector response, whereas the SRM_3 misalignment tolerance cannot be increased.

A complete analysis, applying the principles outlined in Sec. 2 to all degrees of freedom, yields a revised set of accuracy requirements.

The proposed methodology provides a quantitative framework for defining control accuracy requirements, offering a key design input. It enables the relaxation of certain specifications, easing control-system design, and delivers a systematic tool for assessing the impact of operating-point deviations on detector performance and auxiliary degrees of freedom coupling. This approach is directly applicable to commissioning activities and can be generalized to other interferometer imperfections, including thermal and cold optical aberrations.

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