Requirements computation for the Low Frequency third generation gravitational wave detector

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ET design – Where to start?

- We are at the point of starting to work on the final design of ET
  - One of the key points of this design, and in particular for the Low-Frequency detector, is to calculate the requirements of the residuals of the different DOFs (mainly longitudinal and angular in this presentation)
  - These requirements will help us to evaluate the feasibility of the design, and to spot which are the critical points in order to reach the required sensitivity
- The target of this talk is to open a discussion on how should we calculate / establish the requirements for the 3rd generation of GW detectors
  - Give an overview of how are they presently computed and how do we deal with the critical points

Starting from our experience: Which *criteria are still valid* for the new detectors? ◊ Which have been our *weak points* and how can we avoid them already from the design?

Requirements from the DARM readout

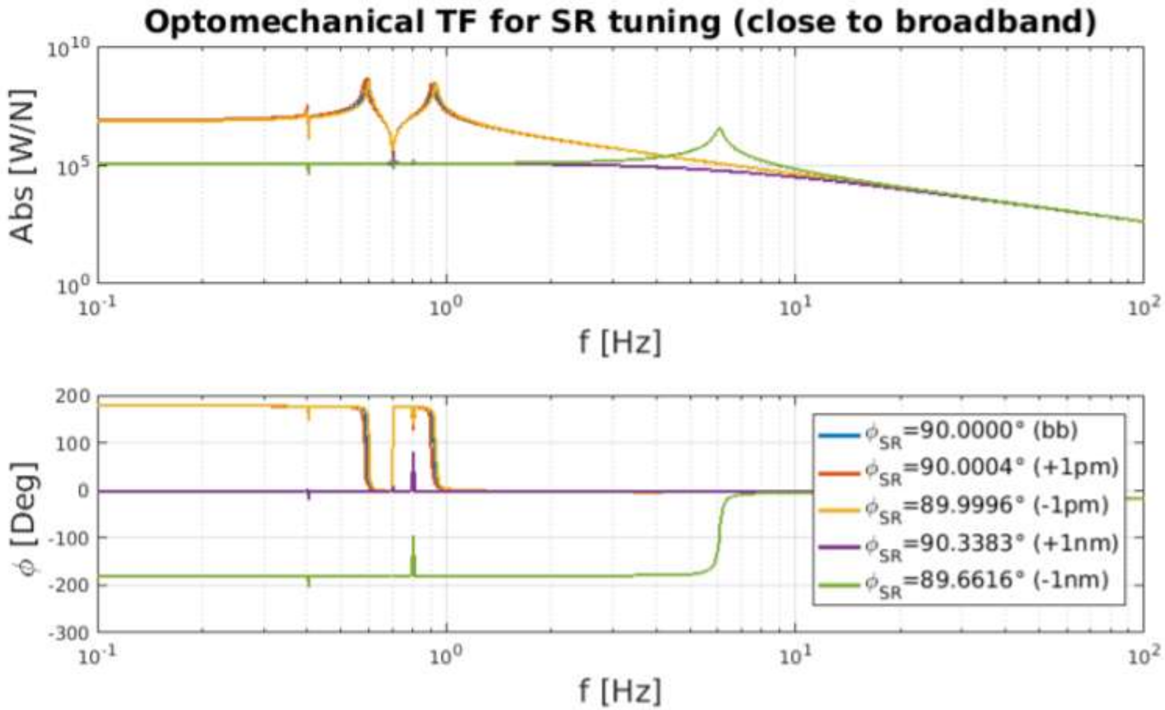
- The type of readout of the DARM dof will change the parameter with the most stringent requirements
  - RF readout [1,2]
    - Amplitude, phase and frequency noise requirements
    - Matching in order to have a good overlap
  - DC readout [3]
    - Up-conversion of low frequency noise around high frequency lines
  - Balanced Homodyne Detection[4]
    - Stability of the laser power
    - Overlapping of the two beams (Beam pointing problems)
    - Backscattering

It is relatively straightforward to evaluate the technical noises affecting DARM readout and to calculate the corresponding requirements

(1) DC readout experiment in Enhanced LIGO, T. Fricke et al., arXiv:1110.2815v2
(2) DC-readout of a signal-recycled gravitational wave detector, S. Hild et al., arXiv:0811.3242
(3) Advanced Virgo Length Sensing and Control steady state design, G. Vajente, VIR-0738A-11
(4) Balanced homodyne readout for quantum limited gravitational wave detectors, P- Fritschel et al., OSA 2014

Auxiliary DOFs

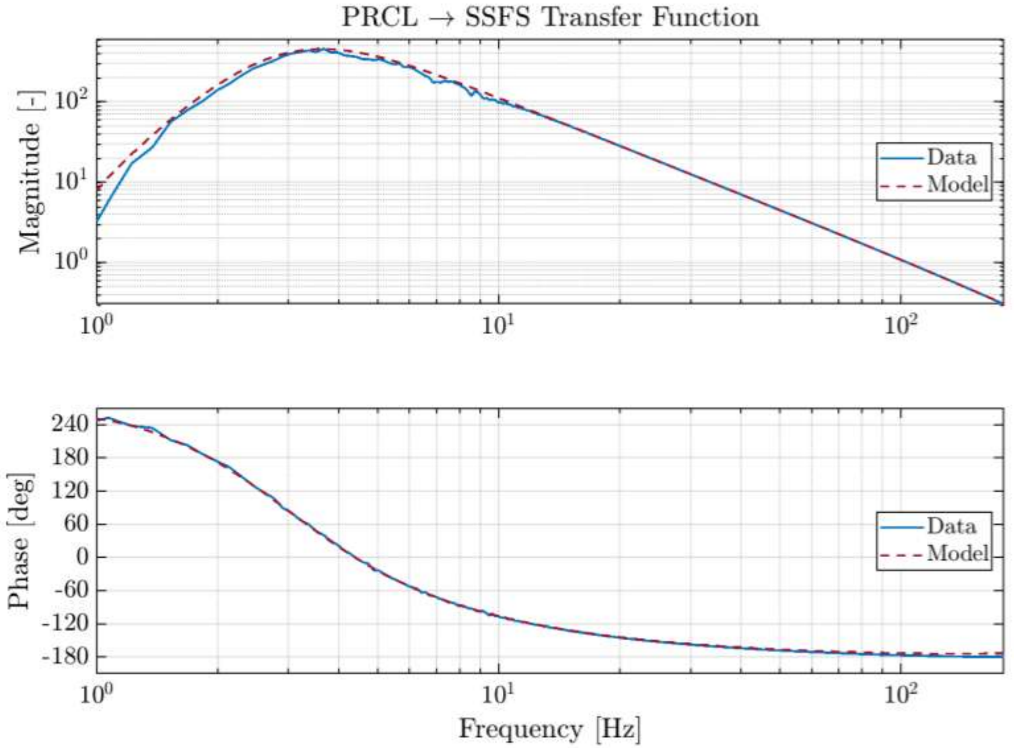
- **Direct couplings:**
  - The requirements on the residual motion of the Auxiliary DOFs are calculated based on their impact on DARM
  - Both because they spoil the residual of DARM or because they modify its TF (ex. SRCL to DARM[1])



(1) Optomechanical response of DARM in presence of Signal Recycling and radiation pressure, M. Boldrini et al., VIR-0210A-20

Auxiliary DOFs

- **Indirect couplings:**
  - Another criteria to be taken in account is the opto-mechanical cross-coupling between DOFs (ex. PRCL length noise impacts on CARM[2])
  - Also the off-diagonal terms of the sensing matrix will worsen the cross-coupling between Auxiliary DOFs



- This cross-coupling between DOFs has proven to be limiting the sensitivity in second generation detectors
  - So far we have mitigated this problem with active noise subtractions both online and offline -> Effectiveness is limited

(2) Interferometer Sensing and Control for the Advanced Virgo Experiment in the O3 Scientific Run, A. Alloca, D. Bersanetti et al., Galaxies, 2020

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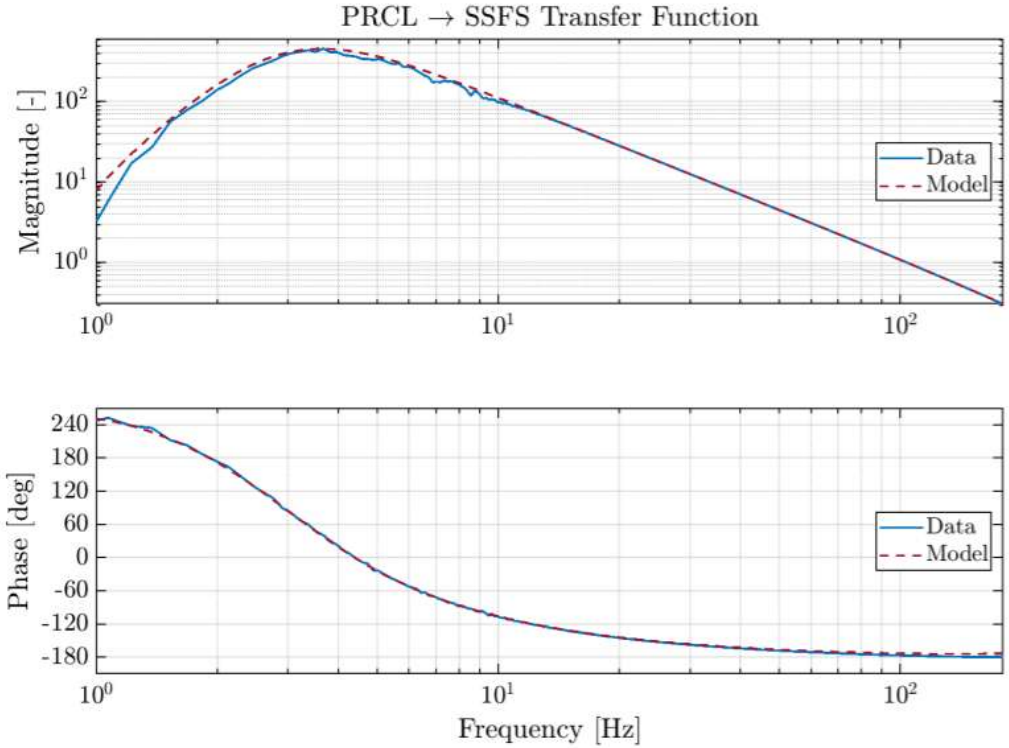

◊ Are noise subtractions still a solution for 3rd generation? ◊ Which requirements would be needed to target for negligible cross couplings? ◊ Perfect diagonal sensing? → To estimate the real impact of these couplings we need to *consider control loops, input noises, etc.*

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Global angular controls

- Coupling inside the detection band
  - The angular mirror motion and the beam spot motion couple into the length of the different DOFs[3,4] -> Usually limited by sensing noise

$$\hat{\Delta L}(f) = \hat{d}_{Spot}(f) * \hat{\theta}_{Mirror} \approx \hat{d}^{RMS}_{Spot} \times \hat{\theta}_{Mirror}(f) + \hat{\theta}^{RMS}_{Mirror} \times \hat{d}_{Spot}(f)$$

- Misalignments scatter into HOMs, decreasing the coupling of the fundamental mode
  - Limits on power and optical gain loss

◊ Is it possible to improve the noise on the wave-front sensors to lower control noises? ◊ Can we improve Seismic Isolation and reduce control bandwidth? ◊ Beam / mirror centering loops can help decreasing the Angle2Length coupling?

(3) Modeling of Alignment Sensing and Control for Advanced LIGO, L. Barsotti and M. Evans, LIGO-T0900511-v4
(4) Prospects for Detecting Gravitational Waves at 5 Hz with Ground-Based Detectors, H. Yu et al., PRL 2018

Non-linear couplings

- Non-linear couplings have also limited the performance of second generation gravitational wave detectors
  - Linear couplings changing in time (ex. modulated by angular degrees of freedom)[5]

◊ Is this something we can model and solve by decreasing the microseism in the first place? ◊ Should we already consider this kind of active subtraction as part of the design? ◊ Foresee requirements / monitoring?

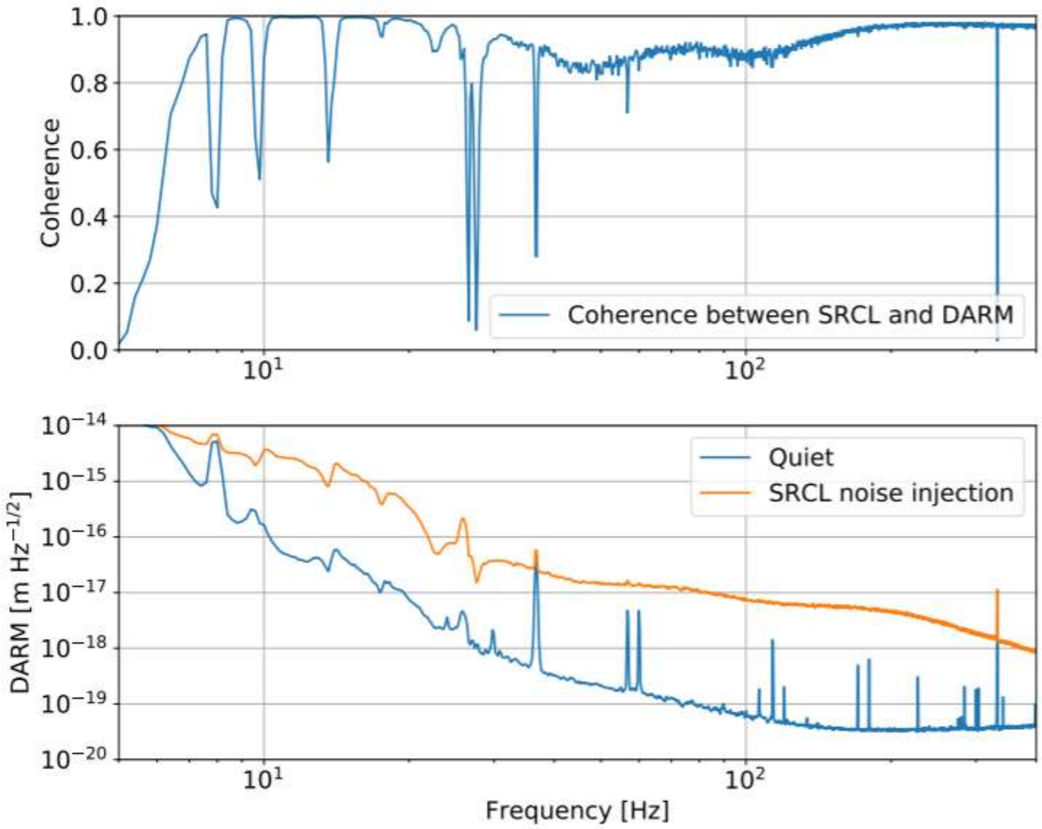

Fig. 1. The loss of coherence suggests that the coupling changes with time

(5) Subtraction of non-stationary noise couplings, G. Vajente, LIGO-T1800525-v4

Summary

- Experience on 1st and 2nd generation of gravitational waves detectors has shown that noise couplings from auxiliary degrees of freedom do limit sensitivity
- Couplings mechanisms are not always direct to DARM or even linear -> a more global view is needed to calculate controls requirements
  - Consider that control requirements might need to be extended to other subsystems
  - Consider additional controls as part of the design: noise subtractions, optical benches motions, seismic isolation, centering…
- If we were to redo the LSC/ASC modelling for 2G now, what would we do differently?

◊ How can we approach this challenge?