Requirements computation for the Low Frequency third generation gravitational wave detector
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

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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\(^1\))

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(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
Auxiliary DOFs

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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.**

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

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

- 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
Experience on 1\textsuperscript{st} and 2\textsuperscript{nd} 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?