An eLISA noise simulator:

Migrating LISA Pathfinder knowledge to eLISA experiment

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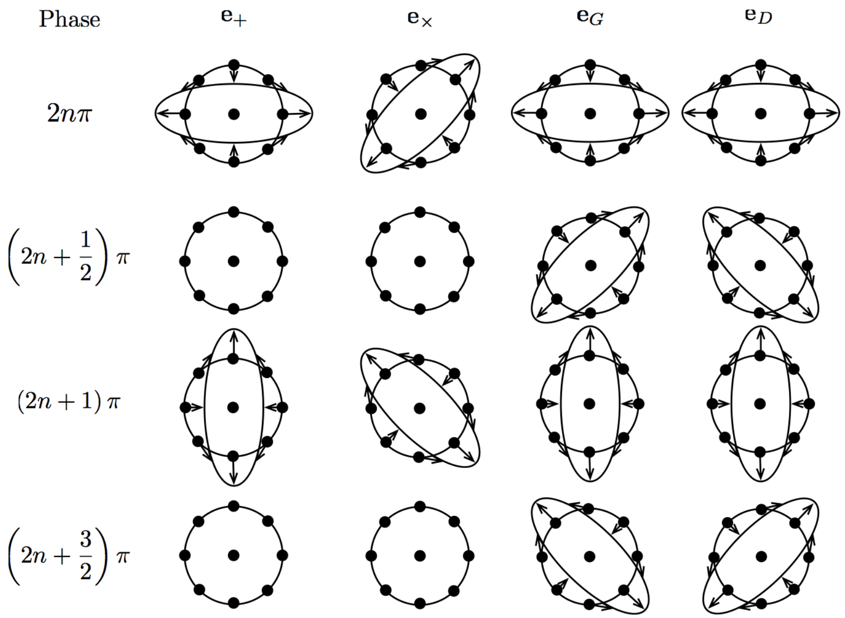
Detection principle: Deformation induced by gravitational waves

- GW: induces oscillating tidal deformations of a ring of free test particles
- It represents a natural detection principle, though the relative deformation is very weak: **the measurement of the relative displacement between free evolving bodies due to GW crossing.**
- Interferometry could provide sufficient precision for their observations.
- Characteristic deformation amplitude for typical sources:

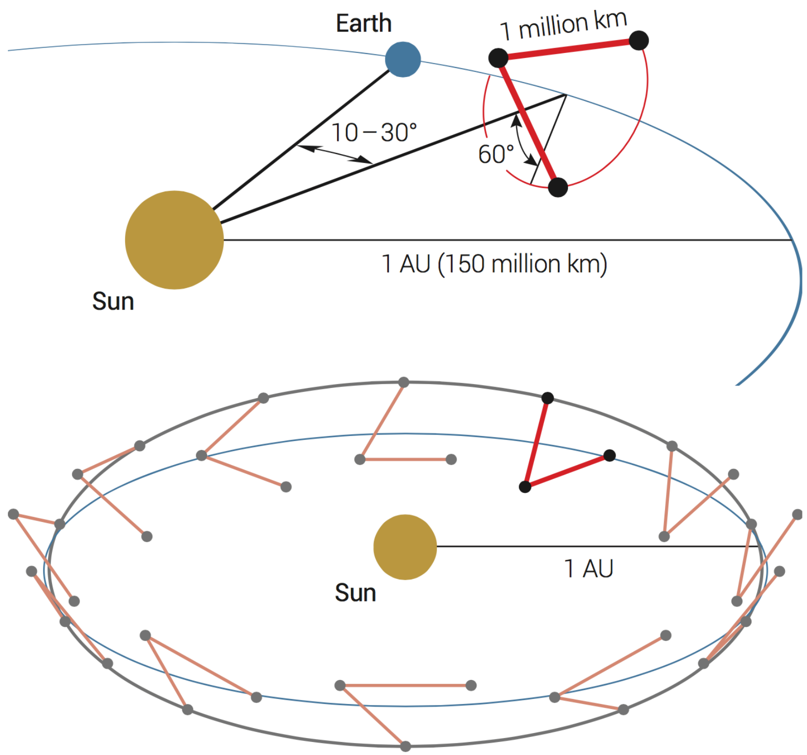


$$\frac{\delta l}{l_0} = -\frac{1}{2} h_{ij}^{TT} n^i n^j$$

$$\frac{\delta l}{l_0} \approx 10^{-21}$$

Detection principle: a space based observatory

- Space based interferometer: benefits from a much larger armlength and a quiet environment
- eLISA constellation:
  - 1 million km armlength
  - 3 S/C: 1 “Mother” and 2 “Daughters”
  - 2 arms Michelson interferometer equivalent
- Satellite = poor inertia reference body. Need of a better reference to distinguish GW effect from relative motion fluctuation.

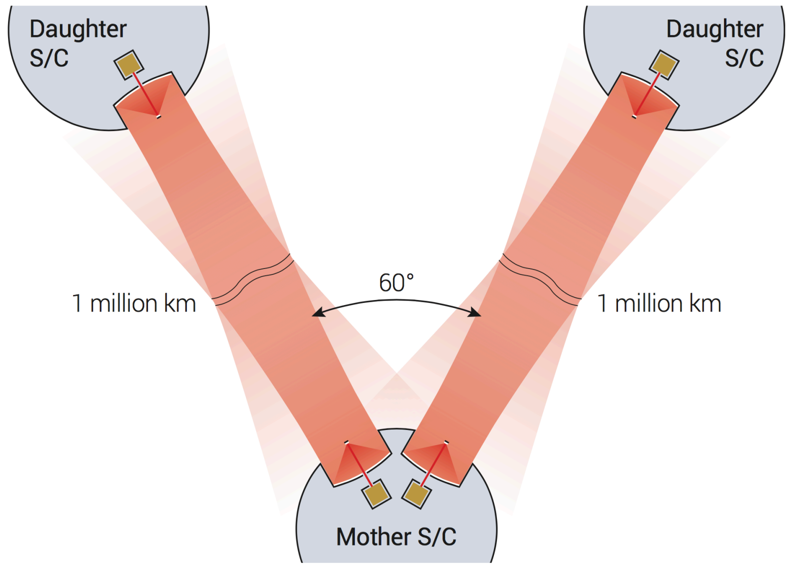


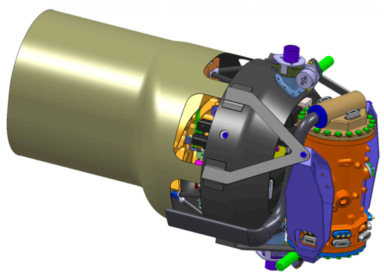
eLISA detector

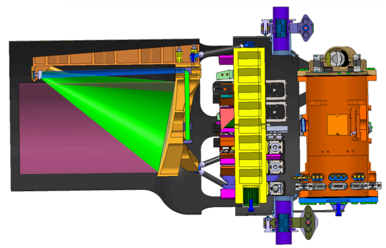
- Satellites contain 1 test mass per link they are involved with. These TMs acts as inertia reference body.

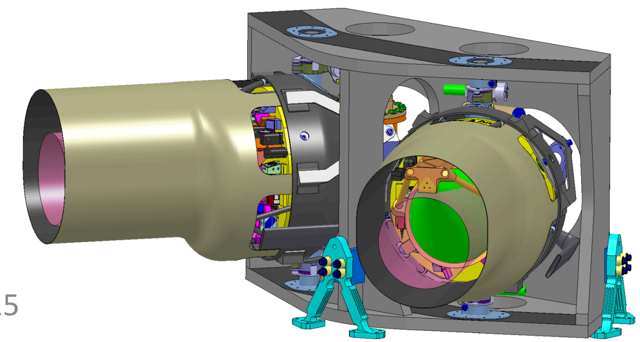
- Large distance between S/C make the laser divergence being very significative: beam diameter about kilometers and power about 280 pW only in reception.

- Movable telescops collect the distant beam. Two mirrors drive the beam towards the optical bench.







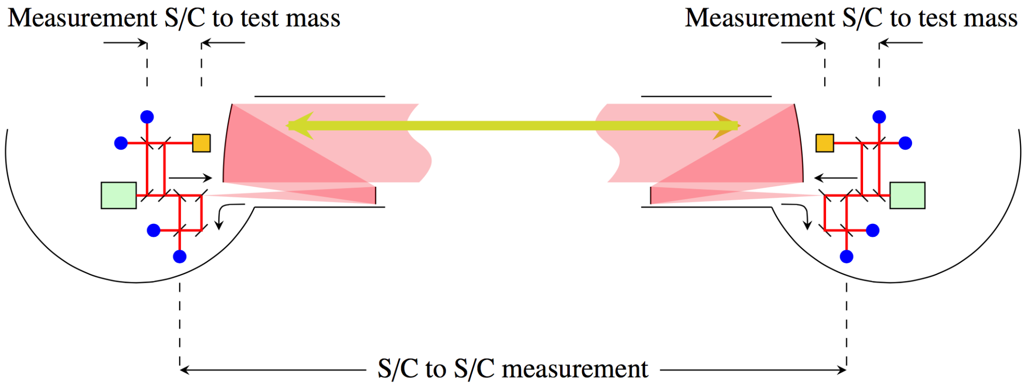


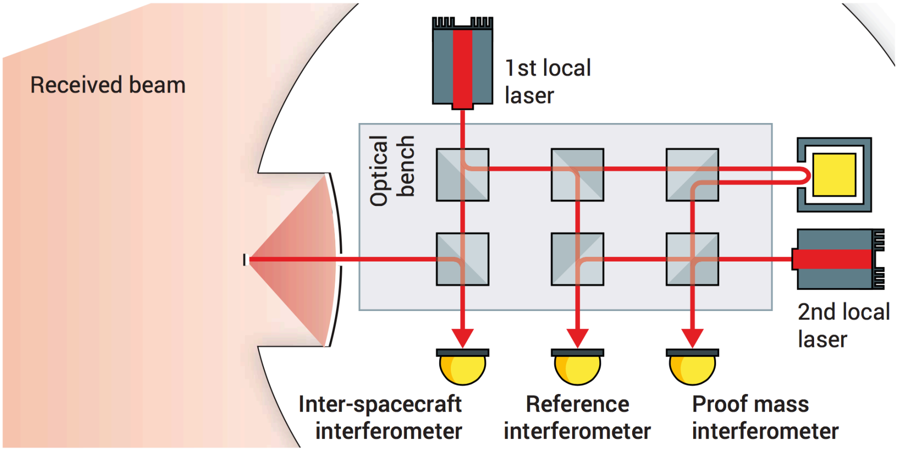
eLISA detector: Interferometric measurements

- Measurement in 3 steps:
  - TM-SC
  - SC-SC
  - SC-TM

- Three interferometry measurements per optical benches:
  - **Science interferometer:** measure the displacement between S/C
  - **Local interferometer:** measure the S/C displacement w.r.t. his reference mass
  - **Reference interferometer:** measure the phase fluctuation between the two local lasers.

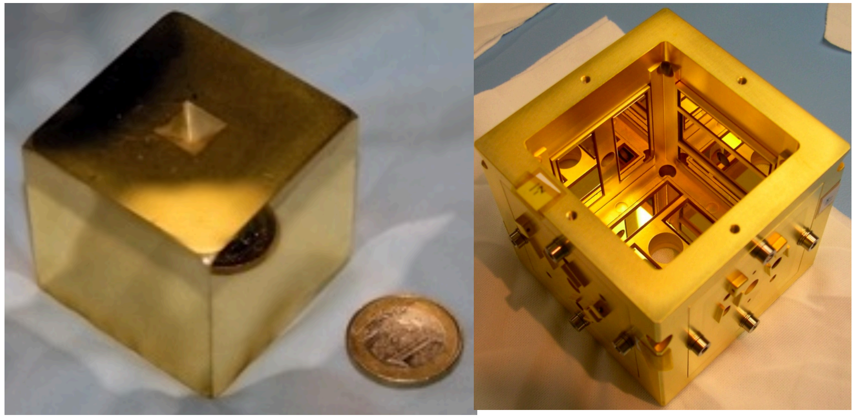
- Heterodyne interferometry: a beat note is modulated in phase by the optical path variation.

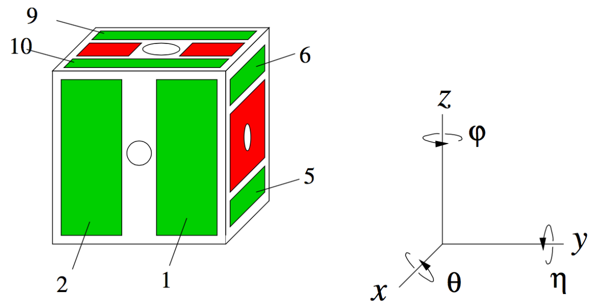


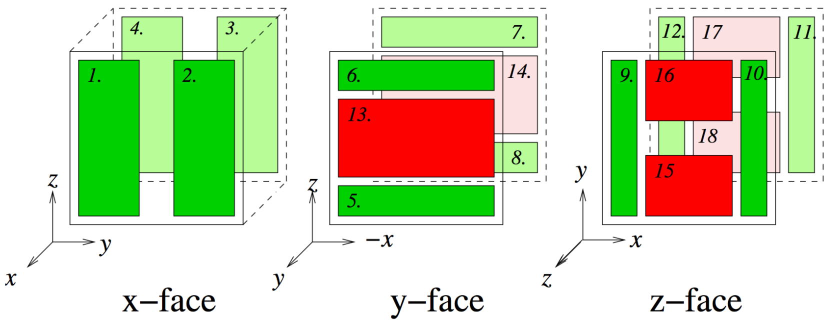


eLISA detector: Gravitational Reference Sensor (GRS)

- Cubic TM, 73% Au 27% Pt, coated with Au, 46x46x46 mm, 1.96 kg.
- Satellite body plays the role of a shield for the TM.
- They are enclosed in electrostatic housings. An electrode set inside the housing make with TM surface capacitive system. Potentials applied and measured to control the proof masses both for linear and angular motion.
- **x-axis called Drag-Free is prevented from direct actuation. The satellite micropropulsion system is used instead.**







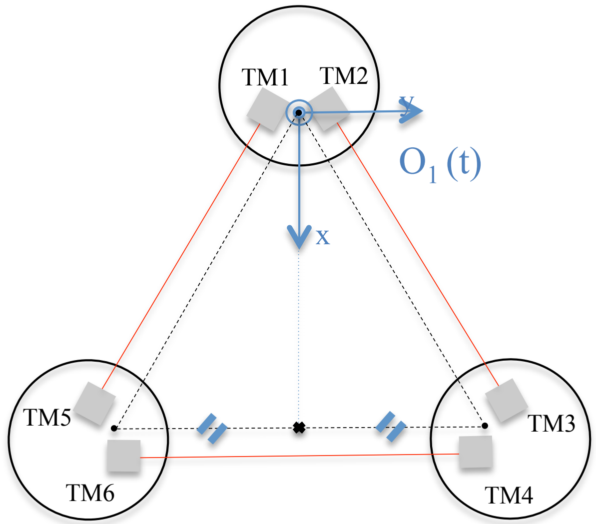
A dynamical simulator for eLISA

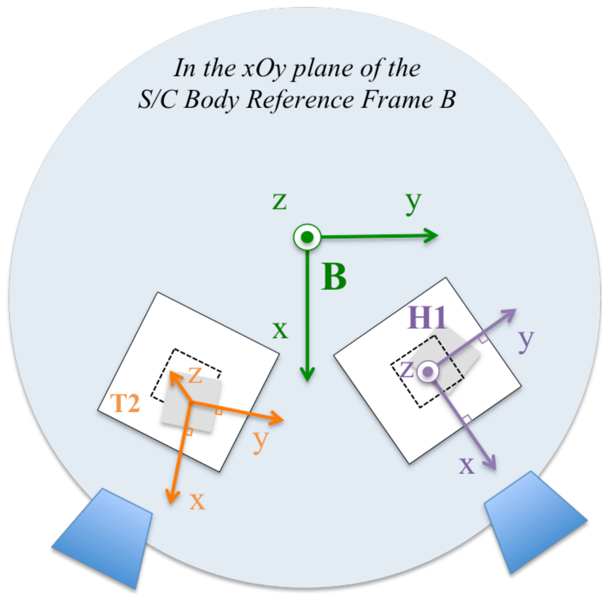
- Main motivations:
  - Response of the whole eLISA system to individual instrumental noise
  - Residual forces applied on the TMs
  - Provides a more realistic noise to LISACode and eLISA DA team in general
  - Allow to optimise the “system configuration” and its individual components
  - Migrate knowledge learned from LISA Pathfinder to eLISA

- The simulator works both in time and frequency domain.

Constellation dynamics

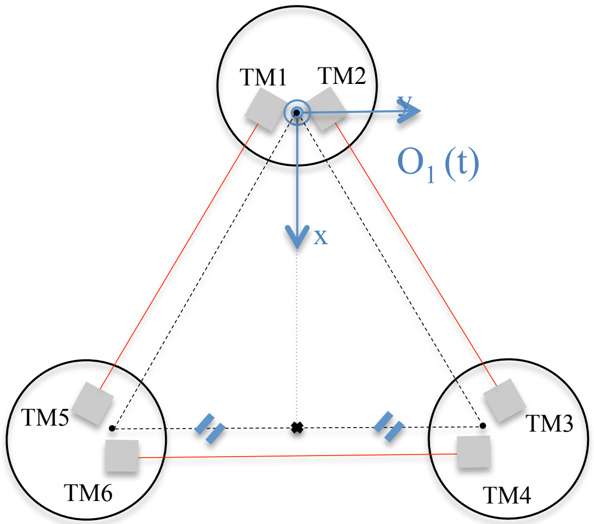
- 1 satellite = 3 bodies = 3 x 6 coordinates:
  - Position of the S/C and TMs CoM
  - S/C and TM attitude (Cardan angles)
- **A control system for both position and attitude is required:**
  - The S/C telescopes have to point towards the distant S/C
  - The TMs have to be kept centred and correctly oriented in their housings
- The definition of various reference frames is an important aspect of this work.

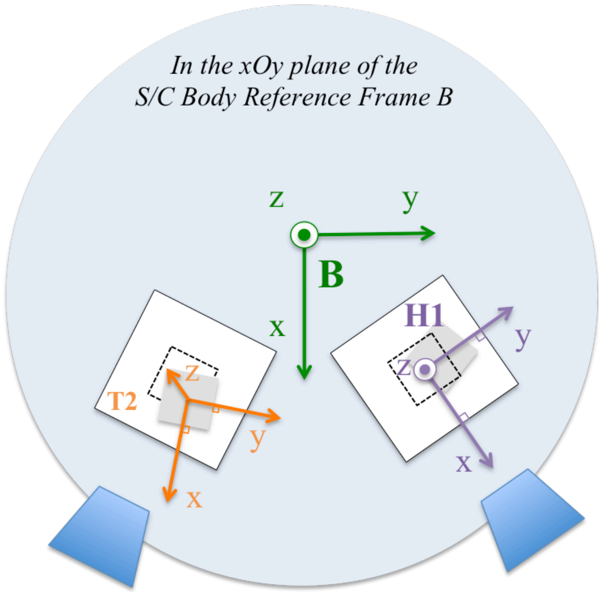




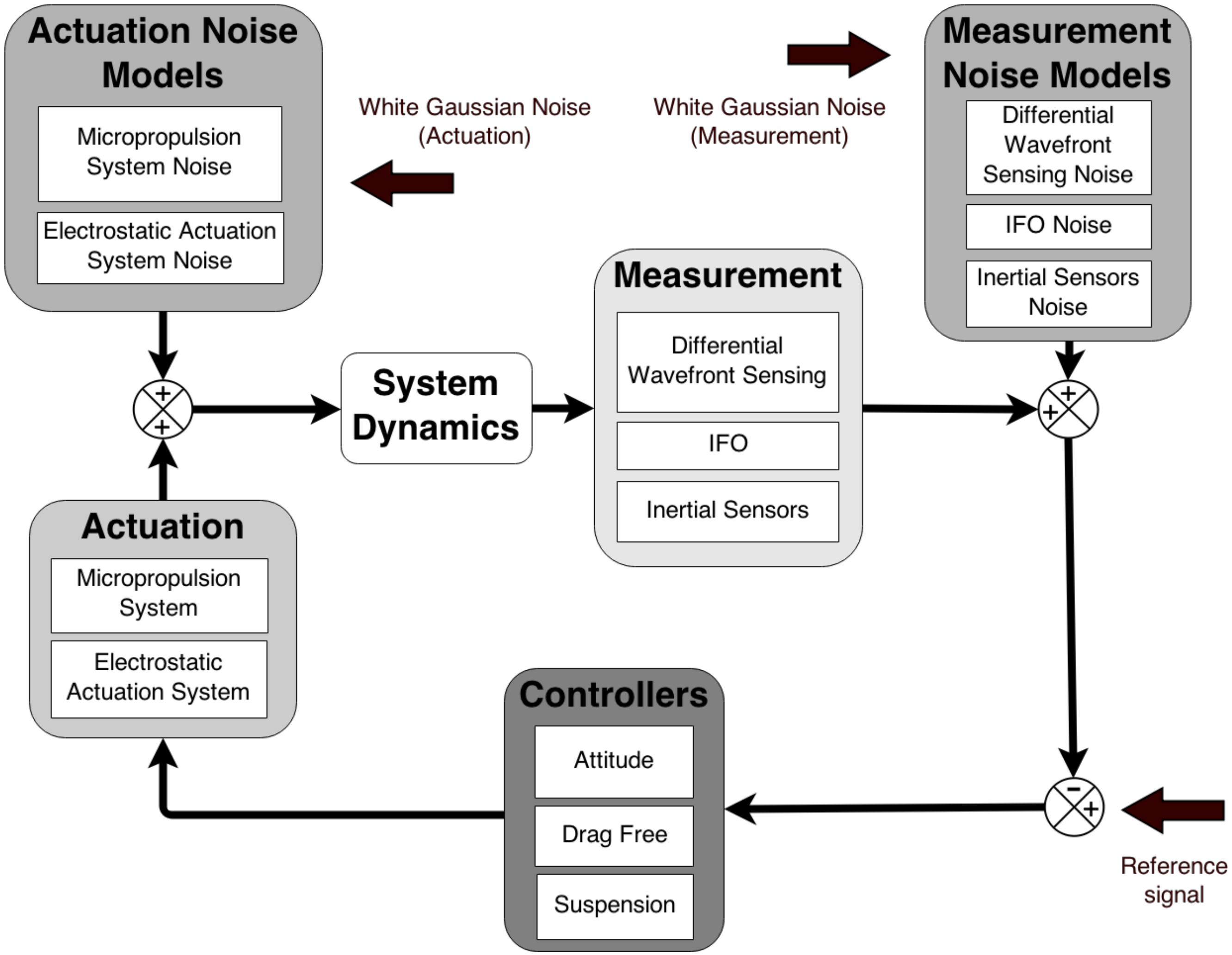
Constellation dynamics

- Modelling task is highly simplified when system can be sketched as an linear time invariant model (superposition principle, frequency domain analysis…).
- **For linearisation process, it is necessary to work around an equilibrium point.**
- Introduction of a new reference frame: The Orbital reference frame O:
  - its centre follows the ideal orbit of the S/C
  - Its orientation is such that the x axis attached to the S/C is aligned with the triangle median.
- **For now, laser telescopes are considered fixed in the simulation.**

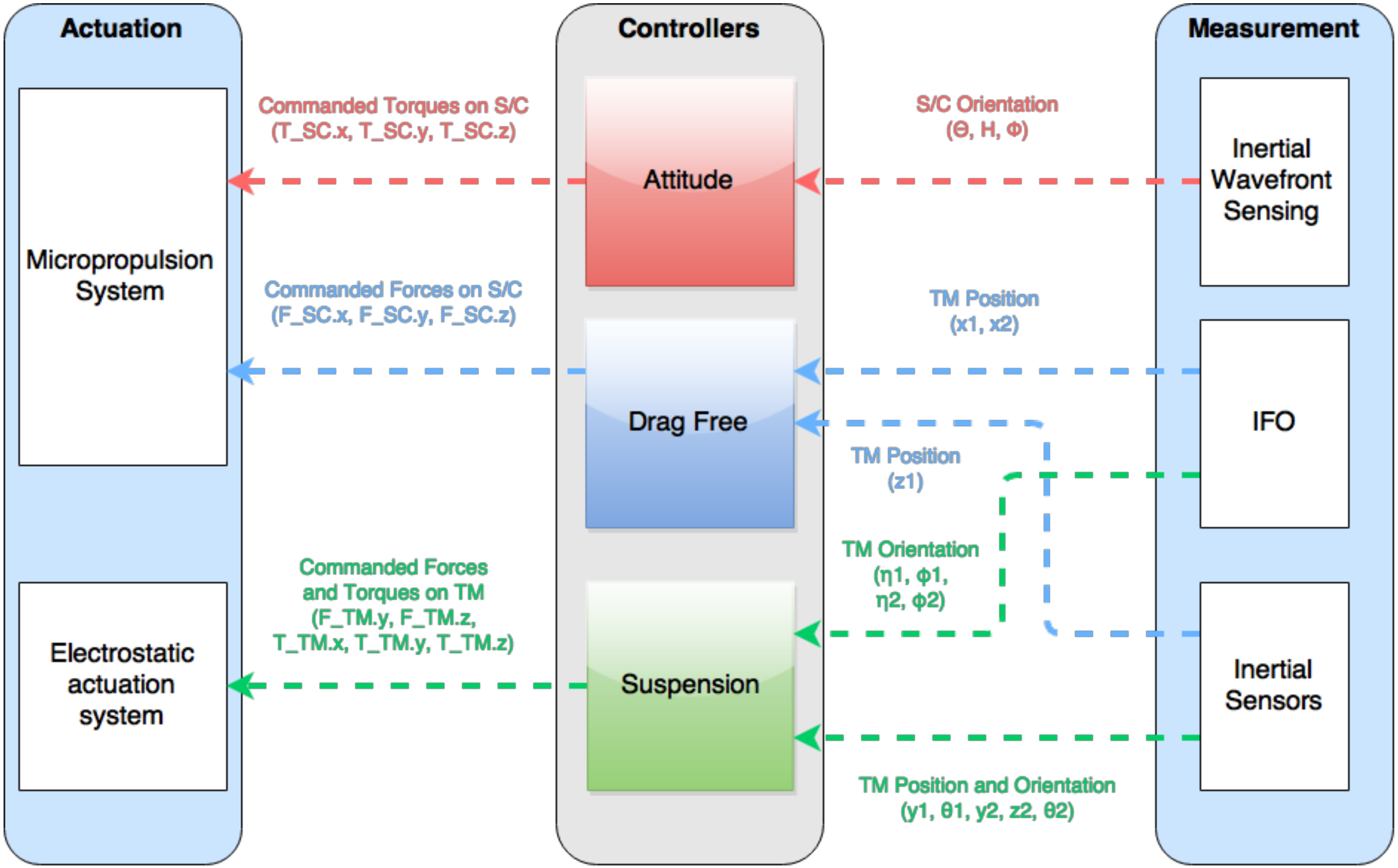




Block diagram: Closed Loop System



Block diagram: DFACS

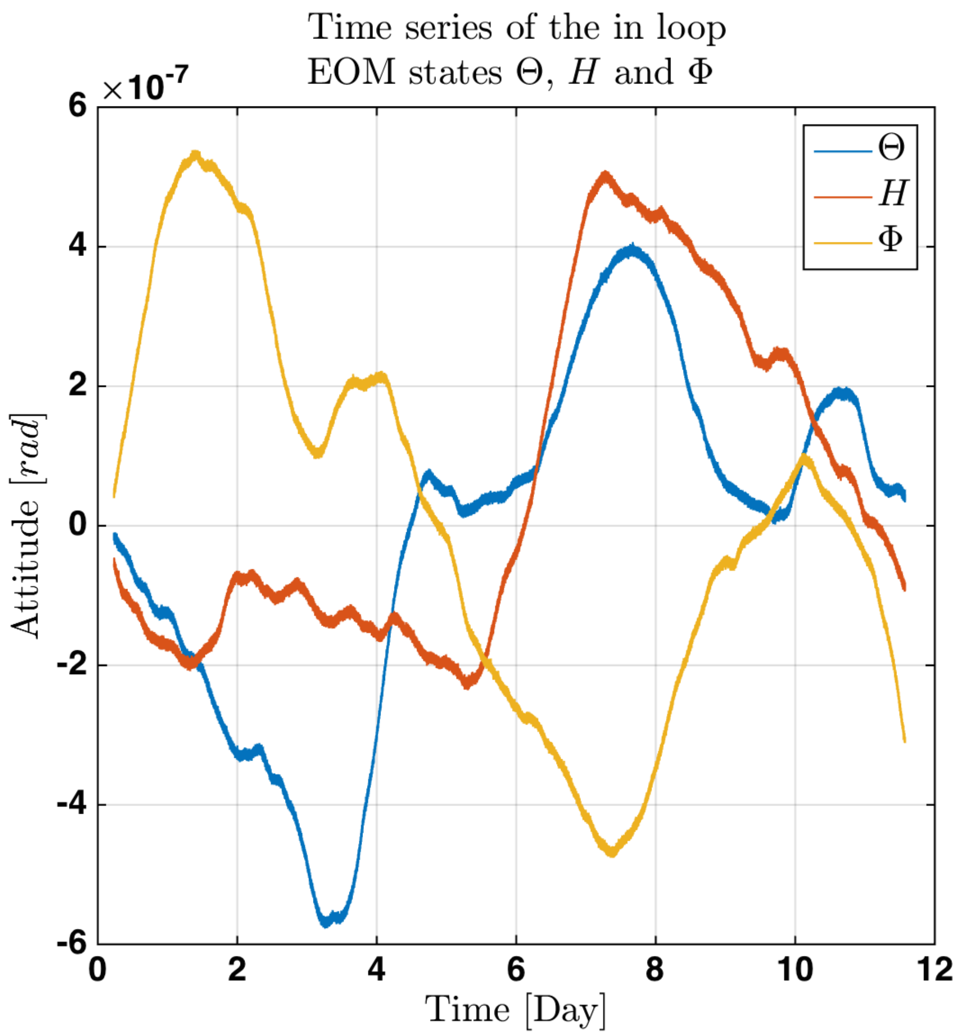


Noise sources

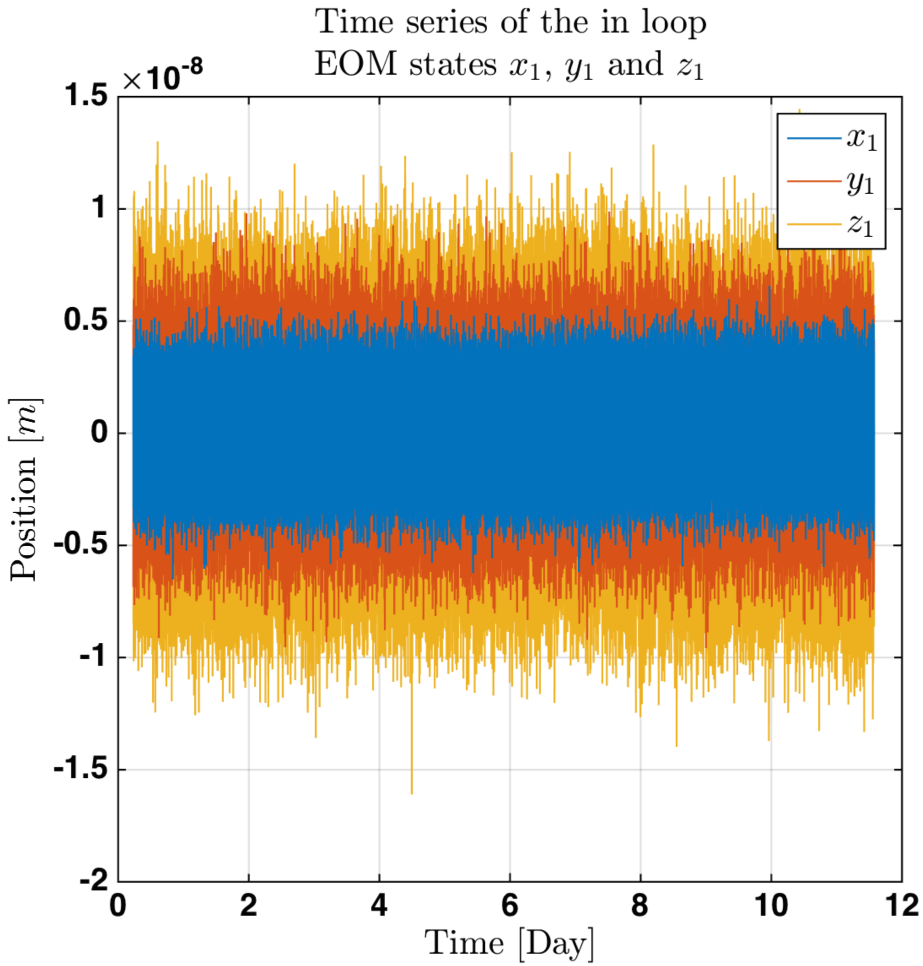
- Actuation Noise: Micropropulsion and Capacitive systems.
- Sensing Noise: IFO, Inertial Sensors and Inertial Wavefront Sensing.
- External force disturbances fluctuation.
- Cross-Talk on both actuation and sensing
- Stiffness between the S/C and the TMs.
- 2 versions:
  - One with Astrium specifications for noise and imperfection
  - Another one with LPF values as provided by the LPF LTPDA SSM.
- All values and frequency dependences used will have to be checked: work in progress.

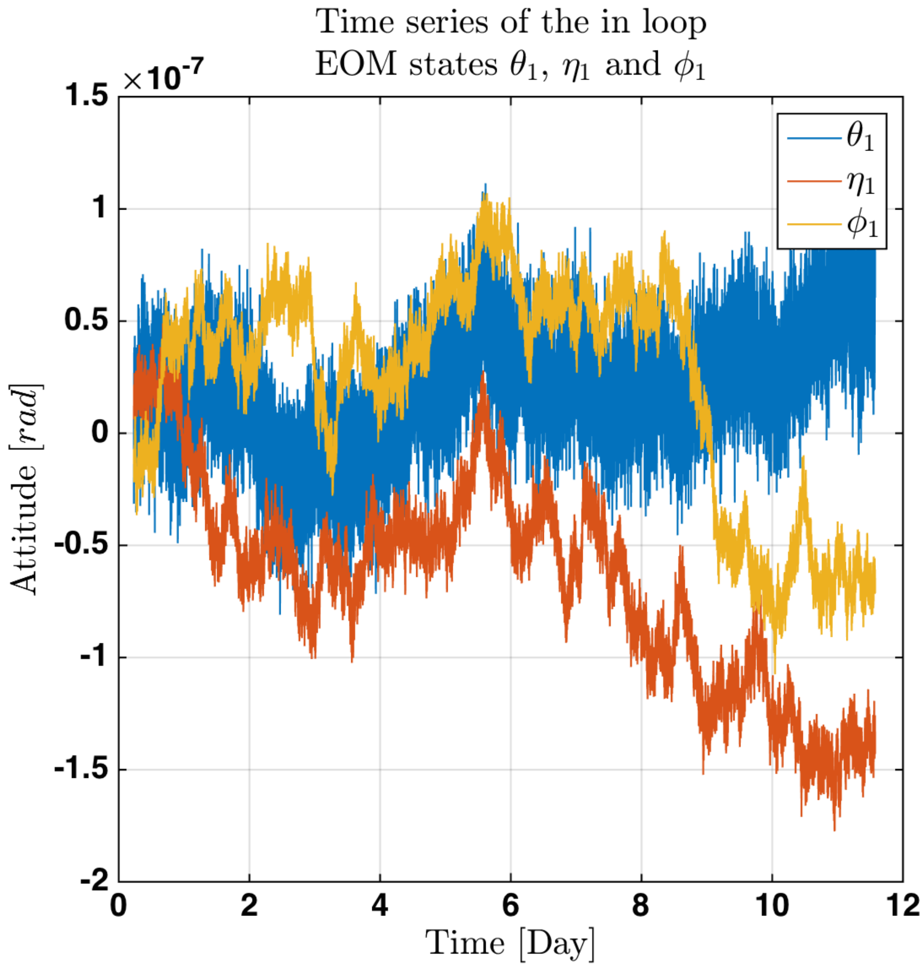
Simulation results

- Two weeks long simulation
- Time evolution of the dynamics state variables:
  - S/C attitude
  - TMs position
  - TMs orientation



Simulation results

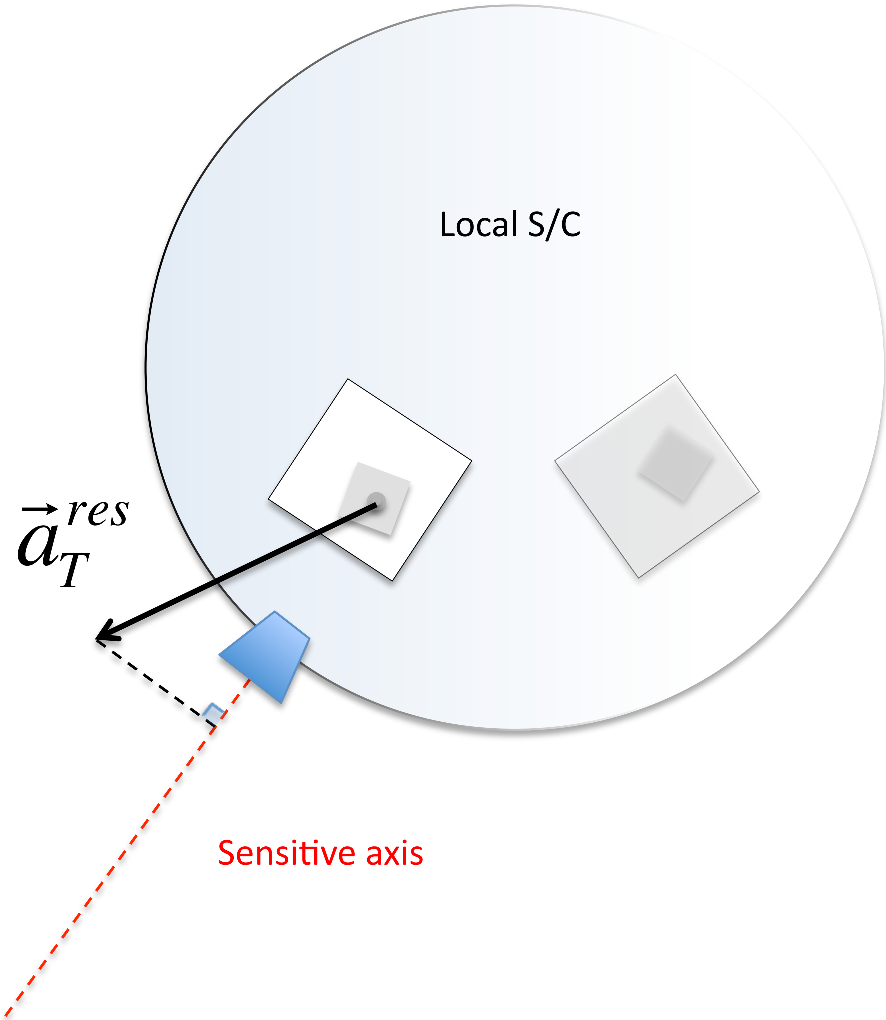




Residual acceleration on sensitive axis

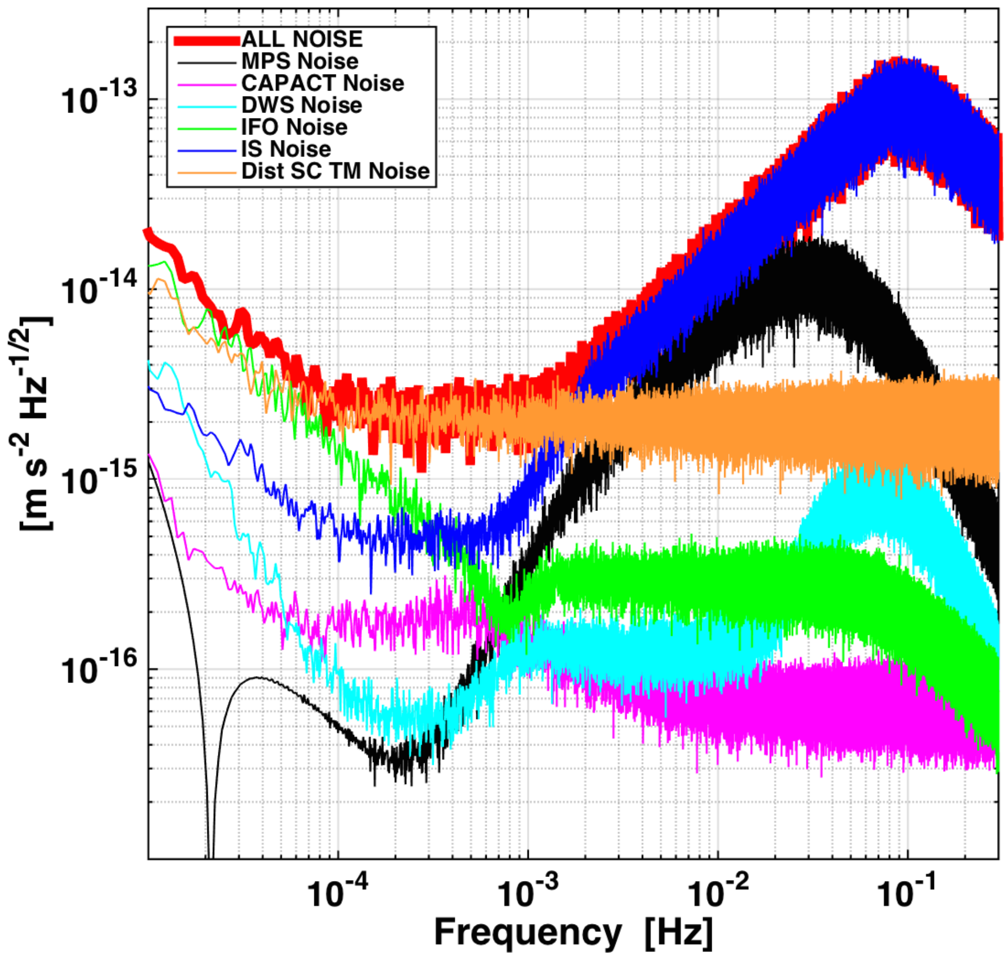
- Our final observable:
  - Residual acceleration computed within the Orbital Reference Frame O.
  - It is then projected on the sensitive axis.
  - Sensitive axis: defined by the axis which links the 2 distant TMs.

- This definition is crucial: we have to check out whether this is the most appropriate one.

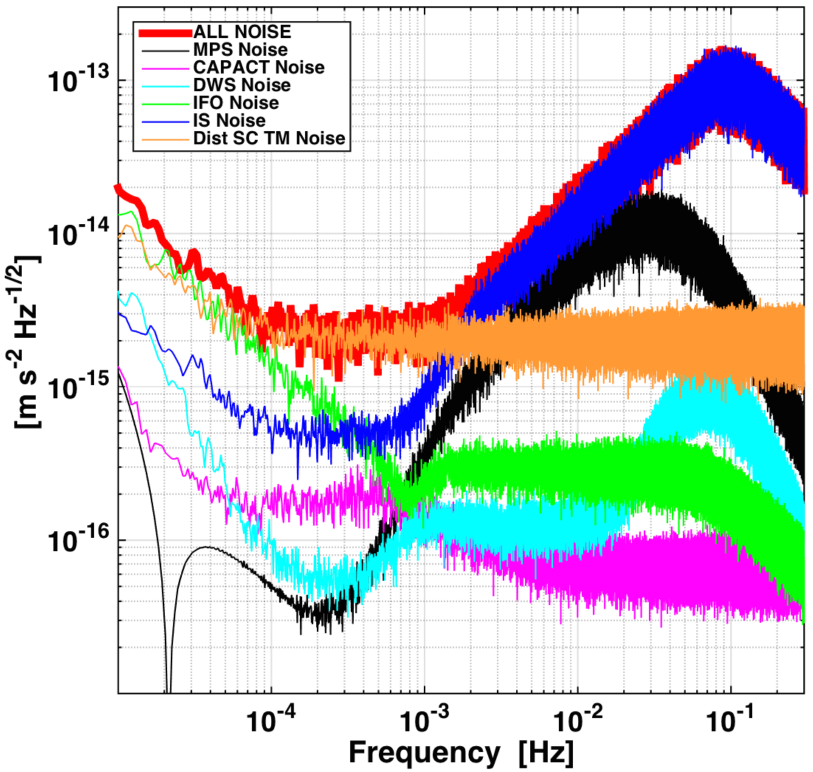


Noise decomposition

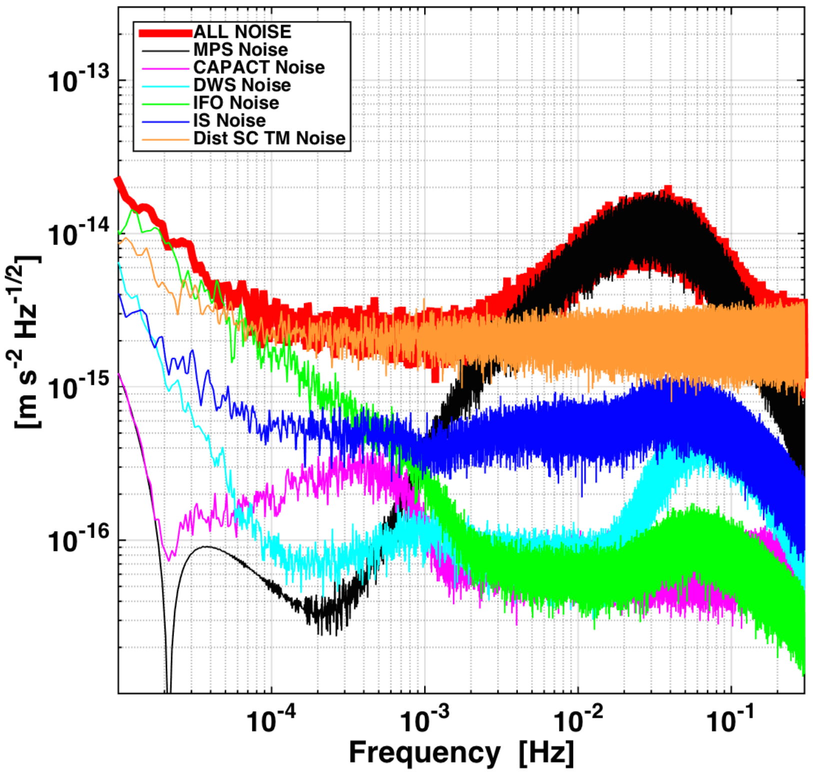
- PSD of acceleration noise time series
- Various noises and disturbances are turned on alternately.
- Allow to identify the the individual influences on the acceleration noise



Noise decomposition: **no crosstalk**

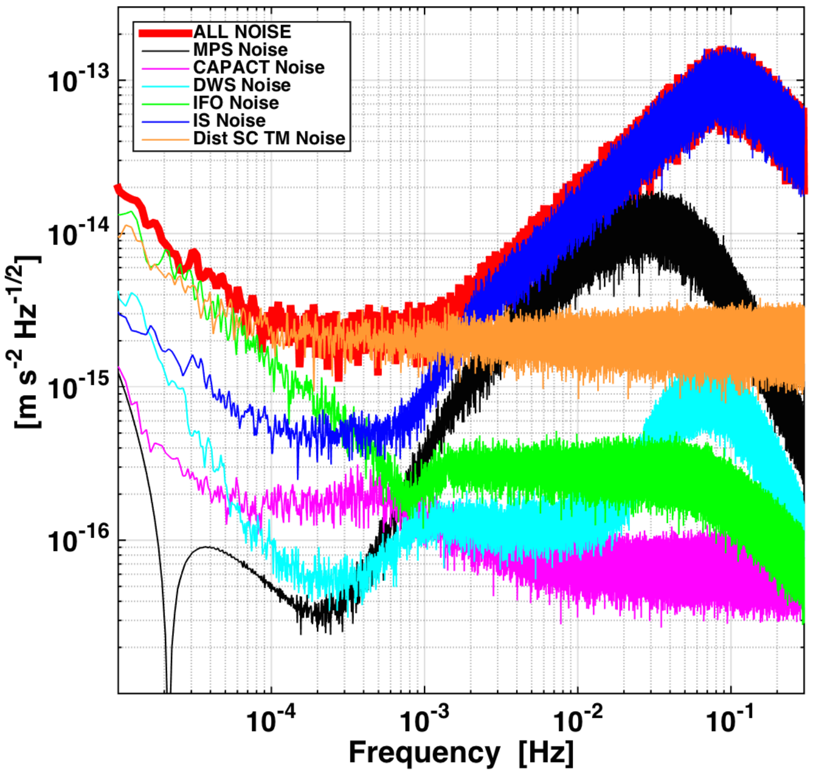


Crosstalk activated

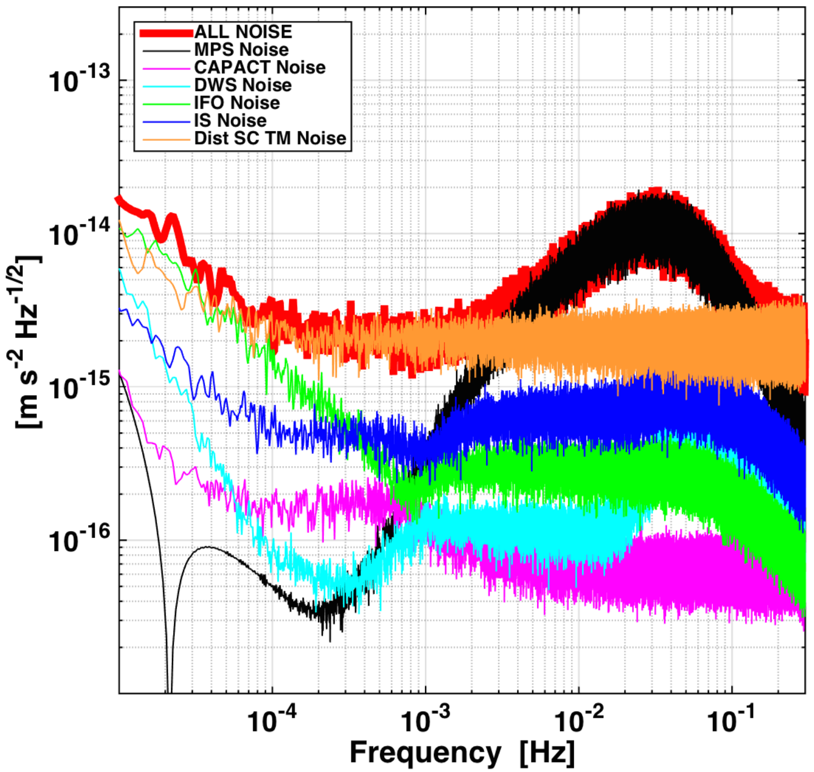


Crosstalk deactivated

Noise decomposition: **no crosstalk from θ actuation to x**

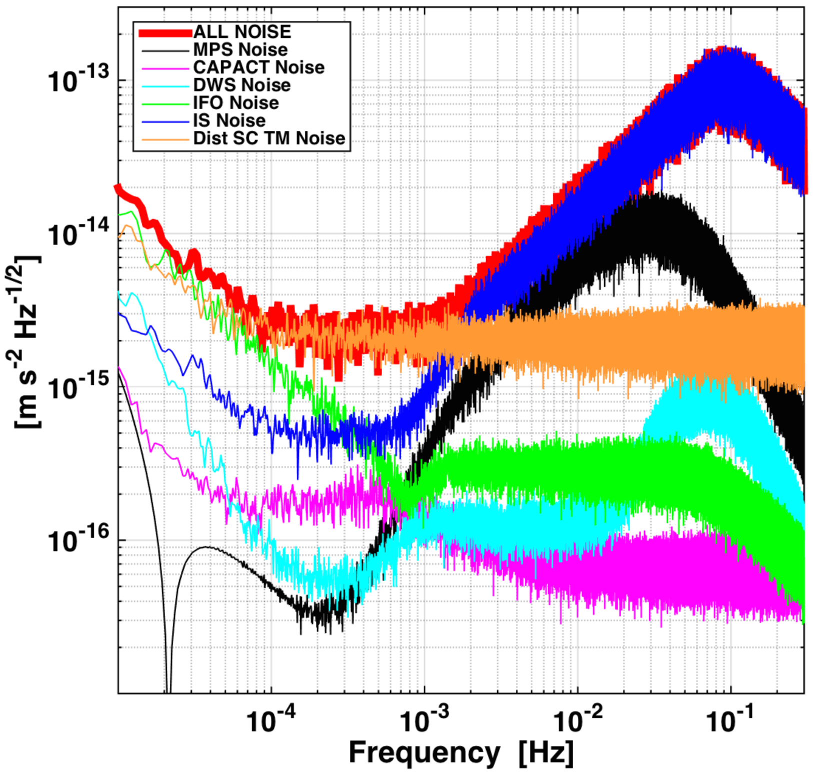


Crosstalk activated

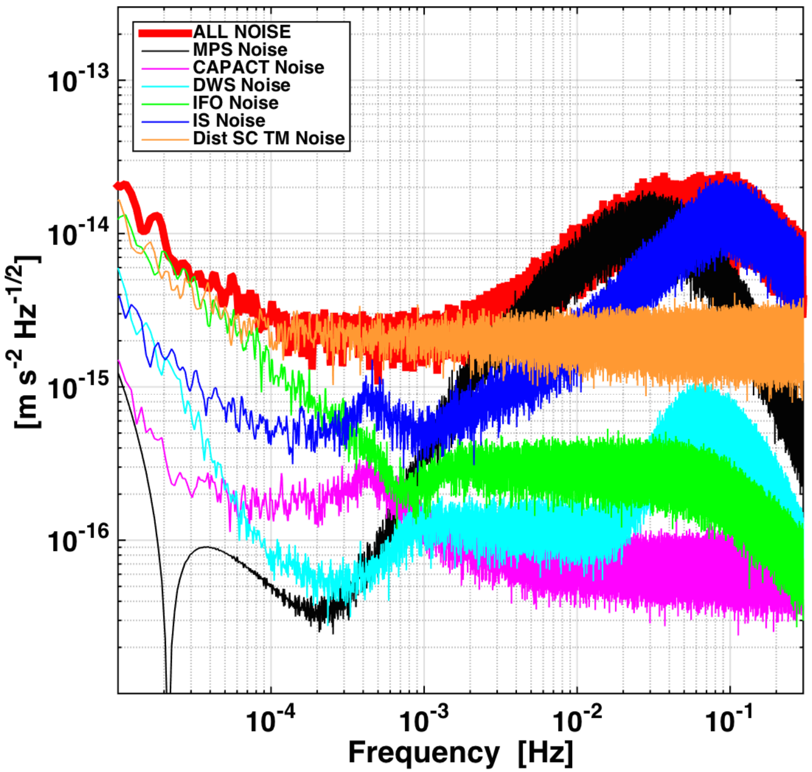


Crosstalk from θ actuation to x deactivated

Noise decomposition: **modified controllers**



LPF controllers



Modified LPF controllers (θ control gain divided by 7)

Future improvements

- Future improvements:
  - Optimisation of the controllers
  - Moveable telescops
  - New or more realistic noises and imperfections (phasemeter, clock, optical bench noise…)
  - Nonlinearities and instationarities
  - Analysis of other eLISA configurations, in particular those of interest for the science case evaluation (best, worst and « medium » cases)
  - Link between this noise simulator and LISACode for GW data analysis