LISA: Instrumentation and on-ground tests

The Photon Path : a manual for students of the Phase

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The introduction

Gravitational waves sources

See Adrien's following talk

1. Introduction
   - GW
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2. LISA Instrument
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   - GRS
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   - PMS
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Data analysis

See Yves's Friday talk

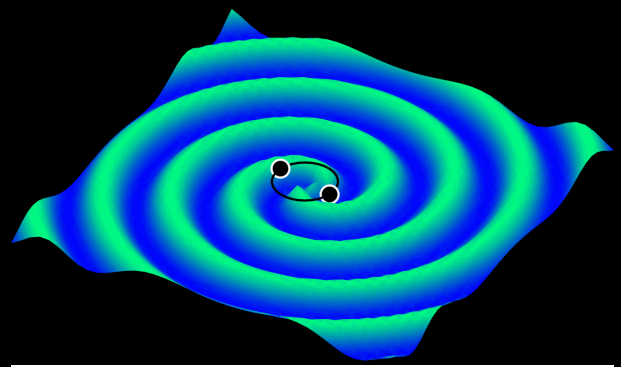
Gravitational waves

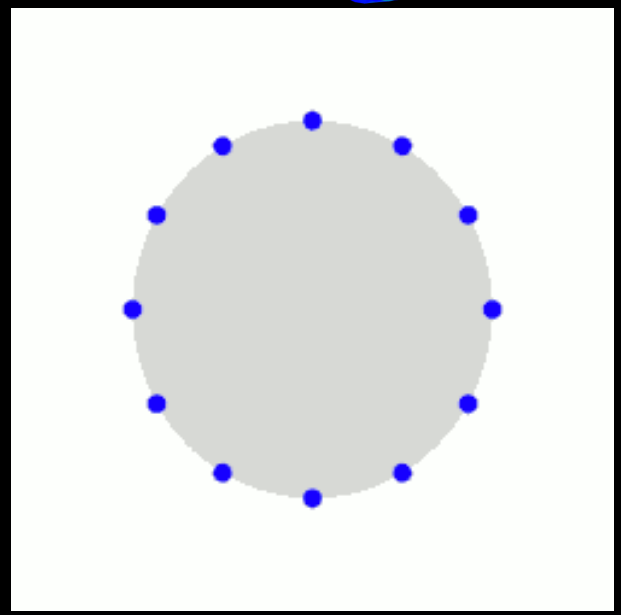
- Accelerating compact objects generate ripples in the fabric of spacetime.
- These waves induce a characteristic strain, h, which manifests as a physical change in distance:

$$\frac{\Delta L}{L} = h$$

- Typical amplitude of 10^{-21} yields

$$\Delta L \sim \text{pm to nm} \quad \text{for L} = 10^6 \text{km}$$

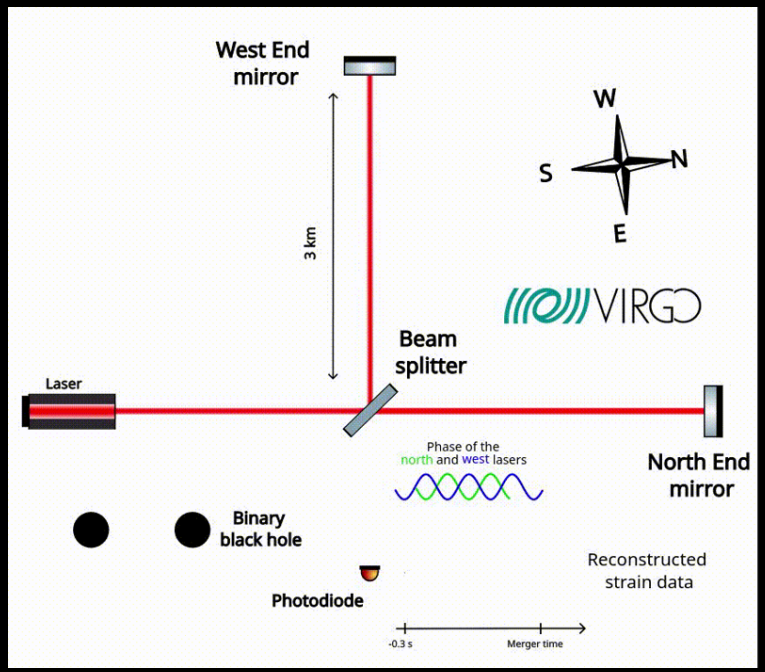




Key idea: Detecting the infinitesimal variation in the optical path length between free-falling masses.

Michelson interferometer principle

- **Basic setup**: A single light source is split by a beam splitter into two perpendicular paths.
- **Reflections**: The beams reflect off two mirrors and recombine at the splitter.
- **Interference**: Recombining beams produce an interference pattern based on their relative phase.
- **Phase shift**: A change in path length ΔL induces a phase shift $\Delta\phi$:



$$\Delta\phi(t) = \frac{2\pi}{\lambda}\Delta L(t)$$

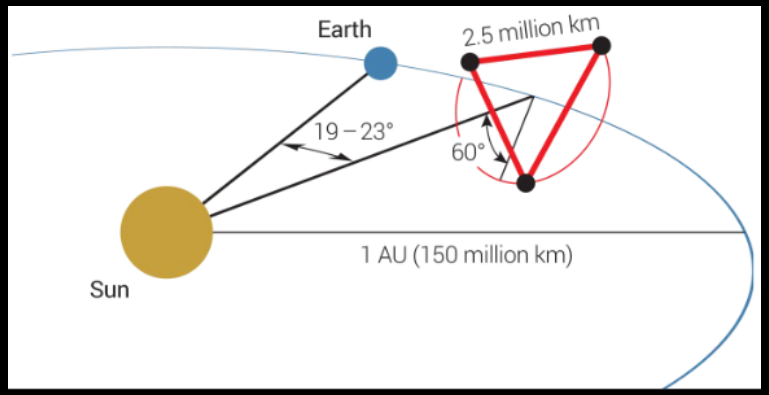
- **Sensitivity**: Small variations in path length relative to the wavelength λ are detectable via intensity changes.

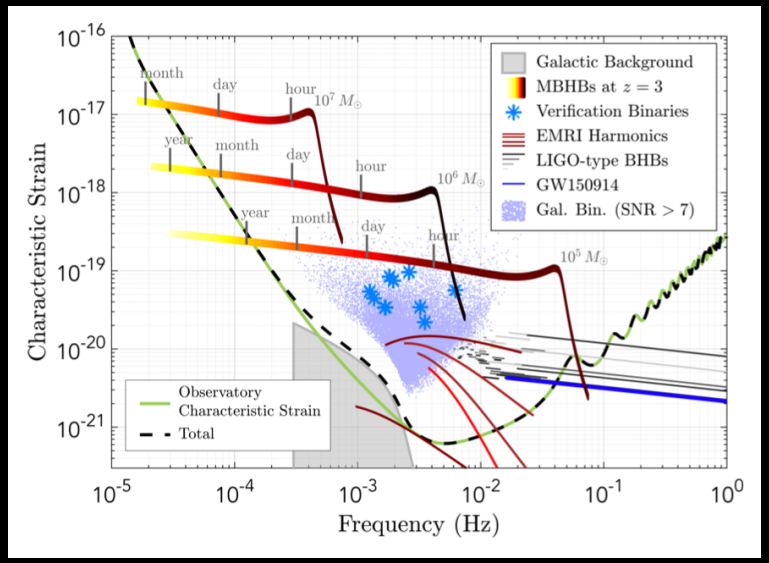
LISA mission overview

- **Constellation configuration**: Three spacecrafts in Earth-like heliocentric orbits forming an equilateral triangle.
- **Measurement technique**: Non-real time interferometry with a 2.5×10^6 km arm length.
- **Gravitational wave band**:

$$0.1\text{mHz} \leq f_{\text{GW}} \leq 1 \text{ Hz}$$

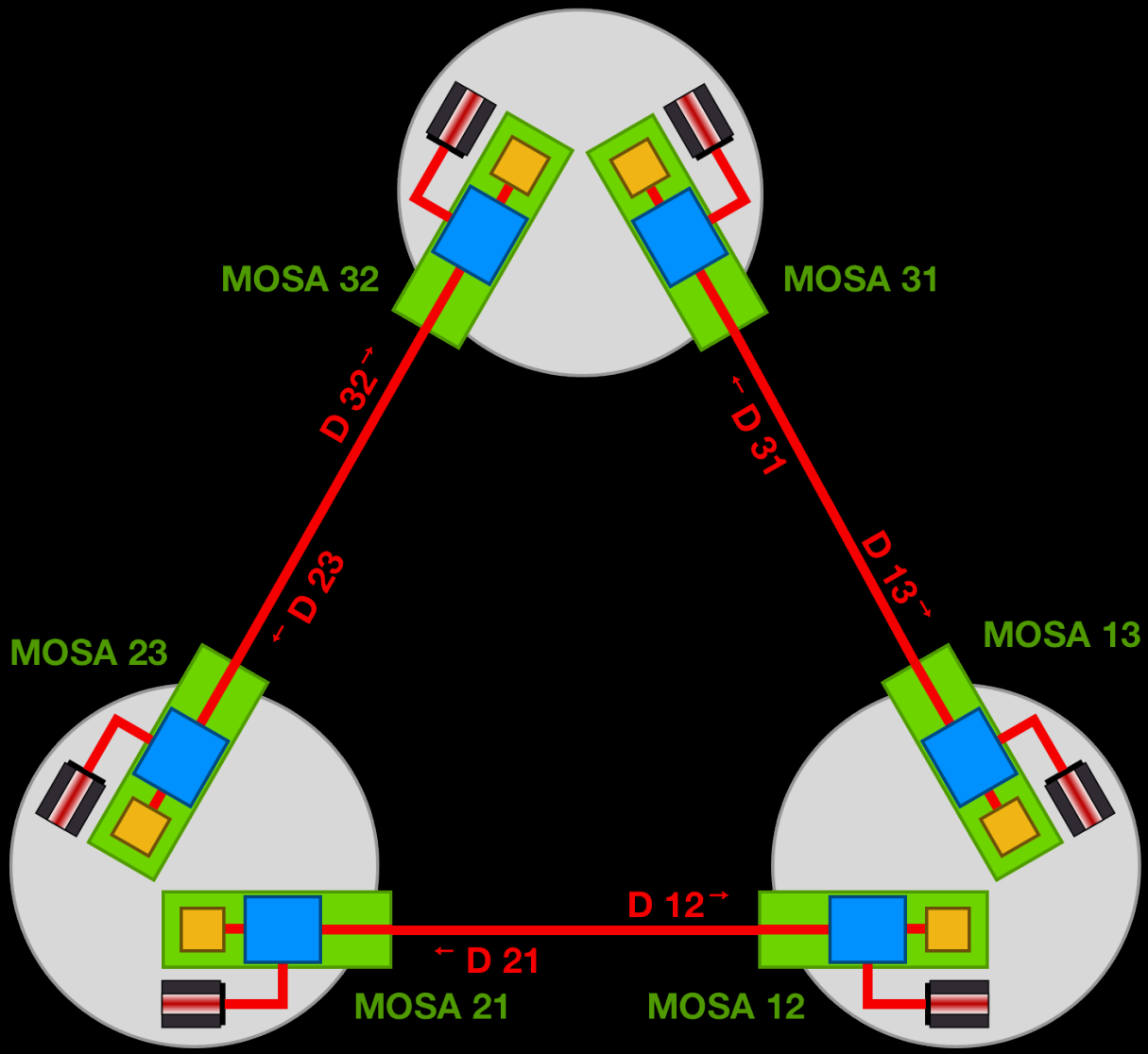
- **Science objectives**: Generation of catalogues containing masses, spins, distances, and sky positions of compact objects.





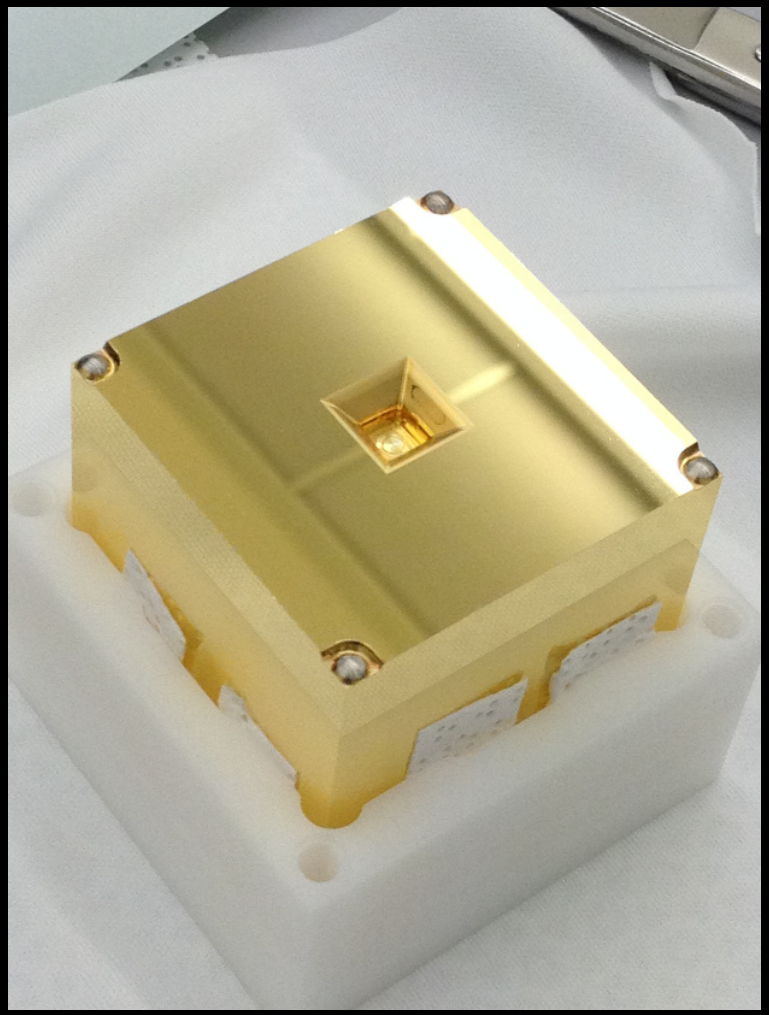
See Adrien's following talk and Yves' friday talk

The instrument



Test Mass (TM)

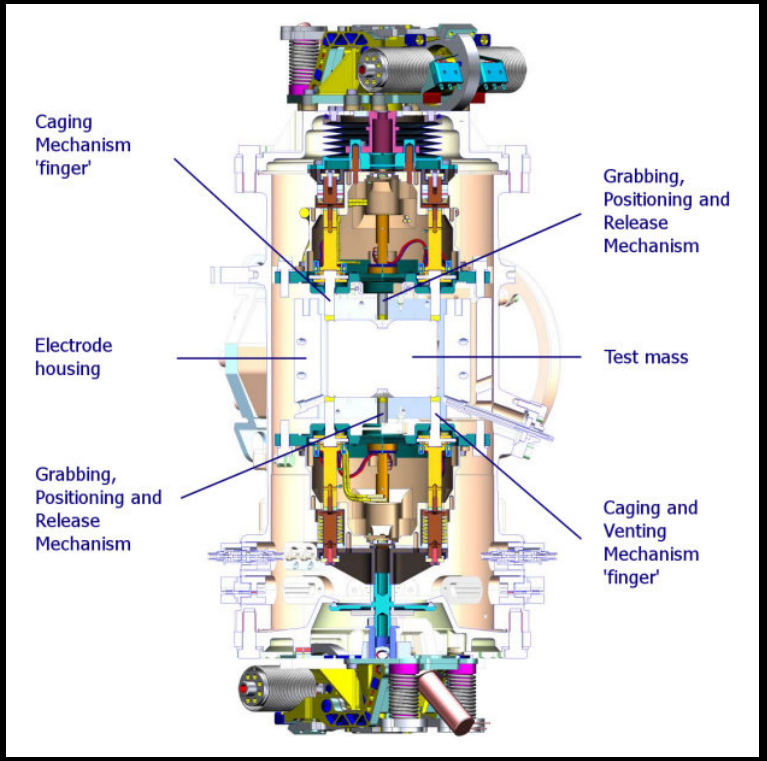
- **Function**: geodesic reference object
- **Physical characteristics**:
  - 46 mm Au-Pt cube
  - High density and magnetic purity to minimize non-gravitational accelerations.
  - Mass $\approx$ 1.93 kg.
- **Requirements**:
  - Perfect free fall.
  - Drag-free control to maintain a true free-fall state.
  - Requires method to remove the cosmic rays build up charges.



LPF Test mass, ESA

Gravitational Reference Sensor (GRS)

- **Function**: Primary shield to ensure a free-fall environment.
- **Characteristics**:
  - **Precision control**: Employs electrostatic sensing and actuation to center the TM.
  - **Contamination control**: Remains in an artificial vacuum until space vacuum is available.
  - **Launch survival**: Utilizes a lock mechanism to protect the TM during high-vibration launch phases.
- **Requirements**: Residual acceleration lower than $3\,\mathrm{fm/s^2}$ at 1 Hz, 15 orders of magnitude lower than Earth's gravity.

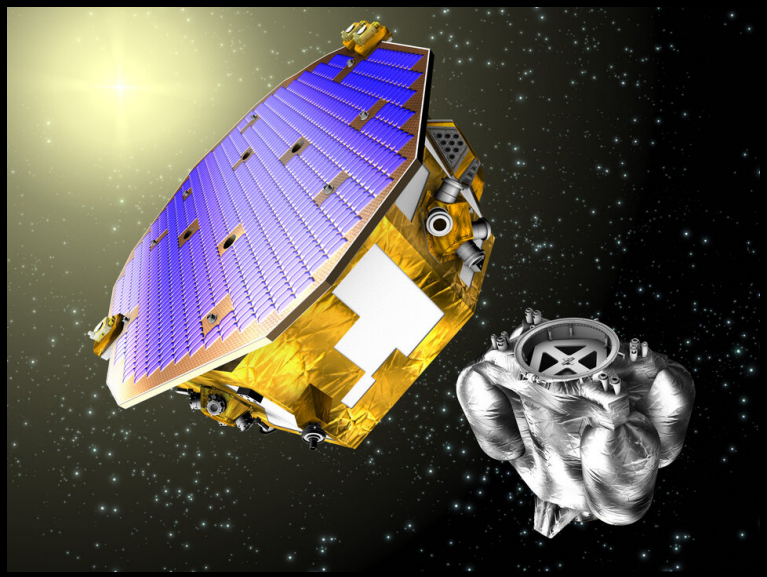


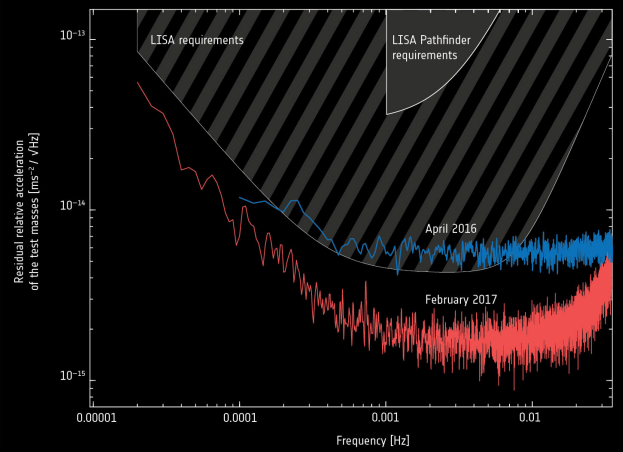
LPF Gravitational reference sensor, ESA

LISA Pathfinder (LPF)

- **Function**: Demonstrate the key technologies for the LISA mission
- **Timeline**: Launched in 2015, completed in 2017
- **Results**: Validated the technologies at the LISA level for everything planned.

Remaining work:
Demonstrate the optical link on 2.5×10^6 km.





LPF, ESA PhysRevLett.120.061101

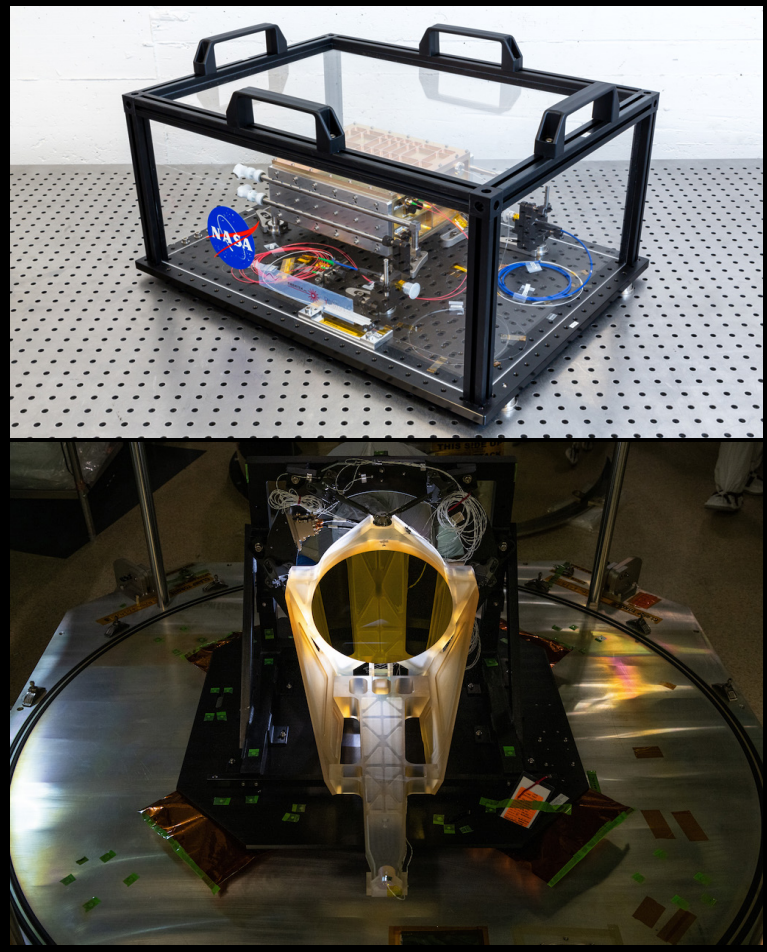
Laser Assembly (LA) and Telescope (TEL)

Laser Assembly

- **Function**: Provides the fundamental carrier beam for interferometry.
- **Characteristics**: 2 W, $\sim$ 10 km beam width at 2.5×10^6 km.
- **Primary noise driver**: laser frequency noise is the dominant noise : 8 orders of magnitude higher than a gravitational wave strain.

Telescope

- **Function**: Primary interface for the optical path between spacecraft.
- **Mirror characteristics**: 30 cm.
- **Collected power**: $2\text{W} \times \left(\frac{0.3}{10^4}\right)^2 \sim \text{nW}$

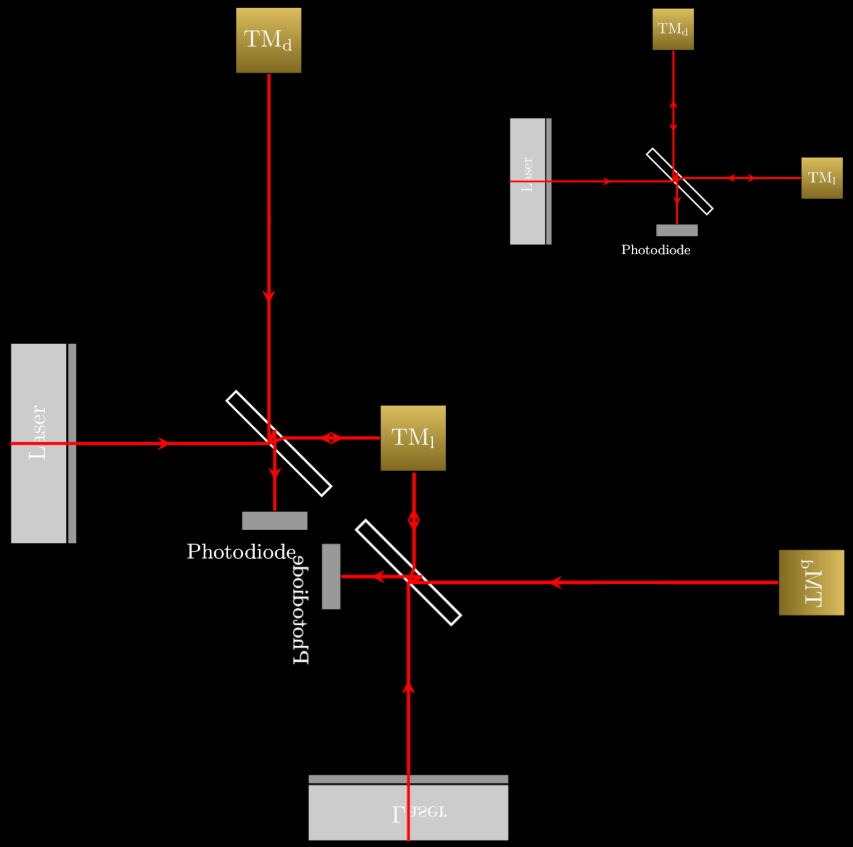


Laser & Telescope, NASA

Conclusion: Real time interferometry is not doable.

Time-Delay Interferometry (TDI)

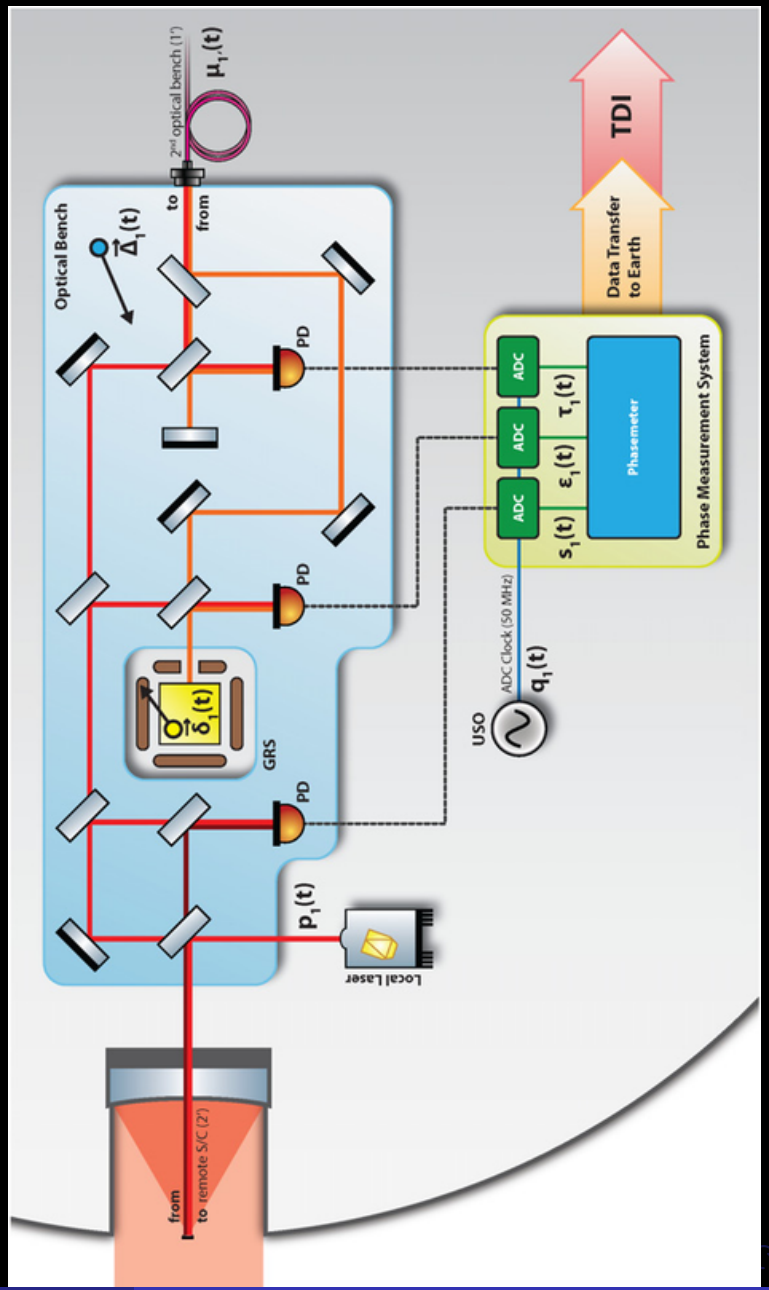
- **Function**: Post-processing algorithm to compensate for LISA's unequal and time-varying arm lengths.
- **Solution**: digital processing to synthetically recombine delayed phase measurements creating a noise-suppressed virtual interferometer.
- **Conclusion**: LISA is not three real time equal arm length interferometers, but 6 delayed unequal arm length interferometers.



$$\Delta\phi(t) \rightarrow \phi_1(t) - \phi_2(t)$$

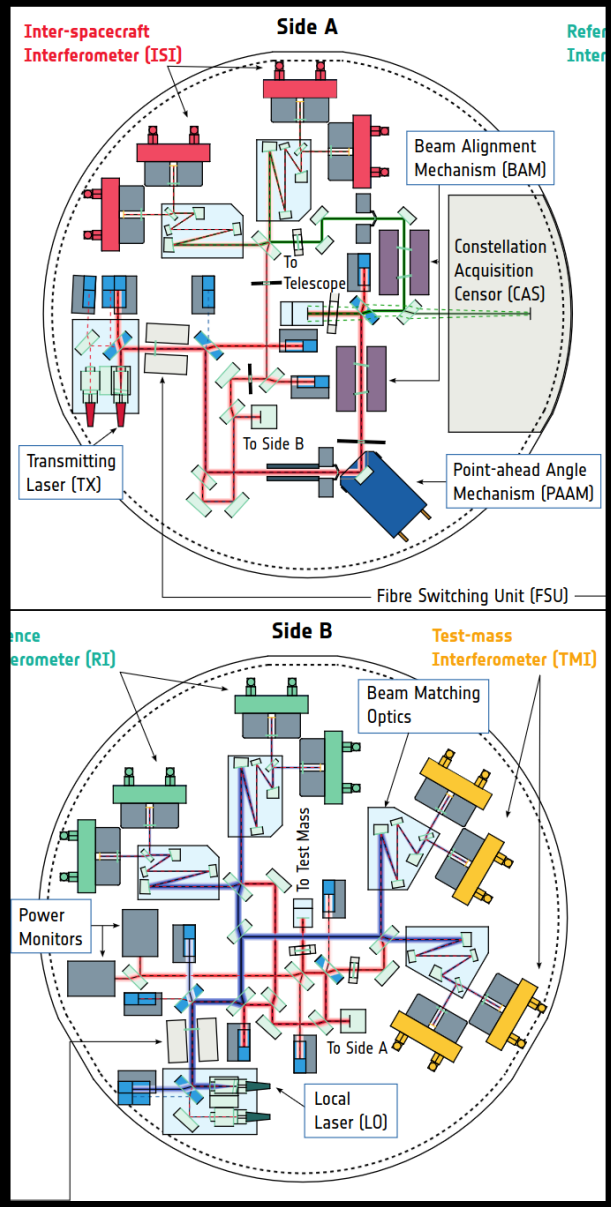
Interferometric Detection Subsystem (IDS)

- **Function**: Measures relative displacement between distant Test Masses via laser interferometry.
- **Architecture**: A complex subsystem, encompassing all equipment serving half of a single spacecraft.
- **Key sub-assemblies**:
  - Optical Bench Assembly
  - Phase Measurement Subsystem
  - Optical Bench Mechanism Control Unit
- **Precision**: Targets displacements lower than 10 picometer at 1 Hz through high-stability optical interfaces.



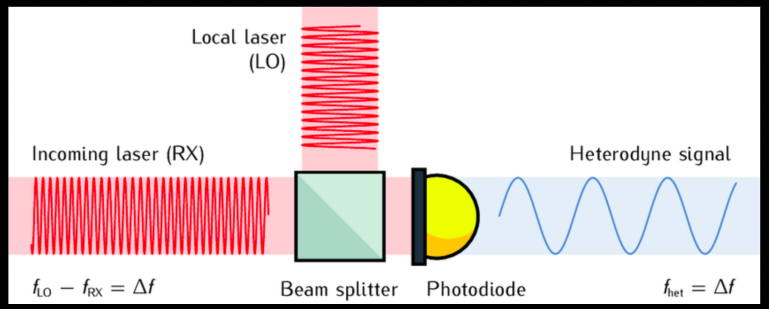
Optical Bench Assembly (OBA)

- **Function**: Central hub of the Interferometric Detection Subsystem.
  - Optical Bench.
  - Quadrant Photo-Receivers.
- **Sub-assemblies**: Interferometers
  - Science: distant OB to local OB
  - Test mass: local OB to local TM
  - Reference: local OB to adjacent OB
- Drives performance of optical interfaces to the Telescope and path length stability.



Phase Measurement Subsystem (PMS)

- **Function**: High-fidelity measurement of relative angular and longitudinal motions of the spacecraft and free-falling test masses.
- **Signal conversion**: Converts GW-induced phase fluctuations of the beam into beatnote photocurrent fluctuations between 5 and 25 MHz.
- **Requirements**: Extreme precision in high-resolution timing, timestamp accuracy, and consistency across the constellation.

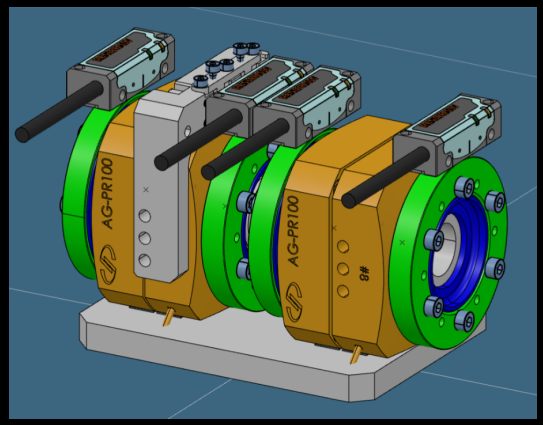


Heterodyne detection principle

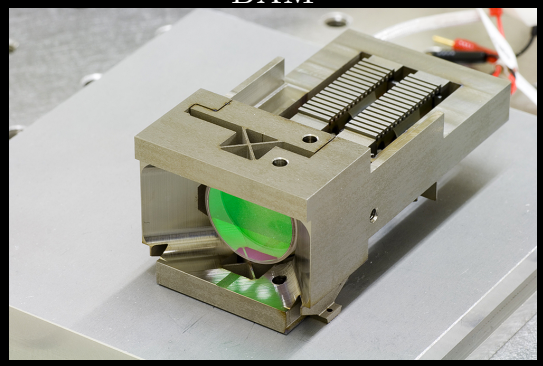
Phasemeter, MPI

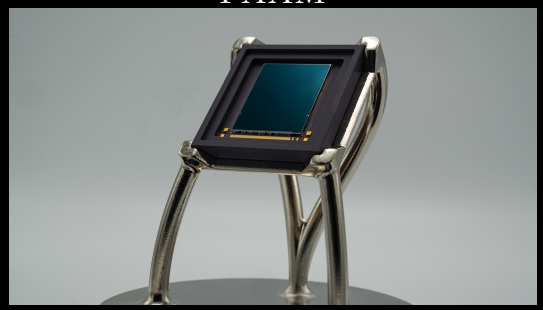
Optical Bench Mechanism Control Unit (OBMCU)

- **Function**: Controls critical moving parts within the Optical Bench Assembly.
- **Sub-assemblies**:
  - **BAM**: Beam Alignment Mechanism for precise optical path stability.
  - **PAAM**: Point-Ahead Angle Mechanism for compensating for signal direction.
  - **CAS**: Constellation Acquisition Sensor for measurement of spacecraft orientation
- **Requirements**: Precise alignment, precise pointing and precise orientation.



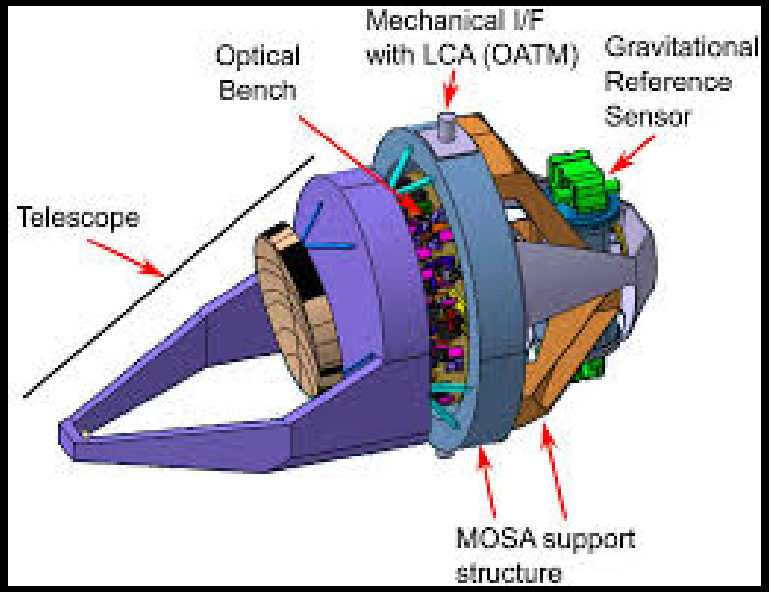
BAM


PAAM


CAS

Moving Optical Sub-Assembly (MOSA)

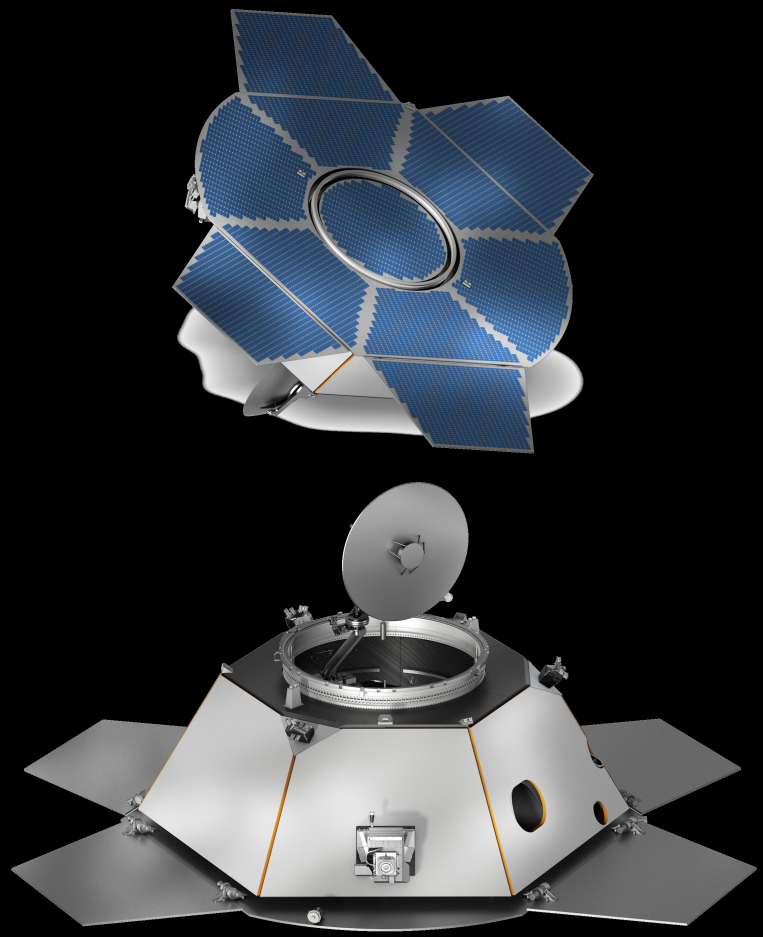
- **Function**: The MOSA is the fundamental opto-mechanical unit of the LISA instrument.
- **Sub-assemblies**: Telescope (TEL), the Optical Bench Assembly (OBA), and the Gravitational Reference Sensor (GRS).
- **Requirements**: Allow differential pointing within a spacecraft to compensate for the constellation orbit variation.



Spacecraft

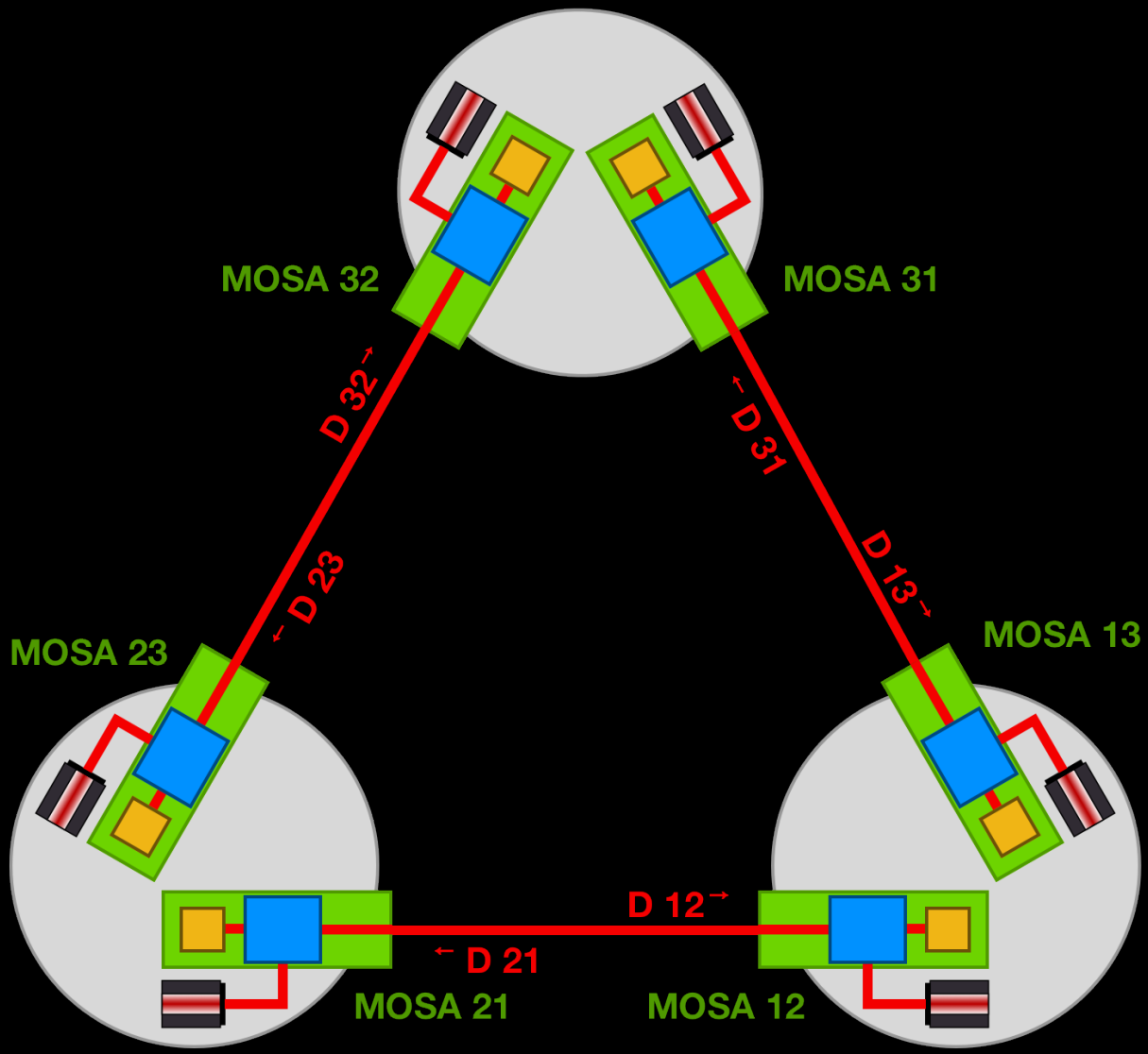
While the MOSA hosts our core metrology, the spacecraft itself must maintain its orbit and communicate:

- **Propulsion**: Fuel reservoirs for initial orbit insertion and station-keeping.
- **Power**: Solar panels.
- **Communication**: Deep space antenna.
- **Drag-free control**: μN thrusters to stay centered on the Test Masses.

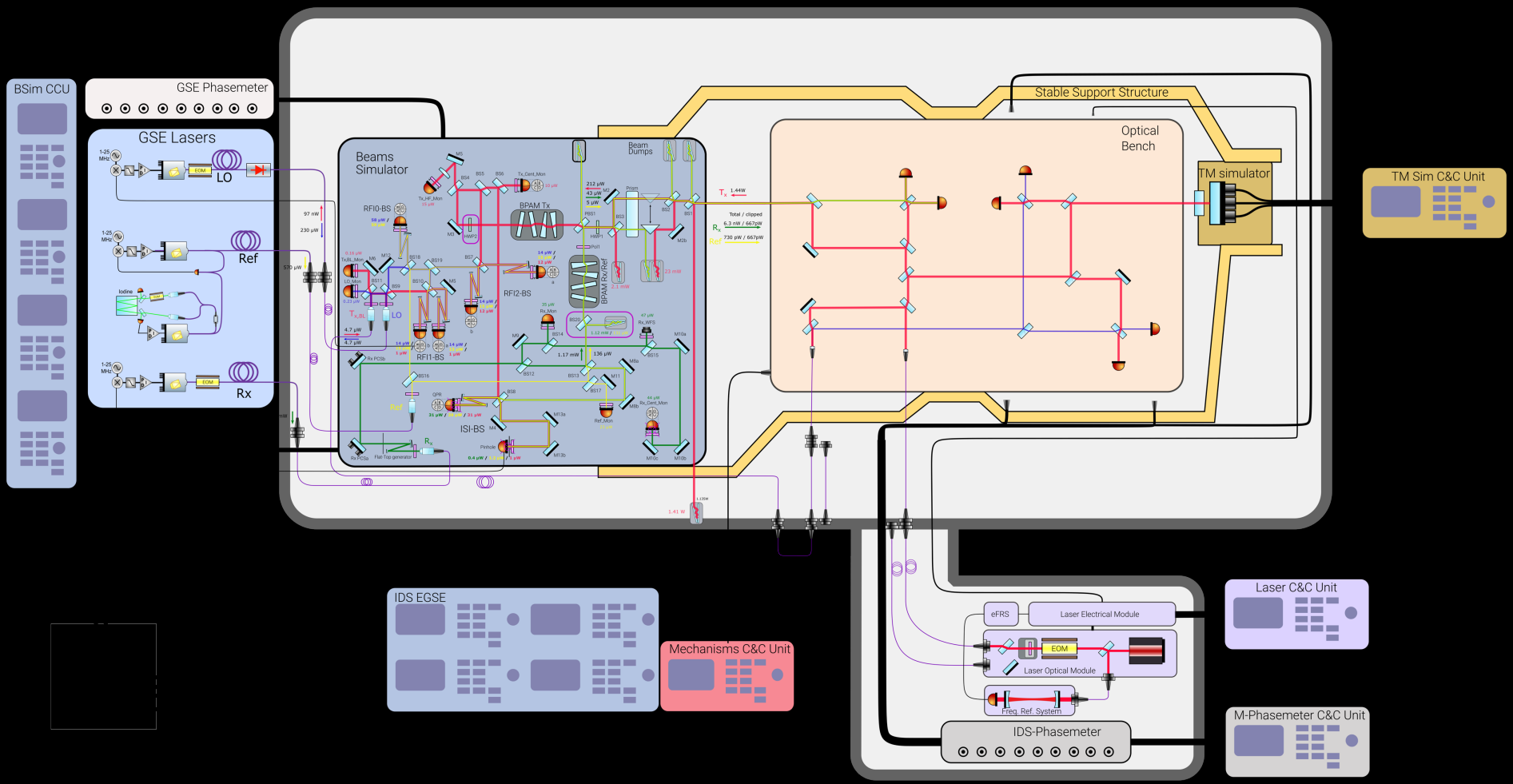


Spacecraft, OHB

The instrument recap



The long road to launch



Responsability: France

Ground Support Equipment : IDS Test Setup

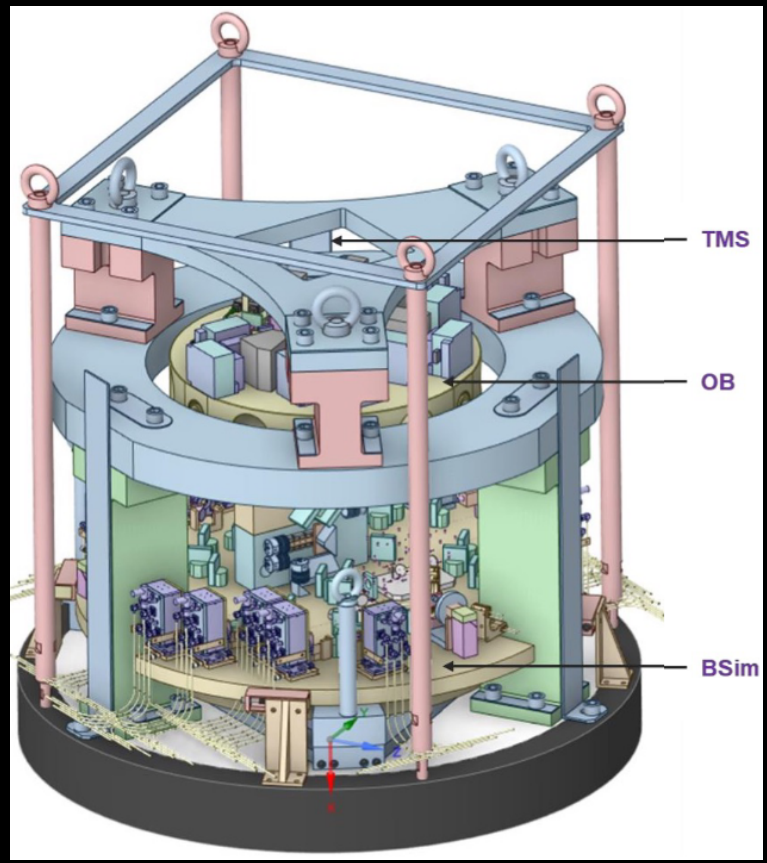
Primary Objectives:

- Verify interferometric performance within the IDS measurement band : at the 10 pm level at 1 Hz.
- Validate mechanical stability and alignment between critical components).
- Characterize noise contributions (thermal, microvibration, and acoustic) at relevant frequencies.

Sub assemblies:

- Test Mass Simulator
- Optical bench
- Beam Simulator

Responsability: APC, CEA, CNES

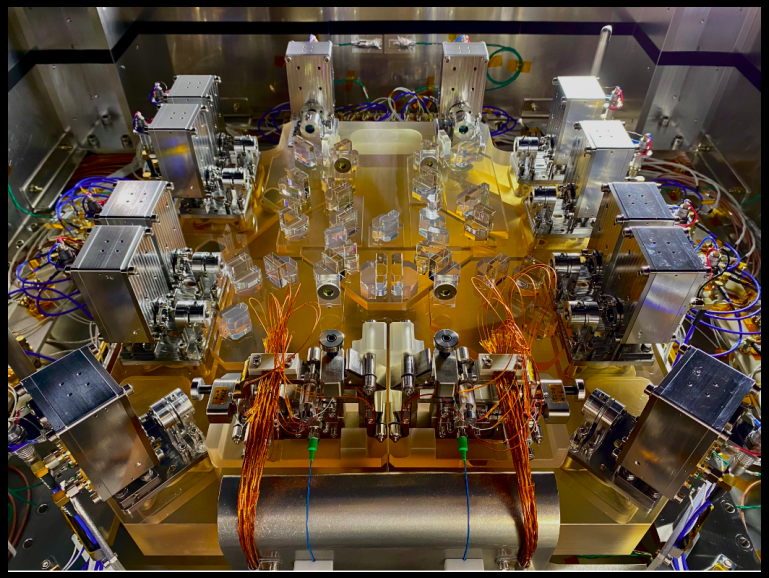


IDS Test Setup CAD model

Beam Simulator (BSim)

- **Function**: Simulates the optical signal of the LISA constellation in a controlled ground environment.
- **Interface**: Integrated within the GSE to mimic the Optical Bench (OB) and Telescope (TEL) reference frames.
- **Requirement**: Must maintain transversal rotation stability (Y and Z axes) to minimize mechanical noise.

Responsability: APC

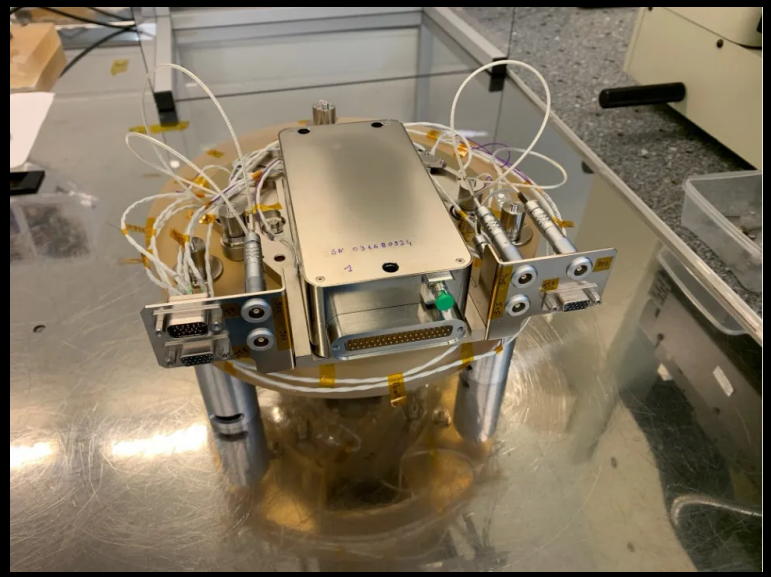


BSim predecessor : Zerodur interferometer
arXiv:2511.16749

Test Mass Simulator (TMSim)

- **Function**: Part of the IDS GSE setup to mimic the physical properties of the actual free-falling test masses.
- **Operations**: Can be actuated in different direction to simulate beam reflection on the test mass.

Responsability: CEA



The end

Conclusion

- LISA is a complex instrument whose technologies:
  - were mostly demonstrated in LISA Pathfinder.
  - are currently being studied for the remaining elements.
- Timeline-wise, the design reviews:
  - were completed in 2025 for the Preliminary Design Review.
  - are scheduled for 2026 for the Critical Design Review.

Thank you for your attention.

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