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The LISA mission: a space-based gravitational-wave observatory

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Summary. — In January 2024, the European Space Agency (ESA) officially approved the Laser Interferometer Space Antenna (LISA) mission, which now moves into the implementation phase. With a planned launch in 2035, LISA is envisioned as the first space-based gravitational-wave observatory, sensitive at frequencies between 100 µHz and 1 Hz, not accessible to ground-based observatories. Given the size of the project and the stringent experimental requirements (measurement of femto-g accelerations with picometer displacement sensitivity, between objects millions of kilometers away), LISA represents a complex challenge from many points of view: technological, scientific, engineering, and organizational. Here we summarize the main features of the mission, with a focus on the contribution from Italy.

1. – Introduction

On January 25, 2024, the European Space Agency (ESA) officially approved the Laser Interferometer Space Antenna (LISA) mission. LISA, currently scheduled for launch in 2035, will be the first space-based observatory for gravitational-wave observation, and will be an international collaboration between ESA, its member states, and NASA.

The LISA concept [1, 2], foresees a constellation of three identical spacecraft, displaced as an equilateral triangle with 2.5×10^6 km sidelength, trailing the Earth on its orbit around the Sun, and connected by laser beams for sub-nm interferometry. LISA is envisioned for a 4-year nominal mission duration, with the possibility to extend it up to 10 years.

In this timespan, LISA will be sensitive to a multitude of gravitational-wave signals, overlapping and superimposing to one another, in the frequency range from 100 µHz to 1 Hz. This frequency band "hosts" signals generated by a plethora of astrophysical sources [2]: massive black hole binaries, inspiralling for days to months, and merging; stellar-mass black hole binaries, inspiralling; orbiting binary stars in the Milky Way Galaxy, mainly white dwarfs, and potentially unknown sources.

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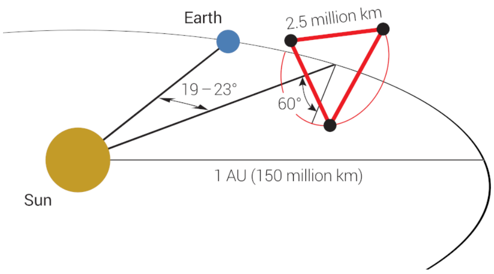
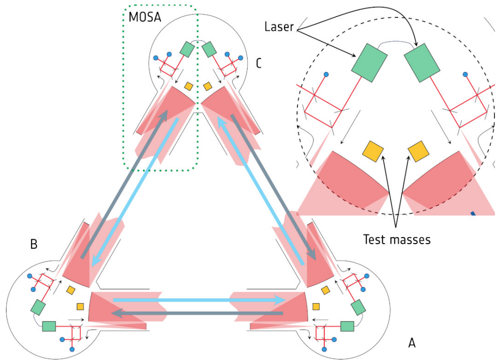


(a) Orbits of the three spacecraft of the LISA mission (not to scale): the constellation, in a near-triangular configuration with 2.5×10^6 km sidelength, will be placed on an Earth-trailing orbit at about 50 million kilometers from the Earth. Reprint from [1].



(b) The LISA constellation, main features: the laser beams, represented schematically, will perform end-to-end interferometric measurements between the 2-kg gold-platinum test masses. The acronym MOSA indicates the Moving Optical Sub-Assembly. Reprint from [2].

Observations from LISA will be complementary to the ground-based observations from the interferometers of the LIGO-VIRGO-KAGRA collaboration, which have been observing gravitational waves since 2015. Indeed, the LISA measurement will take place in a much lower frequency band. The reason why the LISA measurement can not be performed on-ground is the presence of the seismic and Newtonian noise backgrounds on Earth, which hinder the detection of gravitational waves below $\sim$Hz frequencies (see next section about test mass free-fall). Lower frequencies are populated by signals from completely different gravitational-wave sources than the higher ones, making the LISA science case stronger and fascinating.

2. – Free-falling test masses and long-arm interferometry

At the heart of the LISA measurement, will be the Test Masses (TM), 2 kg cubes made of a gold-platinum alloy, two for each spacecraft (represented schematically in Fig. 1b). These TMs will be the end mirrors of the laser interferometers across the long 2.5×10^6 km LISA arms, and will be freely floating inside their respective spacecraft, with no mechanical contacts. Indeed, one of the main challenges for gravitational-wave observation is that the reference objects must act as geodesic references in the general relativistic sense, meaning that they must be in nearly perfect free fall.

The free-fall purity required to achieve the LISA objectives (i.e. a gravitational-wave strain sensitivity of about $10^{-20}\,/\sqrt{\text{Hz}}$ at mHz frequencies) is so stringent that the sole radiation pressure from the Sun, which naturally fluctuates, would totally hinder any detection, which requires a residual spurious acceleration below $3\,\text{fm}\,\text{s}^{-2}/\sqrt{\text{Hz}}$ at mHz frequencies. The foremost strategy implemented to face this challenge is a particular control-loop strategy, which consists of controlling the spacecraft motion with micro-propulsion modules on its external surface, to keep it centered with respect to the TM so that the external force is counteracted and not transmitted to the TM itself, which is effectively shielded. This strategy, called *drag-free* control, is implemented along the laser axis for each of the six LISA TMs.

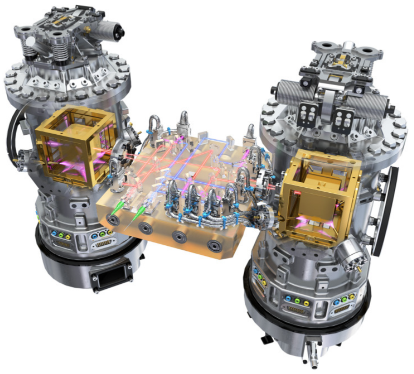
To reach the requirements for gravitational-wave observation, the displacement between the distant TMs must be finely tracked, with a precision better than $15\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at mHz frequencies. End-to-end interferometry will be split into three sections, as shown in Fig. 1b: two local interferometers (TM-to-spacecraft and spacecraft-to-TM on the other end) and a long-arm spacecraft-to-spacecraft. It is essential that the LISA laser arm is so long, as this allows for the required gravitational-wave sensitivity at these low frequencies. The lasers, based on Nd:YAG oscillators, will emit light with 1064 nm wavelength and 2 W power, $\sim 100\,\mathrm{pW}$ of which will reach the other end, will be used for interferometry, phase-locked and sent back at full power. The exact frequency of these lasers will be adjusted according to the Doppler shift caused by the orbit "breathing" modes, so that heterodyne interferometry will be feasible. Moreover, to account for the (small, but still relevant) angular fluctuations of the LISA constellation, each TM, along with its respective telescope, its closest instrumentation, and its optical bench, will be part of a Moving Optical Sub-Assembly (MOSA), which will be slowly moving to ensure accurate pointing toward the distant spacecraft.

In addition to instrumental challenges, on-ground post-processing will be a crucial part of signal recovery, as the raw phasemeter data will contain an overwhelming instrumental laser noise. This issue can be overcome with the so-called Time Delay Interferometry (TDI) technique, consisting of creating virtual interferometry arms capable of suppressing such noise of several orders of magnitude.

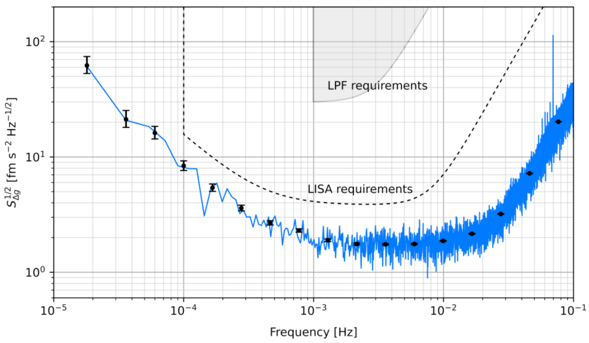
3. – The GRS and the role of LISA Pathfinder

The role of the Italian contribution to the LISA instrument is the design and delivery of the Gravitational Reference System (GRS), which is the LISA system in charge of controlling the TM motion, playing a dominant role in ensuring the free-fall requirement and the absence of spurious external forces above the required threshold. The GRS provides electrostatic active control and sensing of the TM position along all degrees of freedom (except for the application of force along the sensitive interferometric axis, as it is drag-free controlled). It also provides a suitable vacuum environment, with venting-to-space of the vacuum chambers during operations. To counteract the TM charging-up caused by interactions with cosmic rays, and comply with the free-fall requirement, the GRS provides a UV charge management system, with LED illumination of the TM and its surroundings aimed at discharging the TM during operations. In addition to this, the GRS also provides the mechanical launch-lock mechanisms and grabbing-positioning mechanisms, aimed at constraining the TM with a kN preload during launch, and releasing it with a velocity less than µm/s for operations.

The GRS, however, relies on a strong heritage. The LISA GRS will indeed be a near rebuild of the GRS of ESA's LISA Pathfinder mission (LPF). LPF was a precursor of the LISA mission, aimed at assessing the technical feasibility of LISA. Launched in 2015 and operational until 2017, it successfully demonstrated the requirements for LISA [3, 4], paving the way toward its recent adoption, and confirming the GRS as a crucial system for the observation of gravitational waves from space. In Figs. 2a and 2b, we show respectively a rendering of the LPF instrumentation (the LISA GRS will be very similar to this), and the main results from the LPF mission, showing its compliance with requirements. LISA Pathfinder carried onboard a miniature version of the LISA arm: instead of being 2.5×10^6 km long, it was just 38 cm, so it was not sensitive to gravitational waves, but it was to spurious external forces, providing a suitable testing



(a) The LISA Pathfinder instrumentation, and its GRS. The LISA GRS will rely on a strong heritage from the LPF one. [Credits: ESA/ATG medialab]



(b) Results of the LISA Pathfinder mission performance, February 2017 run, showing that the final differential acceleration between the two TM was below the LPF requirements, and even below the LISA requirements.

tool for LISA.

4. – Way forward and GRS testing

The LISA mission has now entered its implementation phase, and is entering its design, prototyping, and testing phase. Prototypes of the LISA electrode housings and charge management system, in particular, will undergo thorough testing campaigns at the facilities at the University of Trento. The prototypes will be mounted on fiber-suspended torsion pendulums with high quality factor, which allow for on-ground testing of many aspects, even though with a reduced sensitivity than on orbit. Such tests will be valuable tools for the next steps towards LISA.

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REFERENCES

[1] Amaro-Seoane et al. Laser Interferometer Space Antenna, 2017. DOI: 10.48550/arXiv.1702.00786.

[2] LISA science study team LISA Definition Study Report. (2024) DOI: 10.48550/arXiv.2402.07571

[3] M. Armano et al. Beyond the Required LISA Free-Fall Performance: New LISA Pathfinder Results down to 20 µHz. *Phys. Rev. Lett.*, 120:061101, Feb 2018. DOI: 10.1103/PhysRevLett.120.061101.

[4] M. Armano et al. Sub-Femto-g Free Fall for Space-Based Gravitational Wave Observatories: LISA Pathfinder Results. *Phys. Rev. Lett.*, 116:231101, 2016. DOI: 10.1103/PhysRevLett.116.231101.