LISA – A GIANT LASER INTERFEROMETER IN SPACE FOR GRAVITATIONAL WAVES DETECTION

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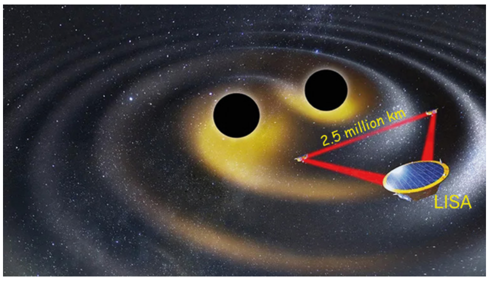

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LISA will be a space-based gravitational-waves observatory to be launched mid-2030, targeting the mHz band, inaccessible from Earth. Using a 2.5 million-km laser interferometer, it measures pm-scale distance variations between free-falling test masses. This article introduces LISA's most critical technologies such as ultra-stable lasers, precision interferometry, ultra-stable optical benches, telescopes, gravitational reference sensors, drag-free control with micro thrusters, Time Delay Interferometry, and stringent stray light control.

Introduction to LISA mission

Gravitational waves (GWs) are perturbations of space-time generated by the accelerated motion of massive systems, such as compact binaries. Propagating at the speed of light, they slightly stretch and compress distances between free-falling objects in orthogonal directions. These effects are extremely small: for astrophysical sources detected so far, relative distance variations are typically ~10^{-21}.

Predicted by Einstein in 1916–1918 [1], GWs remained undetected for a century. Their observation became possible thanks to modern technologies used by ground-based detectors (LVK Collaboration): narrow-linewidth lasers stabilized to ultra-stable optical cavities, large-area mirrors with extremely low losses, free falling test masses and low-noise photoreceivers. Since 2015, these instruments have detected more than four hundred GWs sources, opening a new era of astronomy [2].

While ground-based detectors can only observe sources in the audio-frequency band above 20 Hz, low-frequency sources from μHz up to 1 Hz can be detected only from space, where the quieter environment avoids terrestrial disturbances such as seismic noise. The concept of a laser-interferometric GWs detector in space emerged in the early 1980s [3], with the goal of detecting astrophysical objects inaccessible from ground - such as galactic binaries of white dwarfs, mergers of supermassive black holes,

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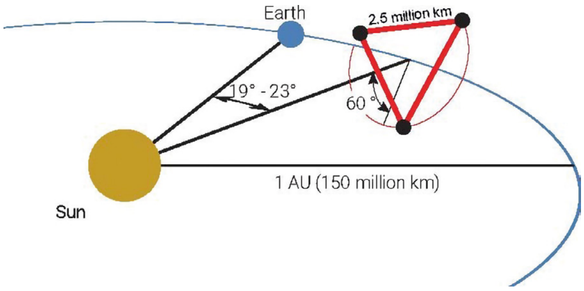


Figure 1. LISA mission orbit (not to scale): three S/C in an equilateral triangle of 2.5 million km arm, trailing on heliocentric orbit, behind the Earth at ~ 50 million km.

or extreme-mass-ratio inspirals - as well as cosmological sources. Furthermore, such an instrument can observe the inspiral of compact binaries that will eventually be detected on Earth, but much earlier in time - from a few hours to up to a year - well before they enter the audio-frequency band of ground-based detectors.

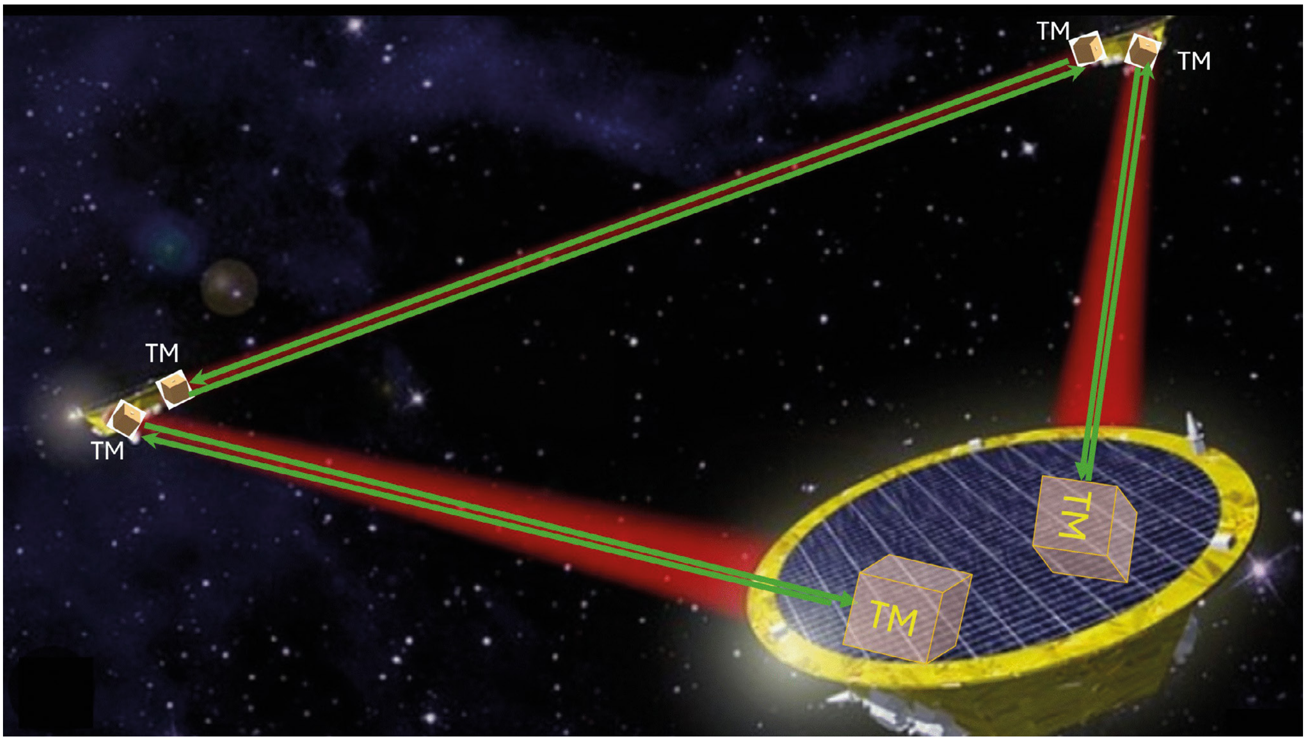
After decades of development and the successful demonstration of free-falling test-mass technology with ESA's LISA Pathfinder mission [4], the Laser Interferometer Space Antenna (LISA) was selected in 2017 [5] as the L3 mission of ESA's Cosmic Vision program and formally adopted in 2024. Launch is planned in the mid-2030s [6].

LISA consists of three spacecraft (S/C) forming an equilateral triangle with 2.5-million-km sides in a heliocentric orbit (Fig. 1). Together they act as a giant space-based Michelson interferometer, with a third arm providing independent measurements of the two GWs polarizations and system redundancy. The formation is centered in the ecliptic plane, 1 AU from the Sun and about 20° behind Earth. Its plane is inclined by 60°, and the S/C orbits are designed to preserve the triangular configuration throughout the year, making the formation appear to rotate once per year around its center.

Each S/C houses two free-falling test masses (TM), one at the end of each arm (Fig. 2). A drag-free control system adjusts the S/C position to follow the TMs, ensuring they remain in near-perfect free fall and serve as inertial references. Along every arm, two laser beams are continuously exchanged between S/C. By comparing the phase of the received light with that of the local laser, LISA measures tiny distance variations projected along the arms—variations that directly reveal the passage of GWs through the three-satellite constellation.

The three S/C will be launched from the Guiana Space Centre in Kourou, aboard an Ariane 6.4. The scientific payload is composed of subsystems developed by sixteen European partners - space agencies, laboratories and industry – together with NASA, under ESA leadership. OHB System AG serves as Industrial Prime Contractor, leading a consortium in which Thales Alenia Space Italy is a core team member responsible, among others, of avionics and telecommunications.

Figure 2. LISA measures pm distance variations between free-falling test masses situated at the end of each arm, using laser beams exchanged between the satellites.



LISA payload critical technologies

The LISA mission relies on several tightly integrated, high-performance technologies that enable the detection of GWs in the mHz frequency band, with a required noise floor below 10 pm/√Hz. The main technologies - shown in Fig. 3 and described below - push the limits of current space optics and engineering, and must operate with exceptional stability and reliability throughout the extended mission lifetime of ten years.

A core technology of LISA is the realization of near-perfect free-fall TMs, which serve as inertial references and act as a mirror for the laser beam. Each S/C houses at the end of the arm a cubic gold–platinum TM (≈2 kg, 46 mm side length), selected for its extremely low magnetic susceptibility and thermal sensitivity. Non-gravitational forces must be reduced so that residual acceleration noise stays below ~3×10^{-15} m·s^{-2}/√Hz above 0.1 mHz. This requires tight control of electrostatic forces (few fN/√Hz), magnetic and thermal fluctuations (few nT/√Hz and <10 µK/√Hz), and of TM charge (< ~10^{7} e-). The surrounding Gravitational Reference Sensor (GRS) provides capacitive sensing and electrostatic actuation with < ~1 nm/√Hz, displacement noise in ultra-high vacuum (<10^{-5} Pa), enabling near-ideal free fall as demonstrated by LISA Pathfinder.

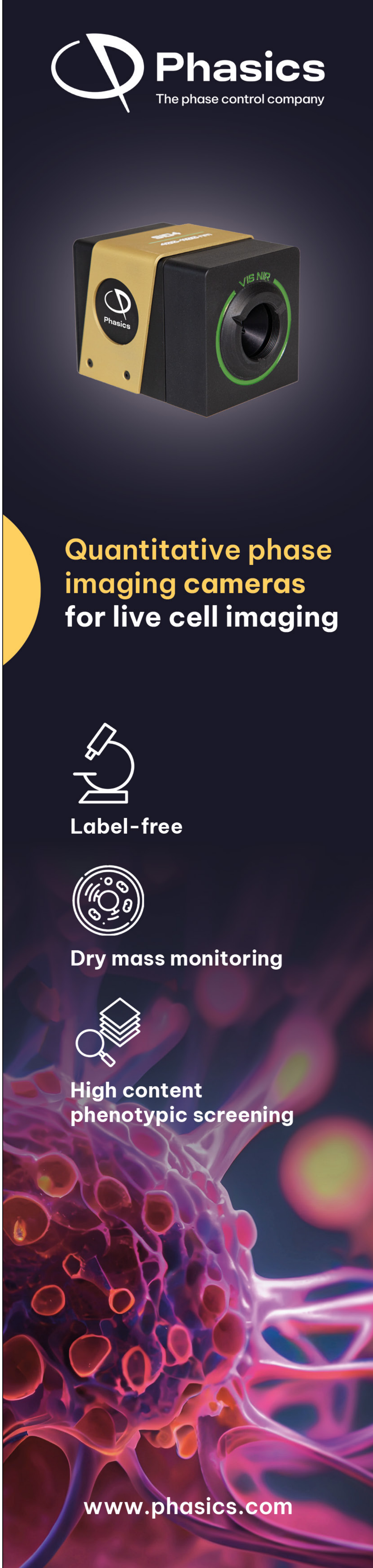
Ultra-high-precision laser interferometry is at the heart of LISA's measurement system. The mission uses single-frequency, continuous-wave Nd:YAG lasers at 1064.5 nm delivering ~2 W, and MHz-beat-note heterodyne interferometry achieves phase readout noise below ~10 µrad/√Hz, corresponding to ~1–2 pm displacement resolution. Despite pre-stabilization to an ultra-stable cavity (~30 Hz/√Hz in the mHz band), laser frequency noise still dominates because of the ~8 s light-travel time over the 2.5 million km arms. Time Delay Interferometry (TDI) suppresses this noise by 8–9 orders of magnitude by combining time-shifted phase measurements from the three spacecraft to synthesize virtual equal-arm interferometers, pushing laser noise well below TM acceleration noise and shot noise across the LISA band.

The optical bench is a central, performance-critical element of the interferometric system, providing a mechanically and thermally ultra-stable platform for measurement. Built as a quasi-monolithic structure from ultra-low-expansion glass-ceramic with optics bonded by hydroxide-catalysis, it offers sub-nanometer long-term stability. Optical pathlength noise must remain below a few pm/√Hz, requiring strict control of thermal gradients, mechanical stress, and alignment.

LISA telescopes are key optical subsystems that transmit and receive the laser beams between S/C while preserving wavefront quality and pointing stability. Each telescope has an aperture of 30 cm and must deliver diffraction-limited performance with extremely low wavefront distortion. Pointing jitter and pathlength fluctuations must remain of ~ few nrad/√Hz and ~1 pm/√Hz to avoid degrading the interferometric phase measurement.

Maintaining the TM in free fall requires drag-free control of the spacecraft, implemented using ultra-low-noise micro propulsion systems. Microthrusters provide continuous thrust at the level of a few µN to counteract non-gravitational forces such as solar radiation pressure, while maintaining thrust noise below a few tens of nN/√Hz in the LISA measurement band. This performance is essential to prevent S/C motion without reintroducing acceleration noise onto the TMs.

Control of stray light is another key technology challenge for LISA. Scattered, reflected, or back-coupled light – whether in fibers or free-space – can coherently mix with the main interferometric signals and generate spurious phase noise. Stray-light-induced heterodyne noise must remain at ~1 pm/√Hz in each interferometer. Achieving this requires careful optical design, dedicated baffles and beam dumps, low-scatter optical coatings, tight control of surface roughness, and accurate knowledge of component-level scattering. Complex optical simulation, including imperfections, and dedicated monitoring equipment's are essential to identify, quantify, and mitigate coherent stray light.



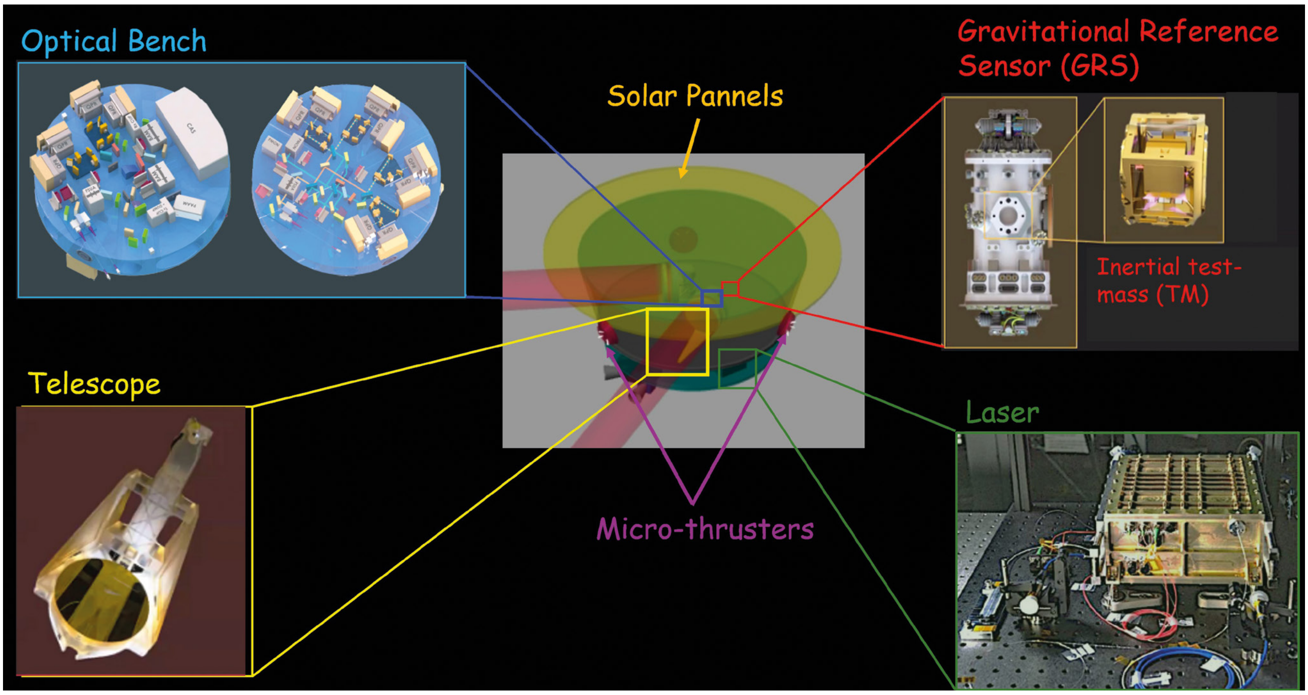


Figure 3. LISA satellite and payload critical technologies.

Finally, low noise photoreceivers and their associated readout electronics are required to detect weak heterodyne signals with high linearity and long-term stability. Shot noise, electronic noise, and parasitic couplings must remain below the allocated displacement noise budget, ensuring that they do not limit the GWs measurement sensitivity.

Dedicated performance tests of the Optical Metrology System (OMS) will support the qualification of LISA's critical interferometric technologies. These tests must confirm that the end-to-end detection noise meets the ~10 pm/√Hz requirement. Using specialized optical, electrical and mechanical ground-support equipment under controlled thermal and mechanical conditions, they will characterize optical pathlength stability, readout noise, stray-light mitigation and the tilt-to-length coupling effects. These activities are crucial for consolidating the OMS noise budget, ensuring compliance with mission requirements, and reducing risk before system-level integration.

Conclusions

LISA brings together an unprecedented combination of ultra-stable interferometry, near-ideal inertial references, drag-free spacecraft control, and advanced signal processing to probe the low-frequency GWs Universe. The mission performance emerges from the coherent integration of these technologies, each operating at the edge of what is achievable in space. By successfully mastering laser stability, precision optics, stray-light control, time-delay interferometry, TM free fall and micro propulsion, LISA opens a new observational window on the Universe, enabling the direct exploration of gravitational phenomena inaccessible by any other means. It is remarkable that this effort, as well as the effort aiming at the processing and interpretation of the future GWs readout data, is indeed pursued by a collaboration of ~10 space agencies, ~40 nations and ~1700 scientists throughout the world. ●

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