# THE LISA MISSION A LASER-INTERFEROMETRIC GRAVITATIONAL WAVE DETECTOR IN SPACE

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## ABSTRACT

The European Space Agency has selected LISA, a Gravitational Wave Observatory, as a cornerstone mission in its future science program Horizons 2000. This observatory will complement the development of ground-based gravitational wave detectors currently under construction. A spaceborne detector will enable the observation of low-frequency gravitational waves in a frequency range from $10^{-4}$ to $10^{-1}$ Hz which is totally inaccessible to ground based experiments. This frequency range is unique in that it is expected to contain signals from massive black holes, galactive binary stars, as well as the most violent events in the Universe.

LISA will attain this low-frequency sensitivity by employing laser interferometric distance measurements over a very long base-line of $5\times10^6$ km. Three of these baselines form an equilateral triangle with spacecraft at each vertex. The cluster of spacecraft is in an earth-like orbit around the sun trailing the earth by 20°.

The spacecraft contain infrared light-emitting Nd-YAG lasers and freely floating test masses made from a special platinum-gold alloy with vanishing magnetic susceptibility. The spacecraft are being kept centered on their test masses using drag-free technology and field-emission electric propulsion, thus letting the test masses follow purely inertial orbits.

Key words: gravitational waves; laser interferometer.

## 1. INTRODUCTION

The origins of the LISA mission can be traced to a series of studies carried out in the US in the 1980s (Faller et al 1985). This led to a proposal to ESA in 1993 in response to the M3 announcement of opportunity (Danzmann et al. 1993) for a joint ESA/NASA mission. That proposal assumed four drag-free spacecraft in heliocentric orbit and was subsequently selected for study at assessment level as a European-only mission. A six-spacecraft version was then proposed in 1994 and later selected as an ESA Cornerstone mission in the Horizon 2000 Plus Programme (Bender et al. 1996). Recently, a light-weight and low-cost version with 3 spacecraft, but identical in all other respects, has been studied by NASA (Team X 1997). This concept is likely to be adopted as the baseline for future studies.

## 2. OVERVIEW

The idea of implementing an interferometer in space is rather straightforward, but the practical realisation requires an intricate blend of optical technology, spacecraft engineering and control. The interferometer mirrors can not simply float freely in space — they must be contained inside spacecraft. Nonetheless, they can be arranged to be floating almost freely inside the spacecraft, protected from external disturbances by the spacecraft walls. As long as the spacecraft do not disturb the mirrors, then, ideally, only gravitational waves would perturb their relative motion. "Drag-free control" can be employed to ensure that the spacecraft always remain centred on the mirrors.

In principle, then, the Michelson interferometer can be realised using three spacecraft: one at the "corner" to house the light source, beam splitter, and detector, plus one at each "end" to house the remote mirrors. There is a practical problem with such a configuration, though. All three spacecraft drift around, and the corner spacecraft would not be able to keep itself aligned with both of the end spacecraft at the same time, if the optics are fixed and the angle between arms changes. One way around this is to have steerable optics inside the corner spacecraft so that alignment can be maintained with the two arms independently, and this is likely to be adopted as the future baseline for LISA. The original LISA cornerstone design instead uses six spacecraft, arranged in a triangular configuration with two at each vertex.

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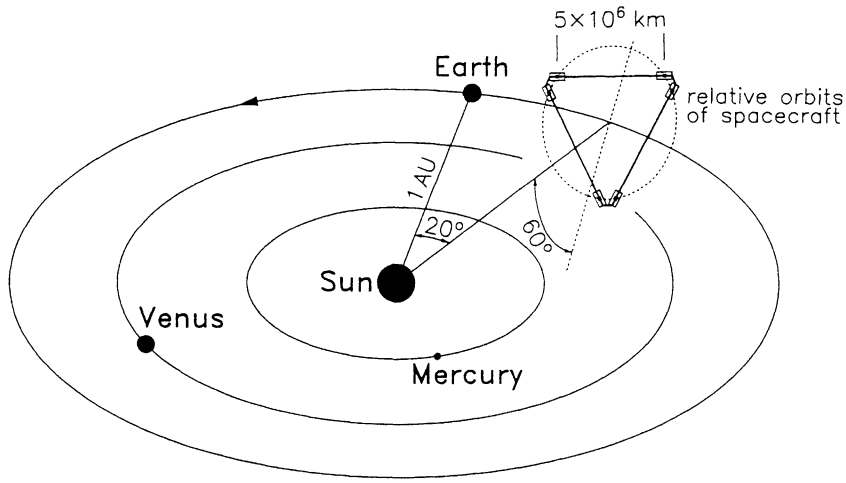


*Figure 1. LISA concept. Six spacecraft in a triangle, with a pair at each vertex. Only four are required for the basic interferometry. The other two provide supplementary science information and some redundancy.*

With this setup, each of the corner spacecraft can dedicate itself to pointing at only one of the end spacecraft, thus eliminating the need to steer the main optics. The corner spacecraft must, nevertheless, communicate with each other using steerable optics — but the separation distance is so much less that the steerable components can be much smaller, and hence more manoeuverable.

Each "corner" pair of spacecraft, separated by 200 km, is located at the vertex of a large triangle whose sides measure $5 \times 10^6$ km in length. This arm length has been chosen to optimise the sensitivity of LISA at the frequencies of known and expected sources. A factor of 2 increase may be desirable. However, an arm length increase beyond that would begin to compromise the high- frequency sensitivity when the light in the arms experiences more than half of the gravitational wave period. An interferometer shorter than $5 \times 10^6$ km would begin to lose the interesting low-frequency massive blackhole sources. It would give less scientific information but would not be any easier to build or operate because the spacecraft and the interferometry would be essentially the same.

Nominally in such an arrangement of spacecraft, any two sides of the triangle (i.e. four spacecraft) can be used for the main interferometry, with the third arm giving supplementary information and redundancy. With the six spacecraft configuration, up to two can be lost without jeopardising the mission (as long as the two failures are not at the same corner), since the basic group of four in an approximate "L" shape is sufficient to perform the full interferometry.

Each spacecraft is actually in its own orbit around the Sun. The six individual orbits have their inclinations and eccentricities arranged such that, relative to each other, the spacecraft rotate on a circle 'drawn through' the vertices of the giant triangle which is tilted at 60° with respect to the ecliptic. With this special choice of orbits, the triangular geometry of the interferometer is largely maintained throughout the mission. The centre of the triangle is located on the ecliptic — 20° behind the Earth — and follows the Earth on its orbit around the Sun. Ideally, the constellation should be as far from Earth as possible in order to minimise gravitational disturbances. The choice of 20° is a practical compromise based on launch vehicle and telemetry capabilities.

The once-per-year orbital rotation of the LISA constellation around the Sun provides the instrument with angular resolution, i.e. the ability to pin-point the particular direction to a source. An interferometer is rather omnidirectional in its response to gravitational waves. In one sense this is advantageous — it means that more sources can be detected at any one time — but it has the disadvantage that the antenna cannot be "aimed" at a particular location in space. For a given source direction, the orbital motion of the interferometer Doppler-shifts the signal, and also affects the observed amplitude. By measuring these effects the angular position can thus be determined. This is analogous to the technique used by radio astronomers to determine pulsar locations.

It is expected that the strongest LISA sources (from very distant supermassive black holes) should be resolvable to better than an arcminute; and even the weaker sources (galactic binaries) should be positioned to within one degree throughout the entire galaxy.

A LISA spacecraft is shown in Fig. 2, and a cross-section of the payload in Fig. 3. Each spacecraft has its own 1 W laser (actually two, one for redundancy), its own two-mirror telescope for sending and receiving light, and an optical bench which is a mechanically-stable structure on which various sensitive optical components are mounted. The mirrors enclosed in each spacecraft are actually 40 mm gold-platinum cubes (also referred to as the 'proof masses'). Each one is located inside a titanium vacuum can at the centre of the respective optical bench. Quartz windows allow access for the laser light.

Within the corner pair of spacecraft, one laser is the 'master', and a fraction of its light (10 mW) is bounced off the back surface of its cube, and sent to the neighbouring corner spacecraft (via the small

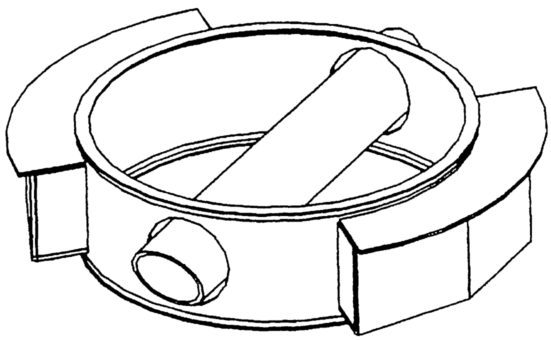

*Figure 2. One of the six identical LISA spacecraft according to the original cornerstone design. The main structure is a ring with a diameter of* 2.6 m, *and a height of* 0.7 m, *made from carbon-epoxy for low thermal expansion. The ring supports the payload cylinder, as shown. Equipment boxes are mounted on the outside of the ring, to house non-precision electronics (e.g. power regulator, computer, radios). FEEP control thrusters (not shown) are mounted at various locations on the outer spacecraft structure. The tops of the equipment boxes support two annular sections of solar array for power generation. A lid on top of the spacecraft (not shown) protects the thermal shields and payload cylinder from direct sunlight.*

steerable optics), where it is used as a reference to 'slave' the local laser. In this way, the main (~ 1 W) beams going out along each arm can be considered as having originated from a single laser. This is vital to the function of the interferometer.

The light sent out along an arm is received by the end spacecraft telescope, bounced off its cube, then amplified using its local laser, in such a way as to maintain the phase of the incoming light. The amplified light is then sent to the corner spacecraft. Amplification at the end spacecraft is required due to divergence of the beam over the very large distances. Even though each outgoing beam is extremely narrow — a few micro radians — it is about 20 km wide when it reaches the distant spacecraft. This diffraction effect, together with unavoidable optical losses, means that only a small fraction of the original output power (~ $10^{-10}$) finally reaches the end diode. If this was simply reflected and sent all the way back, only about 200 photons per hour would reach the corner diode after the round-trip. The phase-signals they carry would be swamped by shot noise, the quantum-mechanical fluctuations in the arrival times of the photons. The amplification brings the number back up to over $10^8$ photons per second — which makes the signal detection straightforward using standard photodiodes. The phase precision requirement for this measurement is seven orders of magnitude less demanding than is routinely achieved (at higher frequencies) in ground-based prototype interferometers.

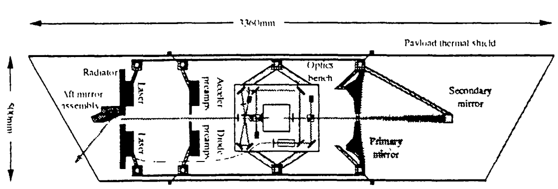


*Figure 3. Cross-section of the payload on each of the six identical LISA spacecraft.*

The resulting round-trip journey from the corner to the end and back, defines one arm of the large interferometer. On its return to the corner spacecraft, the incoming light is bounced off the cube and then mixed with a fraction of the outgoing light on a sensitive photodetector, where interference is detected. The resulting brightness variations contain the phase-shift information for one arm of the interferometer. This signal is then compared (in software on the on-board computer) with the corresponding signals from the other two arms, and some preliminary data processing is done. The results are then transmitted to Earth by radio link.

## 3. THE PAYLOAD CYLINDER

The telescope assembly, a preamplifier disk, a radiator disk, and the optical bench for the interferometry are mounted on a carbon-epoxy payload support cylinder with four stiffening rings surrounded by a carbon-epoxy payload thermal shield cylinder. A shield, cut at a 30° angle at both ends, keeps sunlight from the thermally stable payload interior throughout the heliocentric orbit.

### 3.1. Telescope Assembly

The receiving and transmitting telescope is a Cassegrain system with integral matching lens mounted from the payload support cylinder and protected by a thermal shield. The primary mirror is a double-arch light-weight ultra-low expansion ULE design and has a diameter of 30 cm and a focal length of 30 cm. The secondary mirror is supported by a three-leg carbon-epoxy spider. The beam to the secondary mirror from the instrument package is expanded to a diameter of approximately 3 cm by a suitable lens in the plane of the primary mirror. The optical elements have to be aspherics to reduce aberration in the f/1 telescope and require careful positioning. The temperature noise of the telescope must be less than $10^{-5}\,\mathrm{K}/\sqrt{\mathrm{Hz}}$ at $10^{-3}$ Hz to achieve the desired performance. Active focus control may be required to compensate for any long-term temperature drifts. The required final quality of the plane wavefront leaving the telescope is $\lambda/15$.

### 3.2. The Laser

The light source is a ring laser consisting of two monolithic YAG (yttrium-aluminium-garnet) crystals in series, each pumped by two laser diodes. The nominal single-mode output power is 2 W at a wavelength of 1064 nm. For LISA this has been downrated to 1 W to improve lifetime and ageing properties. The operating temperature for the pump diodes and the YAG-crystal will be maintained by heaters. A complete spare laser will be carried on each spacecraft.

YAG lasers are both light weight and very efficient. The whole laser, including pump diodes, weighs less than a kilogram and will give a continuous optical output power of 1 W for an electrical input to the diodes of 18 W. Furthermore, for a mission duration of a few years, the maintenance-free lifetime of the lasers has to exceed 100 000 hours in the space environment. Diode-pumped Nd:YAGs have already demonstrated achievable lifetimes of 20 000 hours at maximum power, and these lifetimes are considerably improved by operating the laser at half-power.

### 3.2.1. The radiator disk

The radiator disk (a carbon-plate 40 cm in diameter and 1 cm thick) is designed to radiate away the heat ($\approx 20$ W) dissipated by the laser. The aft-mirror assembly, for communication between the near spacecraft, is attached to this radiator disk.

## 3.3. The Optical Bench

The main optical components are located on an 'optical bench', containing the laser beam injection, detection and beam shaping optics, and the drag-free sensor (or "accelerometer"). The proof mass of the drag-free sensor acts as the mirror at the end of the interferometer arm. The bench consists of a solid ULE plate to which all components are rigidly attached. The components are shown schematically in Figure 4. Most components on this structure are passive. Exceptions are a motorised positioner for fibre selection and focusing, photodiodes for signal detection and a phase modulator that allows transfer of information between craft. Light from the laser is delivered to the optical bench by a single-mode fibre. A second fibre coupled to the back-up laser is also provided and may be selected if required.

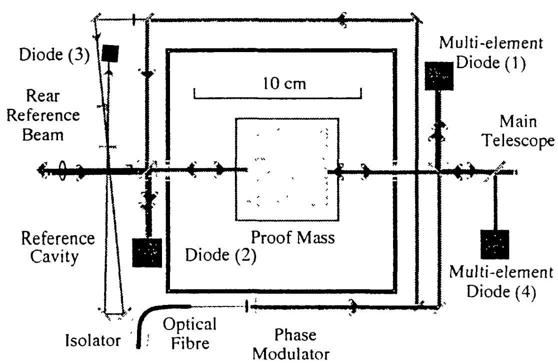


*Figure 4. Diagram of the optical bench. The chosen light path renders the measurement insensitive to movement on the spacecraft. The path followed by light from the local laser is shown in grey and that for light received from distant spacececraft is shown in black. Diode 1 registers the main interferometer signal and diode 2 the signal from the other spacecraft at that vertex, diode 3 is used to lock the laser to the reference cavity and diode 4 is used in pointing the spacecraft.*

About 1 mW is split off the main light beam to serve as the local reference for the heterodyne measurement of the phase of the transponded beam returning from the far spacecraft. This splitting is performed by the finite transmission of the polarising beamsplitter in front of the main mirror. Also, in each craft, a few mW is split off and directed towards a triangular cavity. This cavity is used as a frequency reference in the master craft, with those in the other craft being available for backup purposes.

The incoming light from the telescope is reflected off the proof mass and superimposed with the local laser on the phase measuring diode. An optical isolating arrangement consisting of a polarising beamsplitter and a quarter-wave plate is used to allow the required transmission, reception and phase comparison functions to be carried out in a compact way. On the two spacecraft at a vertex a small fraction (10 mW) of the laser light is reflected off the back of the proof mass and sent to the other vertex spacecraft for phase-comparison with the near spacecraft via the steerable aft-mirror of 1 cm diameter. This mirror is servoed using the signal from an auxiliary quadrant photodiode which senses both the phase difference between the two beams and the direction of the incoming beam from the other central spacecraft. By bouncing the laser beams off the proof mass in the manner described, the interferometric measurement of proof mass position is, to first order, unaffected by motion of the surrounding spacecraft. This allows a relaxation of its relative motion specification (though the requirement on proof mass residual motion with respect to inertial space remains unchanged).

## 3.4. Optical Efficiency

There are two classes of effect that limit the efficiency of the transmission of light from the emitting laser to the detection diode on the far spacecraft. These are the divergence of the laser beam and losses in the various optical components.

### 3.4.1. Beam divergence

Even the best collimated laser beam will still have some finite divergence governed by the size of the final optic. With a Gaussian beam optimised for transmission between mirrors of diameter $D$, with an arm length $L$, and a transmitted power $P$, the power received at the far craft is given by

$$0.50\,\frac{D^4}{\lambda^2 L^2}P\,. \qquad (1)$$

This is the case when the Gaussian beam has a waist (of radius $w$) at the transmitting craft that almost fills the final telescope mirror, $w = 0.446\,D$.

### 3.4.2. Efficiency of the optical chain

There are a large number of components in the optical chain. The main ones contributing to a loss of transmitted power are the fibre, the quantum efficiency, splitters, mirrors and lenses, and interference. All other components in the optical chain are assumed to be perfect. This gives a total transmission of the optical chain of .30. The term for interference is to allow for the fact that some signal is lost due to the imperfect matching of the local reference beam and the received light from the far craft: the local reference beam is Gaussian and the received beam is a 'Top Hat' mode.

## 4. THERMAL STABILITY

A high level of thermal stability is required by the interferometer. Thermal variation of the optical cavity to which the lasers are stabilized introduces phase variations in the interferometer signal, which have to be corrected for by using data from the two arms separately. Thermally induced variations in the dimensions of the transmit/receive telescope will lead to changes in the optical path length. Variations in the dimensions of the spacecraft will change the positions of components which cause a change in the mass distribution and hence cause an acceleration of the test mass.

The thermal stability needed is achieved by using structural materials with low thermal expansion coefficient and by using multiple stages of thermal isolation. The spacecraft and payload structural elements will be made of composite materials with thermal expansion coefficient less than $1 \times 10^{-6}$/K. The optical bench and telescope are supported by the payload cylinder which is weakly thermally coupled to the payload thermal shield which in turn is weakly coupled to the spacecraft body. This provides three stages of thermal isolation for the payload from solar and spacecraft electronics thermal input.

The main source of thermal variation is due to changes in the solar intensity around its mean value of $1350\,\mathrm{W\,m^{-2}}$. Observed insolation variations from 0.1 mHz to 10 mHz can be described by a spectral density with a shallow frequency dependence:

$$1.75 \times \left(\frac{f}{1\,\mathrm{mHz}}\right)^{-1/3} \quad \mathrm{W\,m^{-2}}/\sqrt{\mathrm{Hz}}.$$

To quantify the effects of solar and electrical variations, a simple thermal model for the spacecraft was formed with single nodes for the spacecraft body, solar panels, optical bench, telescope, laser radiator and electronics disk. The temperature fluctuations of the optical bench due to solar fluctuations were found to be well under the value of $10^{-6}\,\mathrm{K}/\sqrt{\mathrm{Hz}}$ at 1 mHz used in the analysis of the laser phase noise. To keep the power variations from producing thermal noise in excess of this, the power dissipation of the payload electronics will have to be controlled to $10\,\mathrm{mW}/\sqrt{\mathrm{Hz}}$ and the power dissipation of the photodiodes on the optical bench will have to be controlled to better than $50\,\mu\mathrm{W}/\sqrt{\mathrm{Hz}}$. The needed control can be achieved with small heaters and voltage and current sensors. The spacecraft electronics do not need to be controlled to better than the 0.1% typical of flight-qualified units.

The secondary mirror of the telescope is supported from the primary by a graphite-epoxy spider with length 40 cm and thermal coefficient of expansion $0.4 \times 10^{-6}$/K. The thermally-induced path-length variations using the thermal model were found to be less than $2\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at 1 mHz, and so are not a major source of noise.

The accelerations caused by changes in the mass distribution of the payload were assessed. The primary payload masses are the optical bench, the telescope, the payload electronics, and the laser/radiator combination. The test mass acceleration noise caused by solar fluctuations was found to be less than $1 \times 10^{-16}\,\mathrm{m/s^{-2}}/\sqrt{\mathrm{Hz}}$ at 1 mHz. The acceleration noise due to thermal variations in the dimensions and component positions of the spacecraft body has not yet been assessed.

## 5. NEW DEVELOPMENTS IN DESIGN

The original ESA cornerstone proposal called for a LISA mission with six spacecraft, with two spacecraft rather close together at each vertex. This makes the pointing control of each spacecraft somewhat easier and provides redundancy in the number of spacecraft, but implies a heavy penalty in terms of launch mass and, correspondingly, cost. Recently, a version with only three spacecraft has been the subject of a study (Team X 1997) in the US.

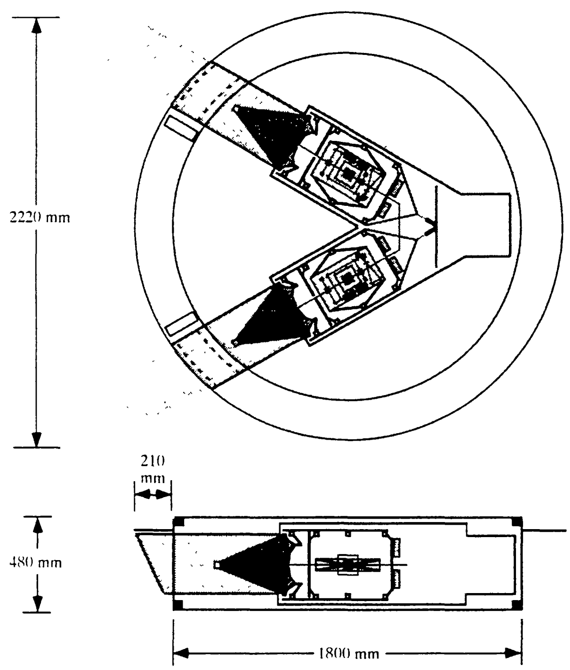


*Figure 5. Schematic diagram of Y-shaped payload and spacecraft assembly.*

The rationale behind a three-spacecraft LISA is to achieve considerable savings in launch mass and cost by giving up redundancy in the number of spacecraft but keeping full science redundancy.

To achieve this, each (single) corner spacecraft carries a Y-shaped payload (see Figure 5) containing the full complement of science instruments formerly contained in the pair of spacecraft at one vertex, e.g. two Cassegrain telescopes with F1 primaries of 30 cm diameter, two ultrastable oscillators (USO) to provide the offset frequencies for frequency locking the lasers and to remove the Doppler shifts of the laser light caused by spacecraft motion, and two optical benches each complete with optics, modulator, drag-free sensor, laser stabilization cavity, and photodiodes. Four laser systems will be provided on each spacecraft, mounted to a radiator disk mounted on the bottom of the spacecraft to radiate waste heat into deep space.

## 6. CONCLUSIONS

LISA is a well-studied mission and the interferometry well understood after more than two decades of experience with ground-based interferometers. LISA is a firm part of ESA's future science program and is now also being discussed as part of NASA's long-term plan. A launch before 2010 seems possible, especially if agreement on a collaborative arrangement between the two agencies can be reached.

## ACKNOWLEDGEMENTS

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