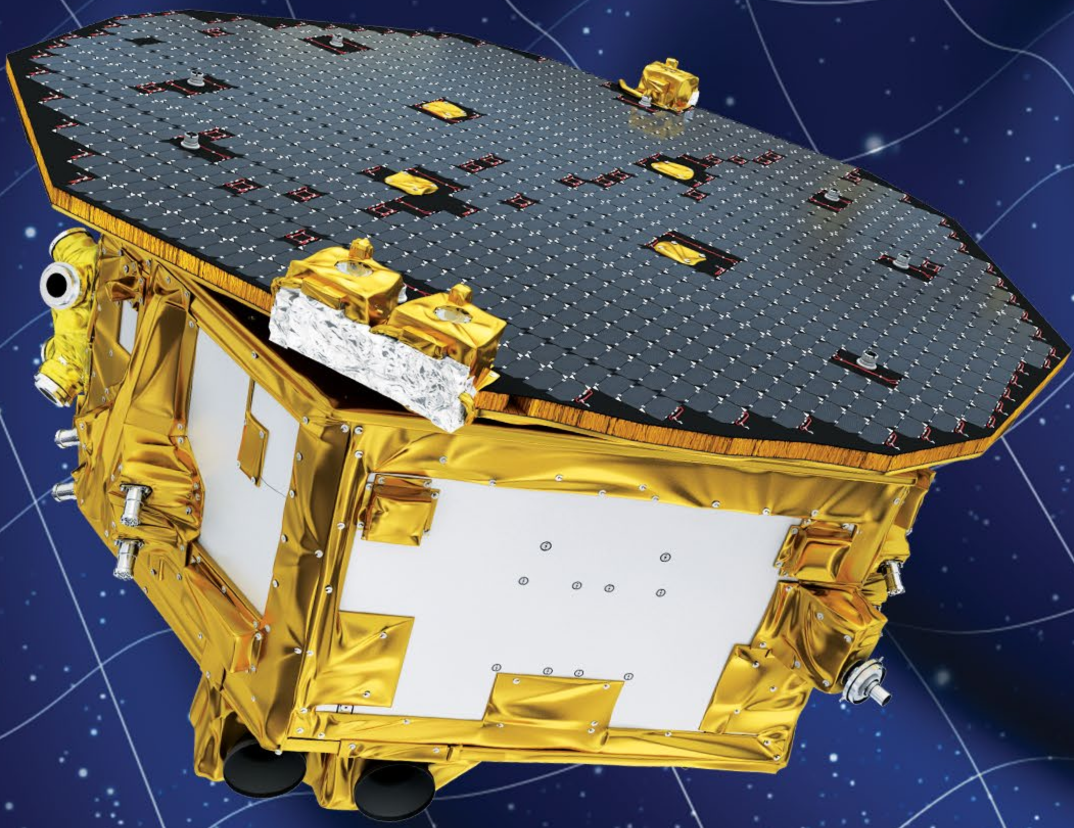

lisa pathfinder

→ FIRST STEPS TO OBSERVING GRAVITATIONAL WAVES FROM SPACE

European Space Agency

ESA'S SPACE SCIENCE MISSIONS

solar system

bepicolombo
Exploring the smallest, densest and least-explored terrestrial planet in the Solar System to unveil its mysterious origins.

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cluster
A four-satellite mission to investigate in unparalleled detail the interaction between the Sun and Earth's magnetosphere.

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rosetta
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solar orbiter
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jwst
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lisa pathfinder
Opening up a completely new way to understand time and space: seeing the Universe through gravitational waves.

planck
Detecting the first light of the Universe and looking back to the dawn of time.

xmm-newton
Using powerful mirrors to help solve mysteries of the violent X-ray Universe, from enigmatic black holes to the formation of galaxies.

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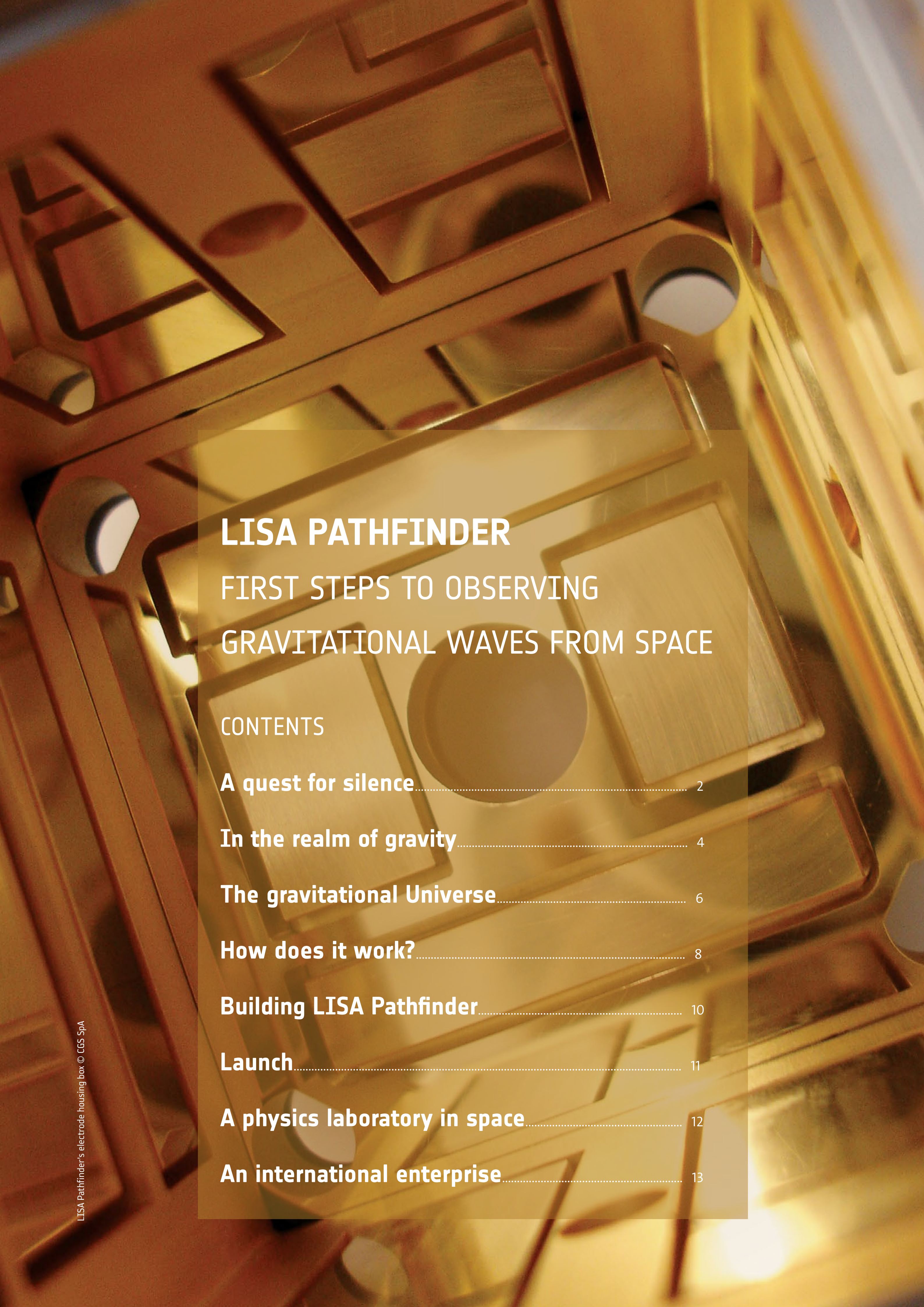


LISA PATHFINDER

FIRST STEPS TO OBSERVING GRAVITATIONAL WAVES FROM SPACE

CONTENTS

LISA Pathfinder's electrode housing box © CGS SpA

→ A QUEST FOR SILENCE

NASA/ESA/Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration and K. Noll (STScI)

Collision between two spiral galaxies, NGC 6050 and IC 1179

Astronomy relies on the observation of light from celestial bodies. For millennia, this meant visible light: only in the 20th century did new technologies and spaceborne telescopes begin to reveal a previously hidden side of the cosmos through the light across the electromagnetic spectrum.

To expand our window on the Universe even further, astronomers can also study other messengers that relay cosmic information beyond light. These include gravitational waves: the ripples in the fabric of spacetime predicted by Albert Einstein's general theory of relativity. Produced by massive bodies in acceleration, these perturbations are expected to be abundant across the Universe. Typical sources are supernova explosions and pairs of orbiting black holes. However, despite the attempts of ground-based experiments to detect them directly, gravitational waves so far remain elusive.

Space offers many advantages in this search, and ESA's LISA Pathfinder mission is a technology demonstrator that will pave the way for future spaceborne gravitational-wave observatories by testing the instrumentation for the first time in that environment.

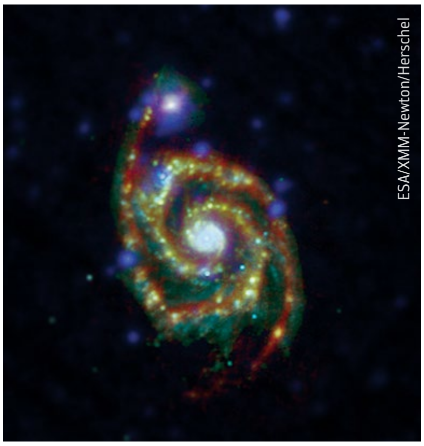
The concept of gravitational-wave detection is based on monitoring two freely falling bodies. As long as all other disturbances can be sufficiently reduced and the two bodies are truly moving under the effect of gravity only, a gravitational wave passing between them would change their separation. LISA Pathfinder will test the underlying and most challenging condition for such experiments: whether it is possible to put two test masses into a near-perfect gravitational free-fall.

Even in space, realising a freely falling system is very complex. There are many non-gravitational forces at play, including radiation pressure from sunlight, charged particles from the solar wind and impacting micrometeoroids, as well as internal effects caused by the spacecraft and its instruments.

For this reason, LISA Pathfinder is a high-tech box that surrounds two freely falling test masses without touching them, shielding them from outside influence by constantly applying tiny adjustments to its position.

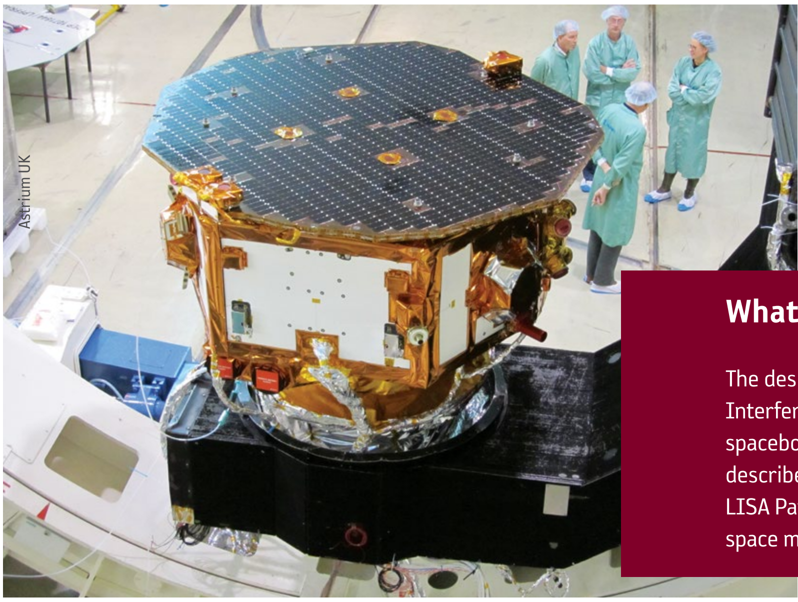
LISA Pathfinder is not aimed at the detection of gravitational waves themselves. Rather, its goal is to prove the innovative technologies needed to reduce external influences on two test masses and to measure their relative motion with unprecedented accuracy, tracking their free-fall by more than two orders of magnitude better than any past, present or planned mission.

LISA Pathfinder will create the most 'silent' place in the Solar System and measure how quiet it actually is.



ESA/XMM-Newton/Herschel

The M51 galaxy in X-rays, ultraviolet and infrared light



LISA Pathfinder
in the cleanroom

What's in a name?

The designation 'LISA' in the mission's name stands for Laser Interferometer Space Antenna, an earlier concept for a spaceborne observatory for gravitational waves, and now used to describe a class of missions based on the original LISA concept. LISA Pathfinder will test key technology for future LISA-like space missions to study the gravitational Universe.

Searching for gravitational waves

On a cosmic scale, the gravitational force is the most influential of the four fundamental forces in the Universe (the others being the electromagnetic force, the strong nuclear force and the weak nuclear force). Gravity drives the formation of stars, galaxies and black holes, and the evolution of the Universe as a whole.

To reveal the power of its action across the cosmos, scientists are seeking gravity's own messengers: gravitational waves. Investigating the gravitational Universe has been identified by ESA as the scientific theme for its L3 mission, the third Large-class mission in the Cosmic Vision science programme.

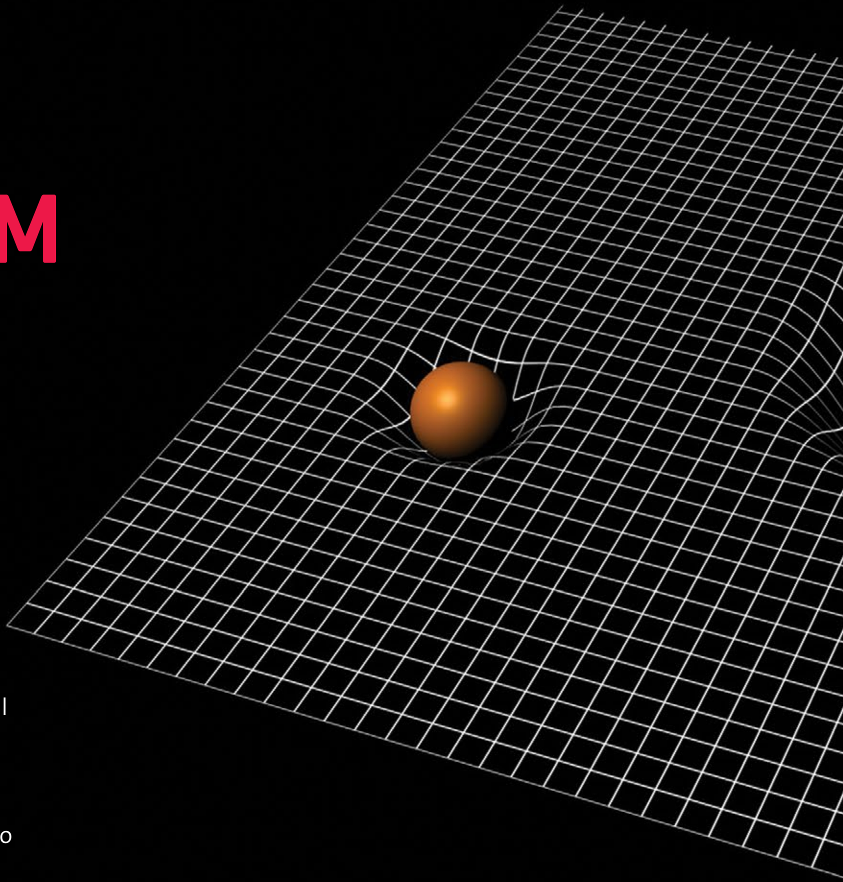
The first experimental efforts to detect ripples in the fabric of spacetime date back to the 1960s, when scientists attempted to measure tiny variations in the length of a massive metal bar caused by passing gravitational waves. Later, new detection methods were developed, the most sensitive of which is based on laser 'interferometry'.

To search for gravitational waves, these experiments use laser beams to monitor the tiny changes in length of two perpendicular arms, each extending up to several kilometres. The length changes could be caused by a variety of phenomena on Earth, both natural and artificial, as well as by the passage of a gravitational wave. Detectors of this type have been built and operated in Europe, Japan and the US, including Virgo, GEO600, KAGRA and LIGO.

A gravitational-wave observatory in space would not be affected by nuisance vibrations near the surface of our planet. In addition, it would be sensitive to low-frequency gravitational waves, which are emitted by different celestial bodies from those emitting the high-frequency waves that the ground-based observatories are trying to detect. LISA Pathfinder will test the core technology necessary for future spaceborne interferometers to detect gravitational waves between 0.0001 Hz and 0.1 Hz.

The Virgo detector for gravitational waves near Pisa, Italy

→ IN THE REALM OF GRAVITY



At the beginning of the 20th century, Albert Einstein's general theory of relativity revolutionised the notions of space, time and gravity. In this new approach, gravity is no longer a force that acts on massive bodies, as viewed by Isaac Newton's universal gravitation. Instead, general relativity links gravity to the geometry of spacetime itself, and particularly to its curvature.

In classical physics, time proceeds constantly and independently for all objects. In relativity, spacetime is a four-dimensional continuum combining the familiar three dimensions of space with the dimension of time, because the observed rate at which time passes for an object depends on its motion relative to the observer.

And there is more: to account for gravity in relativity, the structure of this four-dimensional spacetime must be extended beyond the rules of classical geometry, where parallel lines never meet and the sum of a triangle's angles is 180°. In general relativity, spacetime is not 'flat' but is curved by the presence of massive bodies. As massive bodies move in spacetime, the curvature changes and the geometry of spacetime is in constant evolution. Gravity then provides a description of the dynamic interaction between matter and spacetime.

In the non-flat world of general relativity, free-falling objects subject to gravity alone move along geodesics – the equivalent of straight lines in curved geometry. This concept is fundamental in general relativity, and LISA Pathfinder will achieve the most accurate realisation yet of free-falling test masses moving along geodesics.

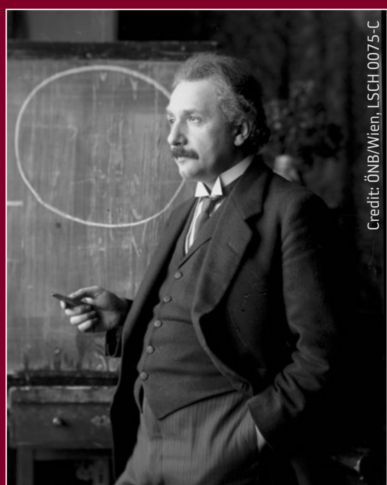
100 years of general relativity

A hundred years ago, Albert Einstein presented his general theory of relativity in four lectures, delivered before the Prussian Academy of Sciences in Berlin between 4 and 25 November 1915.

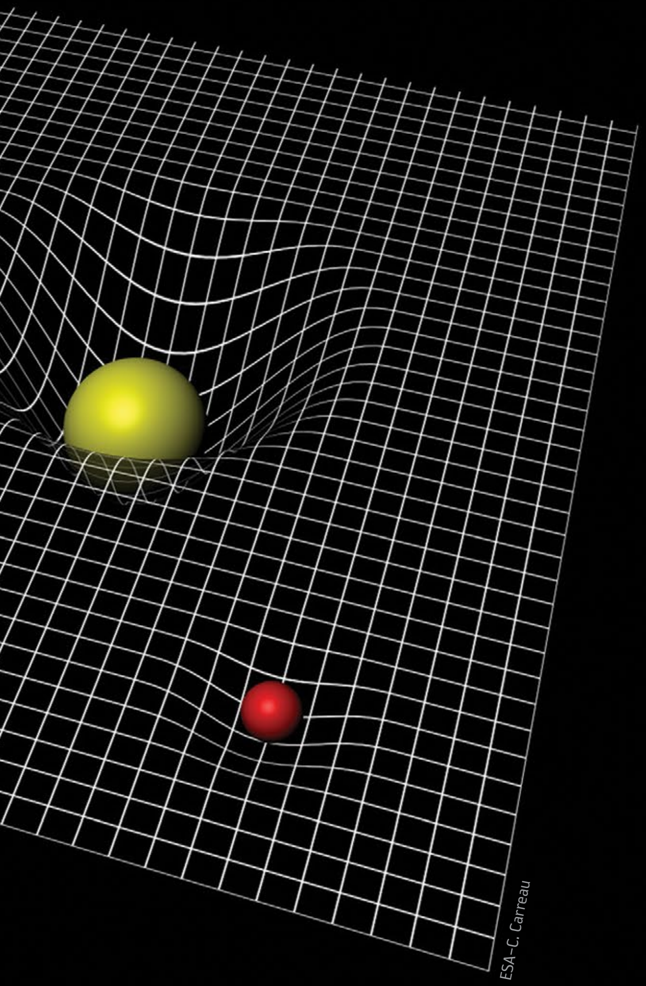
Ten years earlier, in 1905, he had published the special theory of relativity, showing that space and time are not absolute but intimately intertwined, and can be seen to shrink or dilate according to the observer's speed.

Studying the effect of gravity, Einstein could not find a way to address it in the 'flat' spacetime of special relativity, and it took him several years and attempts until he finally completed his general theory.

General relativity is a physical theory using the geometrical formalism developed by Bernhard Riemann and other mathematicians in the 19th century. Using these mathematical tools, Einstein could describe spacetime in a more flexible way, identifying gravity as the source of its curvature.



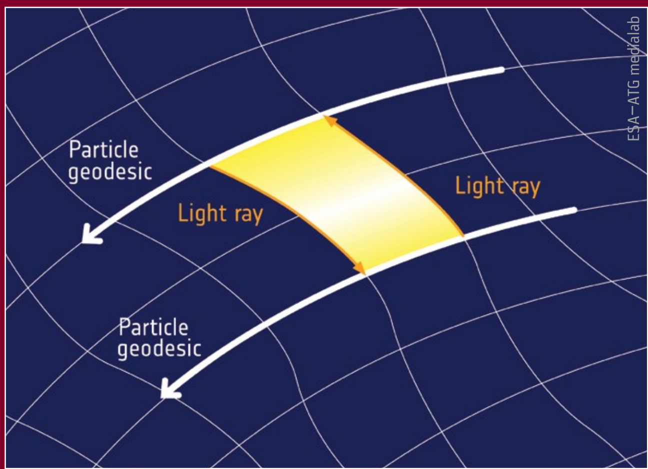
Albert Einstein in 1921



From thought experiment to reality

Einstein was famous for envisaging ‘thought experiments’, investigating the consequences of a particular physical problem only in one’s mind. The following thought experiment, based on an idea proposed by theoretical physicist Felix Pirani, suggests a method for measuring the curvature of spacetime.

Imagine two free-falling particles moving under the effect of gravity alone. The first particle sends a light ray to the second, which receives it and sends it back. Even though light does not have mass, it feels the effect of gravity as it moves through curved spacetime, spending energy to escape the gravitational pull of a massive object and gaining energy upon approaching it. These energy changes translate to changes in the light frequency, so monitoring variations in the frequency of the light rays that the two particles are sending back and forth is a way to measure the curvature of spacetime between them.

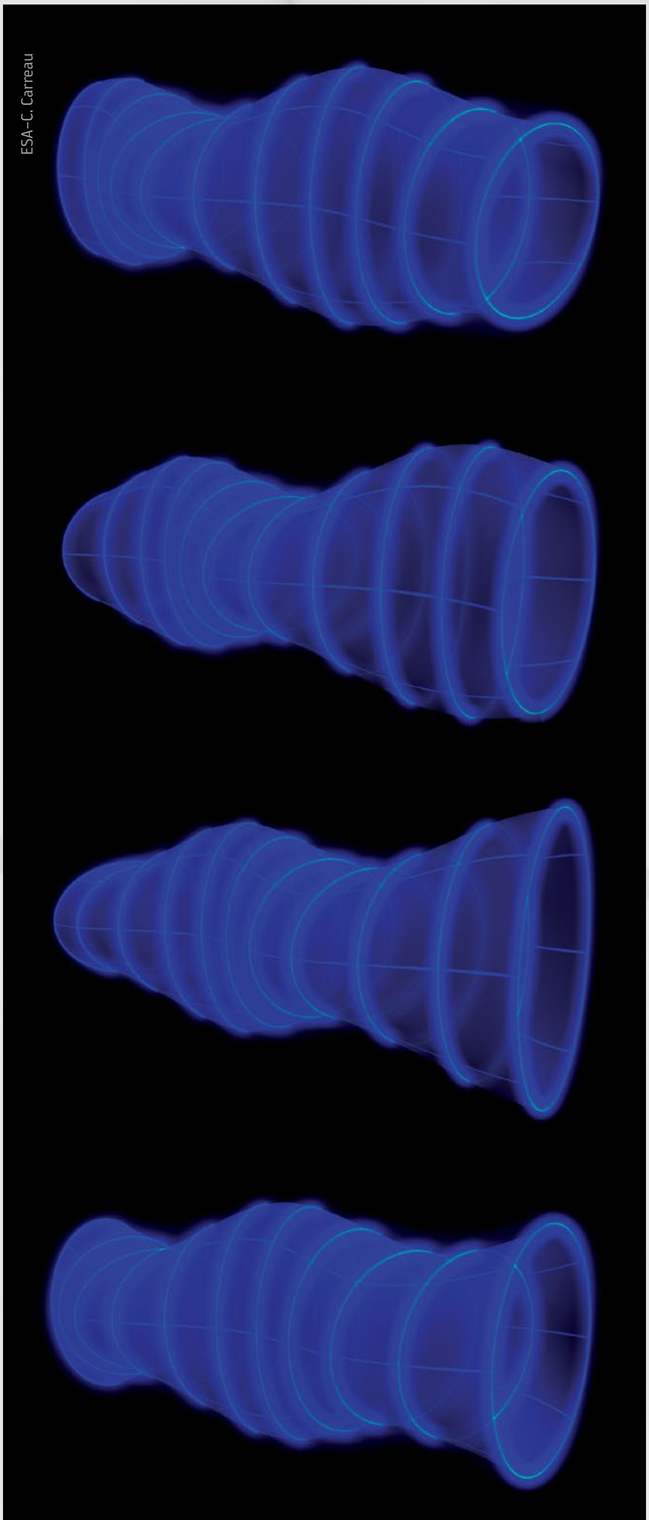


This is the principle underlying the detection of gravitational waves: if a perturbation passes by, it would change the curvature of spacetime between the two particles, leaving an imprint on the frequency of the light they exchange. To demonstrate geodesic motion – the key premise of this thought experiment – it is necessary to have a test environment in which nothing else can influence the light frequency.

LISA Pathfinder’s experiment does not have the sensitivity to detect gravitational waves, and therefore it should not detect any frequency shift in the light exchanged by its two free-falling test masses – any such shift would be due to noise. If these experimental errors can be controlled and reduced sufficiently precisely, a future scaled-up version of such a system should be able to measure the tiny frequency shifts caused by gravitational waves.

> **“Spacetime tells matter how to move; matter tells spacetime how to curve.”**
>
> John Archibald Wheeler

→ THE GRAVITATIONAL UNIVERSE



The characteristic perturbations caused by gravitational waves

According to general relativity, gravity manifests itself as massive objects bending the structure of spacetime. However, something more happens if the gravitational field varies, for example when two massive objects orbit each other. The motion of 'gravitationally charged' bodies through spacetime perturbs its very fabric, imprinting a signal that travels away as a disturbance to the structure of spacetime itself: gravitational waves.

The existence of gravitational waves is one of the key predictions from general relativity. These oscillations consist of sequential stretches and compressions of spacetime, rhythmically increasing and reducing the distance between particles as a wave propagates through the surroundings.

Gravitational waves are emitted by any changing gravitational field. However, gravity is a weak interaction and the perturbations are generally tiny, unless they arise from a very intense gravitational field. This is the case for some of the most extreme astrophysical objects: white dwarfs, neutron stars and black holes.

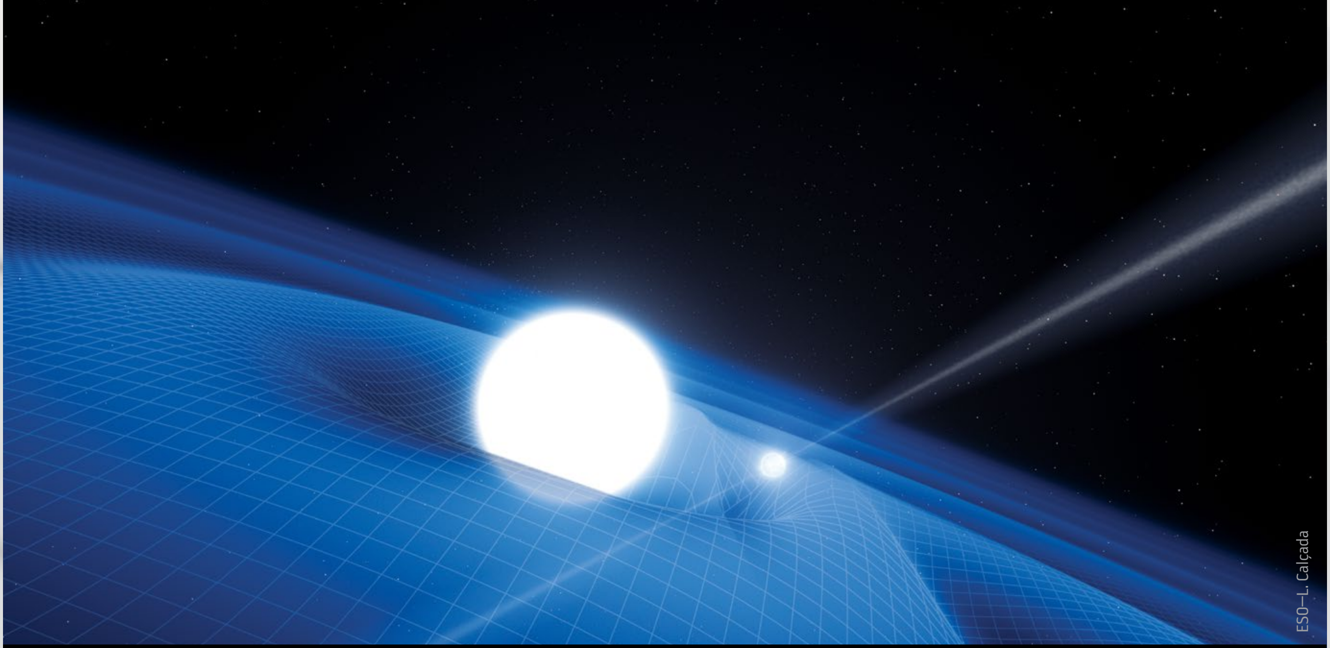
The detection of gravitational waves in the future will provide a new view on these and many other celestial bodies. Spaceborne experiments that will exploit LISA Pathfinder's technology will be able to 'listen' to these cosmic events, revealing information additional to what can be learned by merely looking at the Universe.

Merging black holes

Black holes are extremely dense objects with a gravitational field so strong that nothing, not even light, can escape. Although they cannot be directly observed, they can be detected through their effect on the surrounding matter.

Our Milky Way galaxy contains many small black holes, with typical masses equivalent to a few solar masses, resulting from the collapse of massive stars at the ends of their lives. Besides this, all massive galaxies, including the Milky Way, host supermassive black holes at their cores, with masses between millions and billions of times that of our Sun.

When two or more galaxies merge to form a new larger galaxy, the central supermassive black holes sink to the centre of the new galactic system and coalesce. These are expected to be the most energetic events in the Universe, and one of the strongest sources of gravitational waves.



Spacetime ripples produced by a white dwarf and its pulsar companion

In addition, the origin of supermassive black holes themselves still remains unclear, but astronomers believe that copious numbers of gravitational waves should be emitted during their formation.

Future gravitational-wave observatories will reveal many mysteries about the formation and evolution of the most massive black holes in the cosmos.

Extreme stellar remnants

At the end of their lives, stars leave behind very compact and exotic objects: white dwarfs in the case of low-mass stars like our Sun, and neutron stars or black holes for their more massive counterparts. Owing to their great density, all these remnants exert an intense gravitational pull on the surrounding matter.

Stars often come in pairs, and when one of the two evolves into a compact remnant, it may start devouring matter from its companion. The final product of these binary star systems can be a pair of compact remnants orbiting each other emitting gravitational waves. Astronomers predict many millions of such systems in the Milky Way alone.

Two merging galaxies known as the Mice Galaxies (NGC 4676)

Binary supermassive black holes

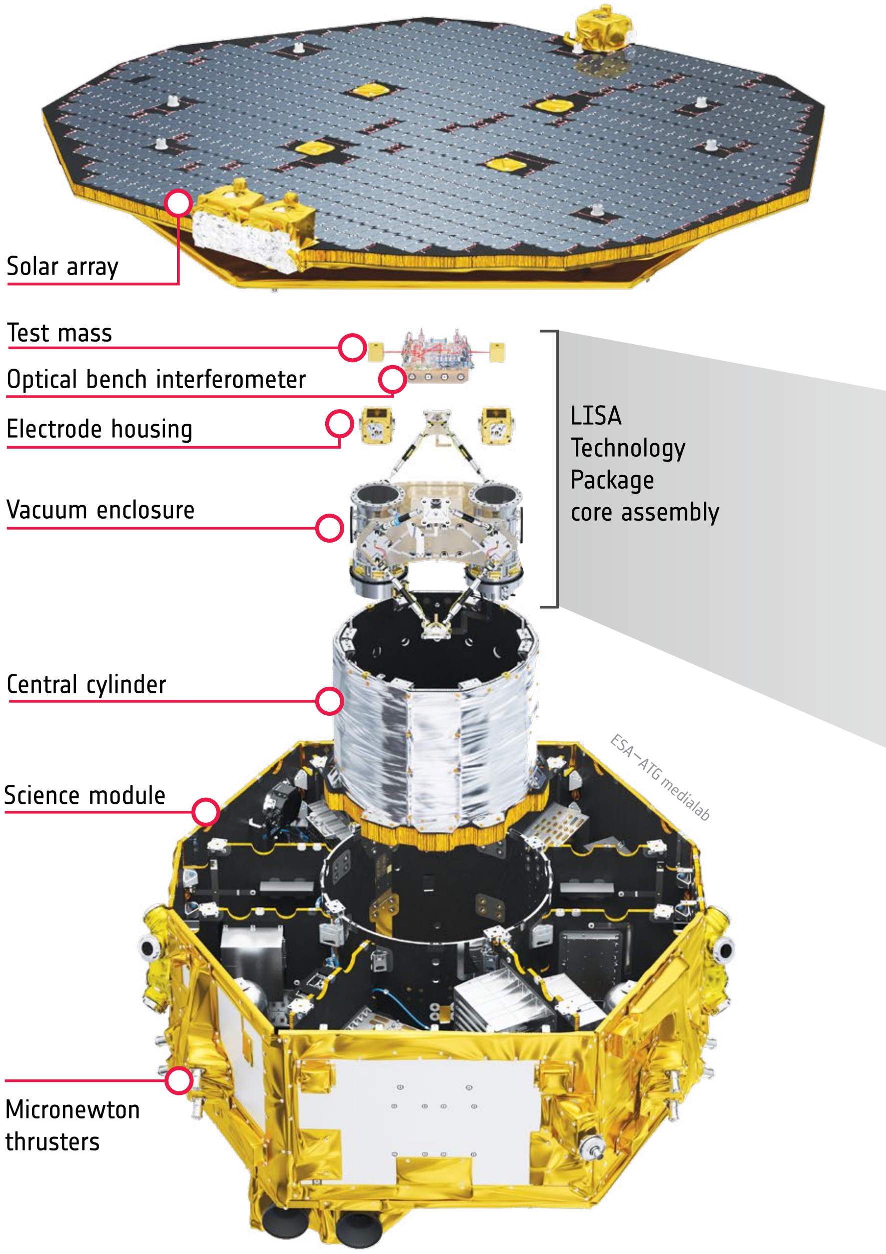
Indirect discovery

While gravitational waves have not yet been directly detected, indirect proof of their existence was found in the late 1970s by a team of astrophysicists led by Joseph H. Taylor Jr. In 1974, Taylor and his student Russell A. Hulse discovered an exotic celestial object: a pulsar in a binary system. Pulsars are rapidly spinning, magnetised neutron stars – the dead cores of massive stars – that can be detected as pulsating sources in radio wavelengths as their two beams of radiation periodically point towards Earth.

This pulsar was the first to be detected with a companion, a neutron star. It was soon clear that this close pair of compact objects, orbiting about their mutual centre of mass in less than eight hours, would be an ideal laboratory for testing general relativity.

After four years of observations, Taylor and other collaborators detected a feeble speeding up of the two remnants, albeit by a tiny amount – 75 millionths of a second every year. This is a consequence of the two dead stars moving into tighter and tighter orbits, just as would be expected if they lose energy emitting gravitational waves. Hulse and Taylor were awarded the Nobel Prize in Physics for their discovery in 1993.

→ HOW DOES IT WORK?



LISA Pathfinder is different from most space missions for astronomy or planetary science, in which the payload is basically a separate unit from the rest of the spacecraft. In fact, during operations, LISA Pathfinder's payload and spacecraft will act as a single unit, with the spacecraft being part of the experiment itself.

LISA Pathfinder will perform the first high-precision laser interferometric tracking of orbiting bodies in space. It will demonstrate that two independent test masses can be monitored as they free-fall through space, reducing external and internal disturbances to the point where the relative test mass positions can be measured and remain stable.

To achieve the purest free-fall motion ever obtained in space, it is necessary to eliminate any non-gravitational forces acting on the two test masses to the highest degree possible, shielding them from pressure due to sunlight, from charged particles of the solar wind and from micrometeoroids. The test masses must not be in mechanical contact with the spacecraft and every effort must be made to minimise internal electrical, magnetic and thermal forces, and even the change of gravitational pull between the spacecraft and the masses themselves.

In a full-scale gravitational-wave observatory, the test masses would be housed in two individual spacecraft separated by about a million kilometres: on this scale, passing gravitational waves would change the distance between the cubes at the level of picometres (10^{-12} m) and would thus become measurable.

Solar array

The solar array provides power to the instrumentation, while acting as a thermal shield. It contains three solar sensors that make sure the array is constantly facing the Sun.

The test masses

Two identical solid cubes made of a metallic alloy (73% gold, 27% platinum), measure 46 mm on each side and weigh 1.96 kg each. One of the two cubes is designated as the 'master', and the spacecraft is commanded to move in order to remain centred on this cube.

Optical bench interferometer

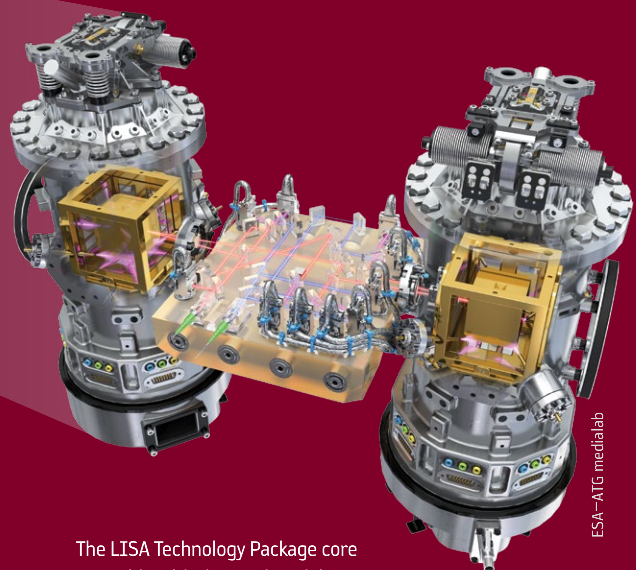
The two cubes are separated by 38 cm, with a highly stable optical bench in between. The optical bench holds the mirrors of a laser interferometer, able to measure the relative separation of the cubes at picometre resolution by bouncing laser light off the highly reflective surfaces.

Electrode housing

Each cube is surrounded by an electrode housing box, several millimetres away on all sides. As

The jewel in the crown

The optical bench interferometer, made from a 20 cm by 20 cm block of Zerodur ceramic glass, is the central component of LISA Pathfinder's payload. A set of 22 mirrors and beam-splitters, bonded onto its surface, directs laser beams across the bench. There are two beams: one reflects off the two free-falling test masses (red in the figure below) while the other is confined to the bench (blue). By comparing the length of the different paths covered by the beams, it is possible to monitor changes accurately in distance and orientation between the two test masses.



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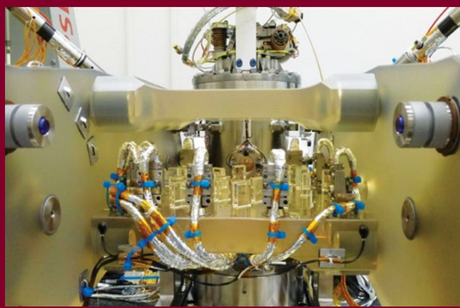
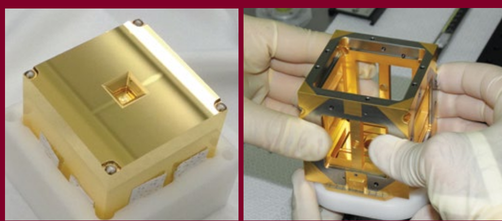
The LISA Technology Package core assembly, with the two inertial sensors and the optical bench interferometer between



Built and tested at the Institute for Gravitational Research at the University of Glasgow, UK; photo by Airbus DS

Optical bench of LISA Pathfinder



CGS SpA

A gold–platinum test mass (left) and its housing with the electrodes removed (right)

external forces batter the spacecraft, this will move relative to the free-falling cubes. The walls of the electrode housing boxes are fixed with respect to the spacecraft and will provide, through capacitive displacement sensors, an indication of position and rotation changes with respect to the cubes.

LISA Technology Package core assembly

The heart of the mission, comprising the two inertial sensors around each test mass, and the optical bench between them. The test masses, inside their electrode housings, are initially held in position by a caging mechanism designed to keep them secure during launch, and which retracts once in orbit. Each of the two inertial sensors is held in a vacuum enclosure that is opened to space once the spacecraft reaches its operational orbit; this is to avoid any minute force caused by the movement of residual gas molecules remaining in the vicinity of the test masses.

Central cylinder

The cylinder holds the central elements of the payload, isolating them from the other components of the payload and spacecraft.

Science module

This structure carries the subsystems to support the operation of the craft and the performance of the scientific experiments. The outer panels accommodate the startrackers, the medium-gain antenna and several sets of small thrusters.

Micronewton thrusters

These microthrusters apply forces of 1–100 millionths of a newton (micronewtons) to shift the spacecraft and keep the master test mass centred in its housing. As a comparison, a snowflake falling in a vacuum under the effect of Earth's gravitational field would feel a force of about 30 micronewtons. The thrusters on LISA Pathfinder will perform ten of these minuscule centring manoeuvres every second.

→ BUILDING LISA PATHFINDER


ESA–ATG medialab

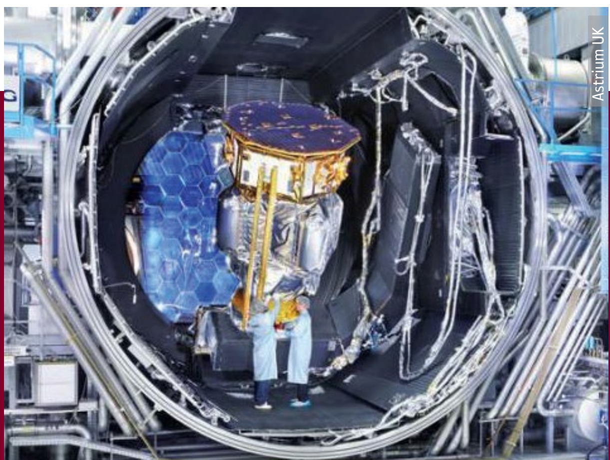
Science and propulsion modules

LISA Pathfinder consists of a science module, with an outer diameter of 231 cm and a height of 96 cm, and a separable propulsion module. The propulsion module will gradually raise the initial orbit until it reaches the operational one, and will be discarded shortly before entering the final orbit.

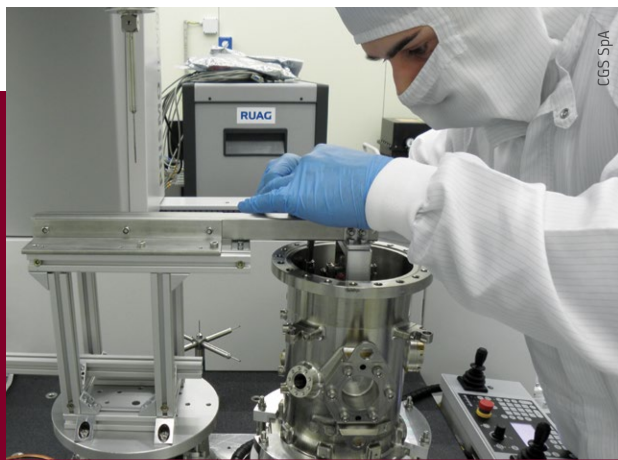
The science module contains the payload, and at its heart is the LISA Technology Package, provided by European industry, research institutes and ESA.

The LISA Technology Package includes the inertial sensors, the optical metrology system and the payload computer and diagnostic system. The inertial sensors and optical metrology system provide signals to the Drag-Free and Attitude Control System, running on the main computer, whose role is to maintain the position of the satellite relative to the test masses. In turn, this sends commands to the micronewton thrusters, as well as back to the inertial sensors. The propulsion system of the LISA Technology Package consists of three clusters of micronewton thrusters installed on three of the panels of the science module; these are cold-gas (nitrogen) thrusters, based on those originally developed for ESA's Gaia mission.

In addition, NASA has supplied its Disturbance Reduction System, contributing to the mission goals by validating additional technology for future drag-free spacecraft. It will be run as a separate experiment and at different times from the full European system, but will start by receiving measurement input from the inertial sensors of the LISA Technology Package. It will then use its own drag-free control software and two clusters of micronewton thrusters, mounted on two opposite panels of the science module, to control the position and attitude of the spacecraft. The Disturbance Reduction System uses colloidal micronewton thrusters, which generate propulsion by charging small drops of liquid and accelerating them through an electric field.


Astrium UK

Final preparation ahead of the space environment testing



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Checking alignment on one of the inertial sensor heads for the LISA Technology Package

→ LAUNCH

Liftoff of a previous Vega

LISA Pathfinder is scheduled for launch in late 2015 on an ESA Vega rocket from Europe's Spaceport in French Guiana. Vega is Europe's latest vehicle for lofting small payloads into a wide range of low orbits, from equatorial to polar. The three solid-propellant stages are topped by a restartable liquid-propellant upper module for attitude and orbit control, and satellite release. For LISA Pathfinder, the upper module will fire twice.

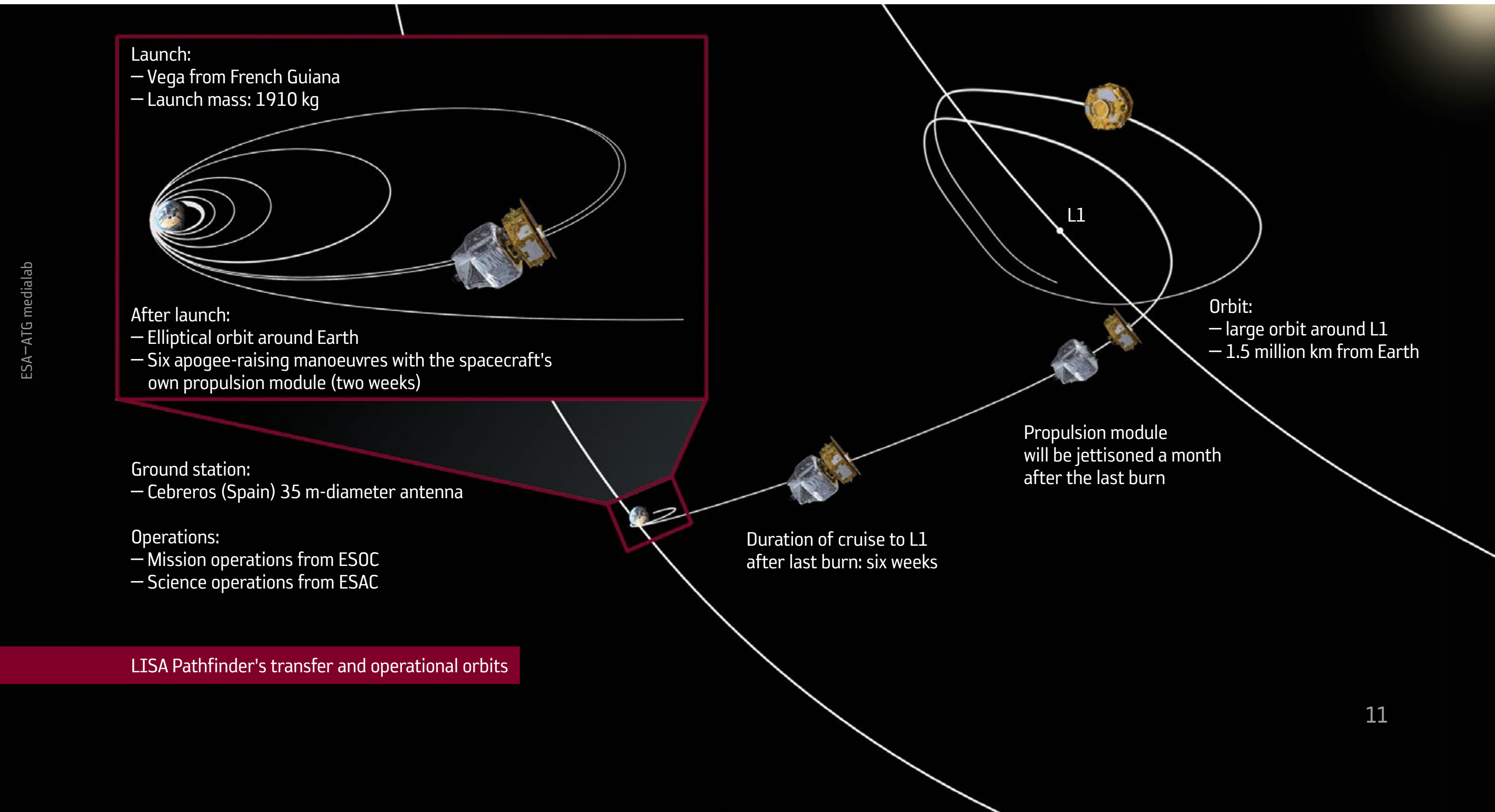
Vega has flown several times to date, completing its mission each time. The launch of LISA Pathfinder is part of ESA's initial exploitation phase to demonstrate flexibility of the Vega system.

Journey of LISA Pathfinder to its operational orbit

LISA Pathfinder will operate from a vantage point in space about 1.5 million km from Earth towards the Sun, orbiting the first Sun–Earth 'Lagrangian point', L1. At this location, a spacecraft follows our planet on its path around the Sun.

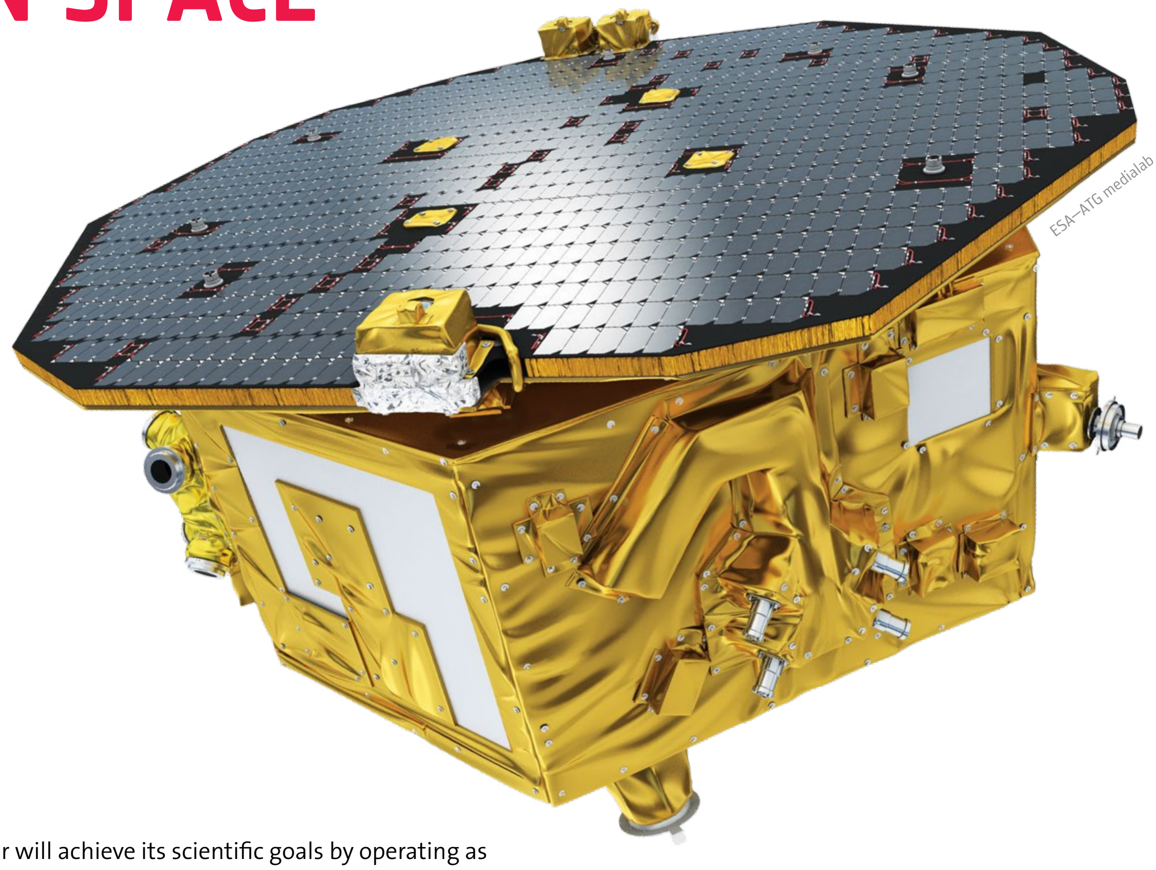
Vega will first put the spacecraft into an elliptical orbit around Earth with perigee at 200 km, apogee at 1540 km and an inclination of about 6.5°. From there, LISA Pathfinder will use its own propulsion system to perform a series of manoeuvres to raise its apogee, and will eventually reach its operational orbit, a 500 000 × 800 000 km orbit around L1. The propulsion module will separate from the science spacecraft during the transfer into the operational orbit, about a month after the final burn. The total transfer phase will last about eight weeks.

This orbit around L1 has been chosen because it fulfils the mission's stringent requirements on thermal and gravitational stability: it is an intrinsically 'quiet' place in space, far from massive bodies that would induce tidal forces on the spacecraft; it enjoys constant illumination from the Sun; and it has a quasi-constant distance from Earth for communications.



LISA Pathfinder's transfer and operational orbits

→ A PHYSICS LABORATORY IN SPACE



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LISA Pathfinder will achieve its scientific goals by operating as a physics laboratory in space. The normal operations phase will last six months, split into three months for the experiment involving the full LISA Technology Package and three months for the Disturbance Reduction System.

The ground segment has two operational centres, both provided by ESA. The Mission Operations Centre (MOC) at the European Space Operations Centre (ESOC) in Darmstadt, Germany, will be responsible for the launch and early orbit phase, the transfer phase and all operations during the routine phase. The Science and Technology Operations Centre at the European Space Astronomy Centre (ESAC) near Madrid, Spain, will interface with the scientific community and the MOC, taking care of scheduling, data processing and archiving.

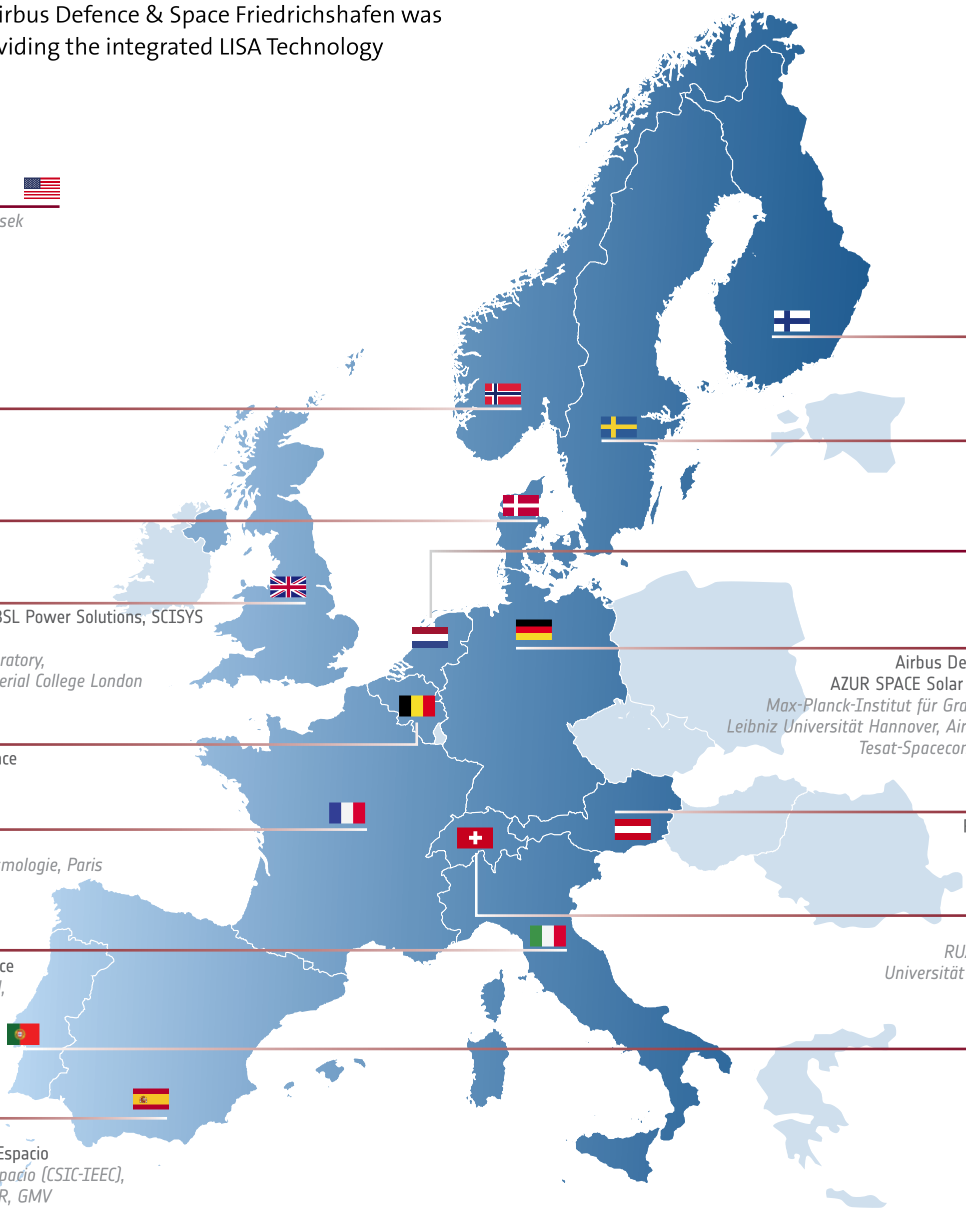
During science operations, LISA Pathfinder will communicate with Earth for 6–8 hours per day using ESA's 35 m-diameter X-band deep-space dish at Cebreros, Spain. Given the relatively short duration of the operations phase, the mission scientists will work in a highly interactive fashion, analysing the data immediately after reception in order to select and configure the investigations to be carried out on the following days.

The Cebreros deep-space antenna near Avila, Spain

→ AN INTERNATIONAL ENTERPRISE

The technical team behind LISA Pathfinder involved more than 40 companies and research institutes from 14 European countries and the US. The prime contractor, Airbus Defence & Space Stevenage, led the industrial team building the spacecraft, while Airbus Defence & Space Friedrichshafen was responsible for providing the integrated LISA Technology Package payload.

The subsystems for the LISA Technology Package were provided by a consortium of European companies, research institutes and ESA. The US contributed the Space Technology 7 (ST7) Disturbance Reduction System payload.



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Instituto de Ciencias del Espacio (CSIC-IEEC),
UPC-IEEC, IFAE, NTE–SENER, GMV

Finland
RUAG Space

Sweden
RUAG Space

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Airbus Defence & Space, IABG,
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