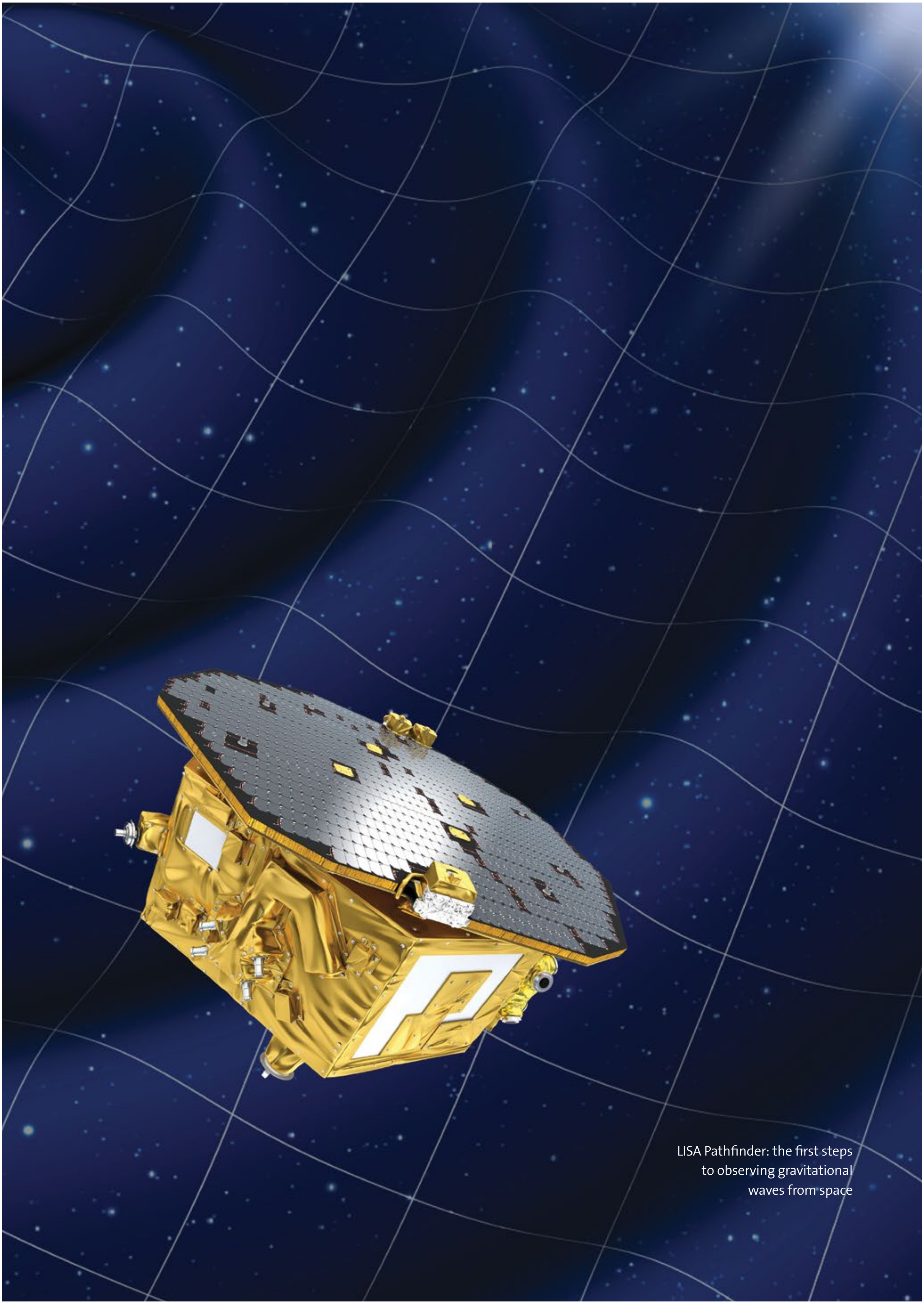

LISA Pathfinder: the first steps
to observing gravitational
waves from space

→ SEEING THE UNIVERSE THROUGH GRAVITATIONAL WAVES

The LISA Pathfinder mission

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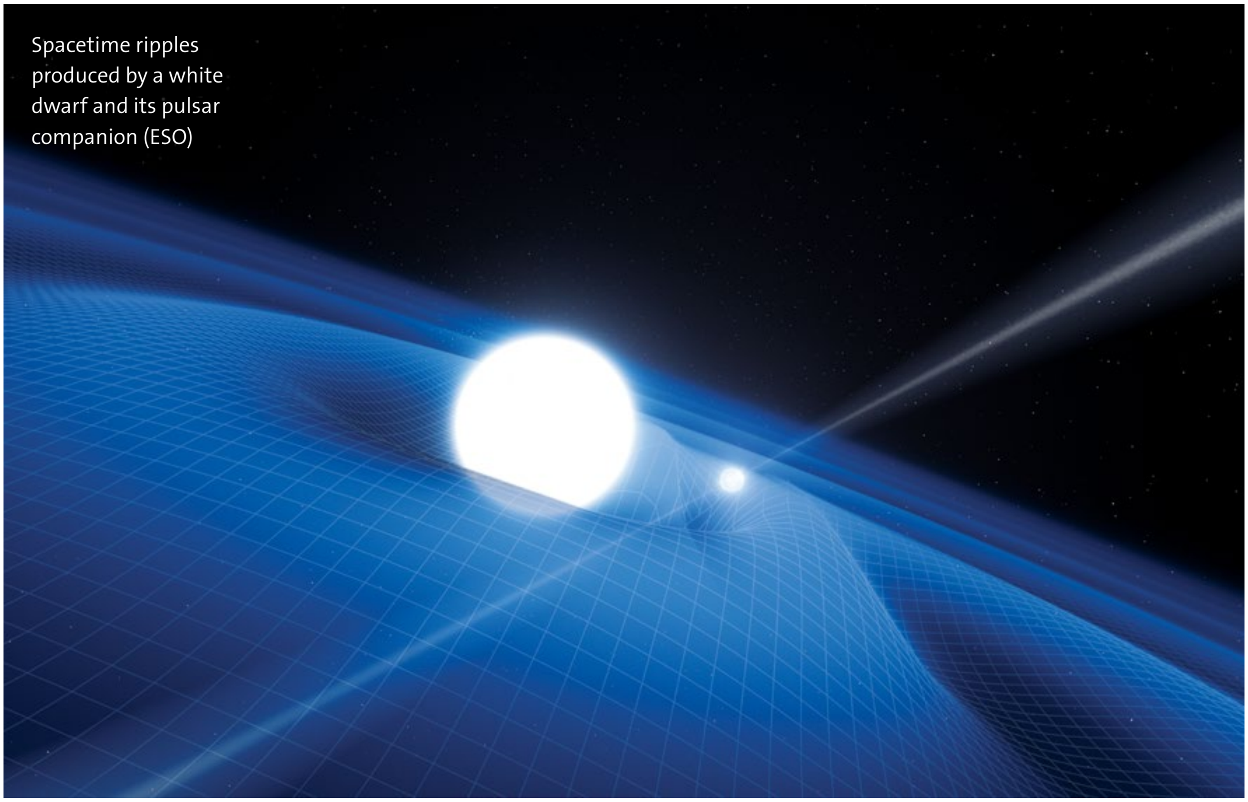
ESA's LISA Pathfinder will help to open up a completely new observational window into the 'gravitational Universe', proving new technologies needed to measure gravitational waves in space.

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 of the wider electromagnetic spectrum.

To expand our window on the Universe, 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. Understanding their signature will tell us a lot about black holes, compact double stars and other exotic objects.

Space offers many advantages in this search. ESA's LISA Pathfinder mission is a technology demonstrator that will



Spacetime ripples produced by a white dwarf and its pulsar companion (ESO)

pave the way for future spaceborne gravitational-wave observatories, by testing their 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 freefall.

Even in space, creating 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 th spacecraft and its instruments.

So the LISA Pathfinder design at first glance seems simple: 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.

But this is not as easy as it sounds. LISA Pathfinder is not aimed at the detection of gravitational waves themselves. 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 freefall by more than two orders of magnitude better than any past, present or planned mission.

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Science and propulsion modules

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

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. 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 for several kilometres.

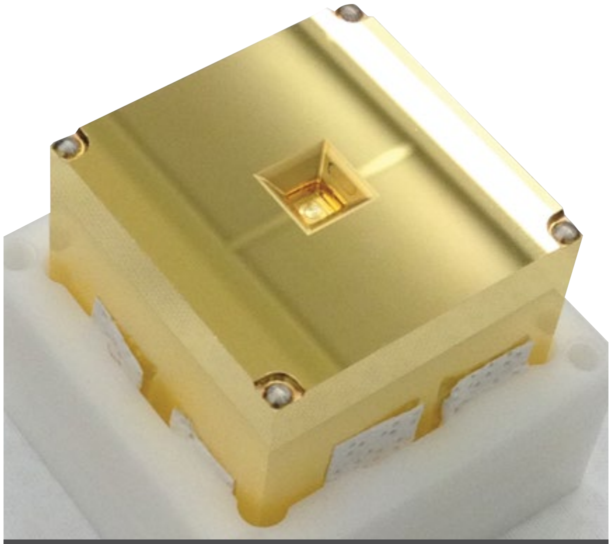
The length changes could be caused by a variety of phenomena on Earth, both natural and artificial, as well as by the passage of a gravitational wave. Detectors of this type have been built and operated in Europe, Japan and the USA.

However, a gravitational-wave observatory in space would not be affected by nuisance vibrations near the surface of our planet. But it would be sensitive to low-frequency gravitational waves, which are emitted by celestial bodies different 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.

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 Taylor Jr. In 1974, Taylor and his student Russell Hulse discovered an exotic celestial object: a pulsar in a double star 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.



↑ One of the two LISA Pathfinder test masses, each a solid cube of metallic alloy (73% gold, 27% platinum) measuring 46 x 46 mm and weighing 1.96 kg

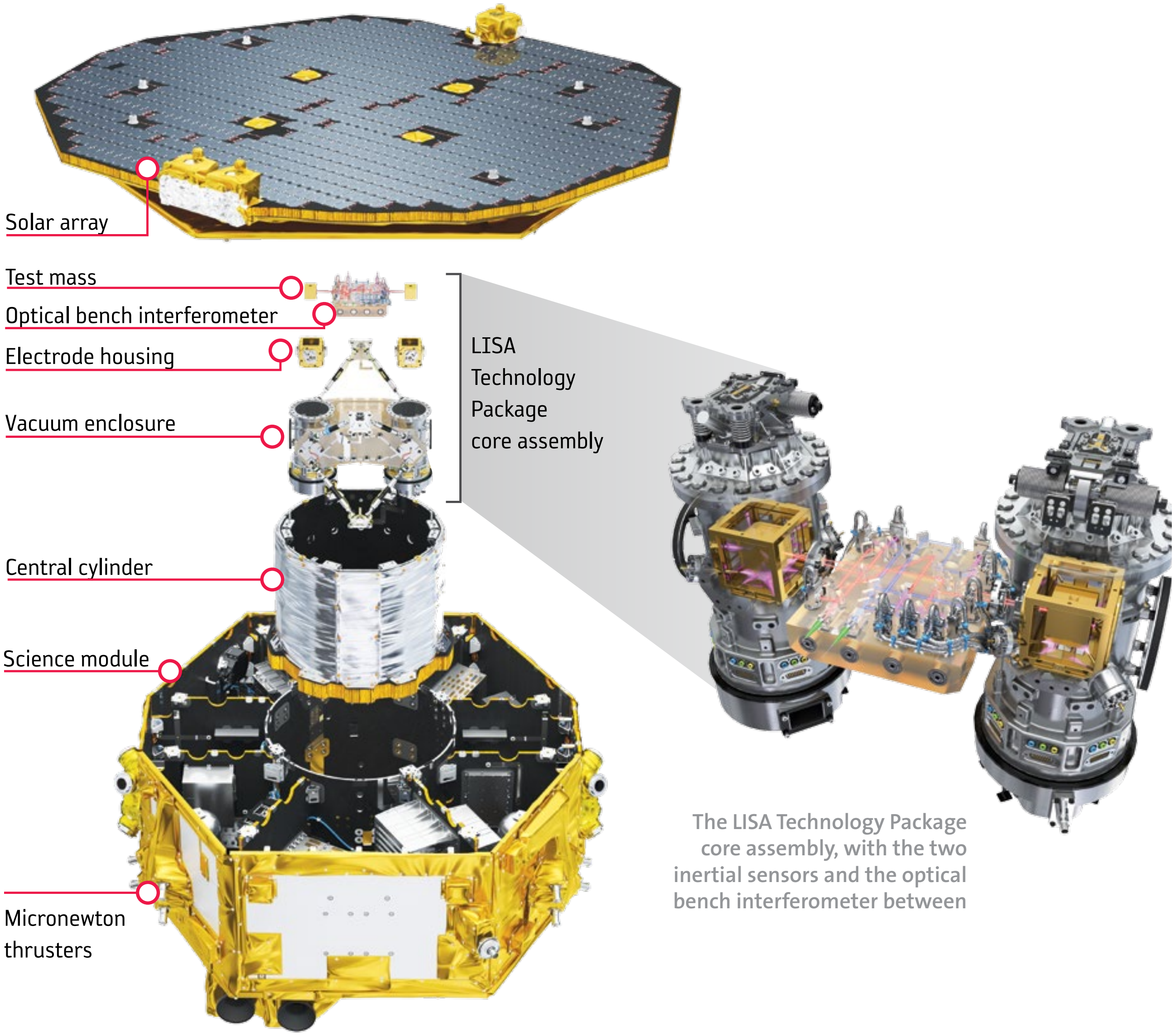
After four years of observations, Taylor and his team detected a feeble speeding up of the two remnants, albeit by a tiny amount – 75 millionths of a second every year. This is a consequence of the two dead stars moving into tighter orbits, just as would be expected if they were losing energy by emitting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

How will it work?

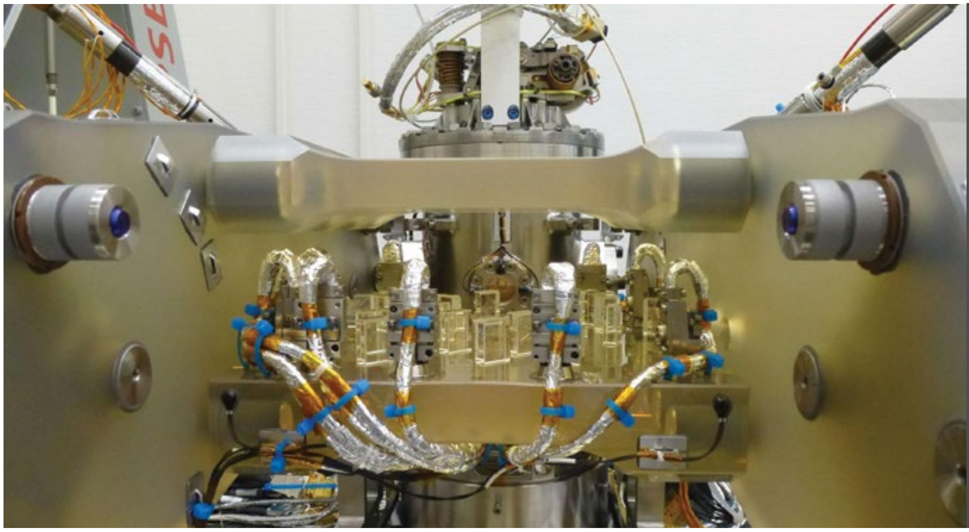
LISA Pathfinder is different from most space missions for astronomy or planetary science in which the payload is basically a separate unit from the rest of the spacecraft. In fact, during operations, LISA Pathfinder's payload and spacecraft will act as a single unit, with the spacecraft being part of 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 freefall 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 freefall 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 LISA Technology Package core assembly, with the two inertial sensors and the optical bench interferometer between



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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

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.

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 freefalling test masses – any such shift would be due to noise. If these experimental errors can be controlled and reduced sufficiently and precisely, a future scaled-up version of such a system should be able to measure the tiny frequency shifts caused by gravitational waves.

In such 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 therefore would become measurable.

The spacecraft

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, namely the LISA Technology Package, provided by European industry, research institutes and ESA.

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

↑ The LISA Pathfinder science module and propulsion modules on the Vega launch vehicle adapter at IABG, Ottobrunn, in June (ESA/U. Ragnit)

This package is the heart of the mission: two inertial sensors around each test mass, and the highly stable 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.

The propulsion system for the science module consists of three clusters of micronewton thrusters; these are cold-gas (nitrogen) thrusters, based on those originally developed for ESA's Gaia mission. 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.

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. In addition, NASA has supplied its Disturbance Reduction System, contributing to the mission by validating additional technology for future drag-free spacecraft.

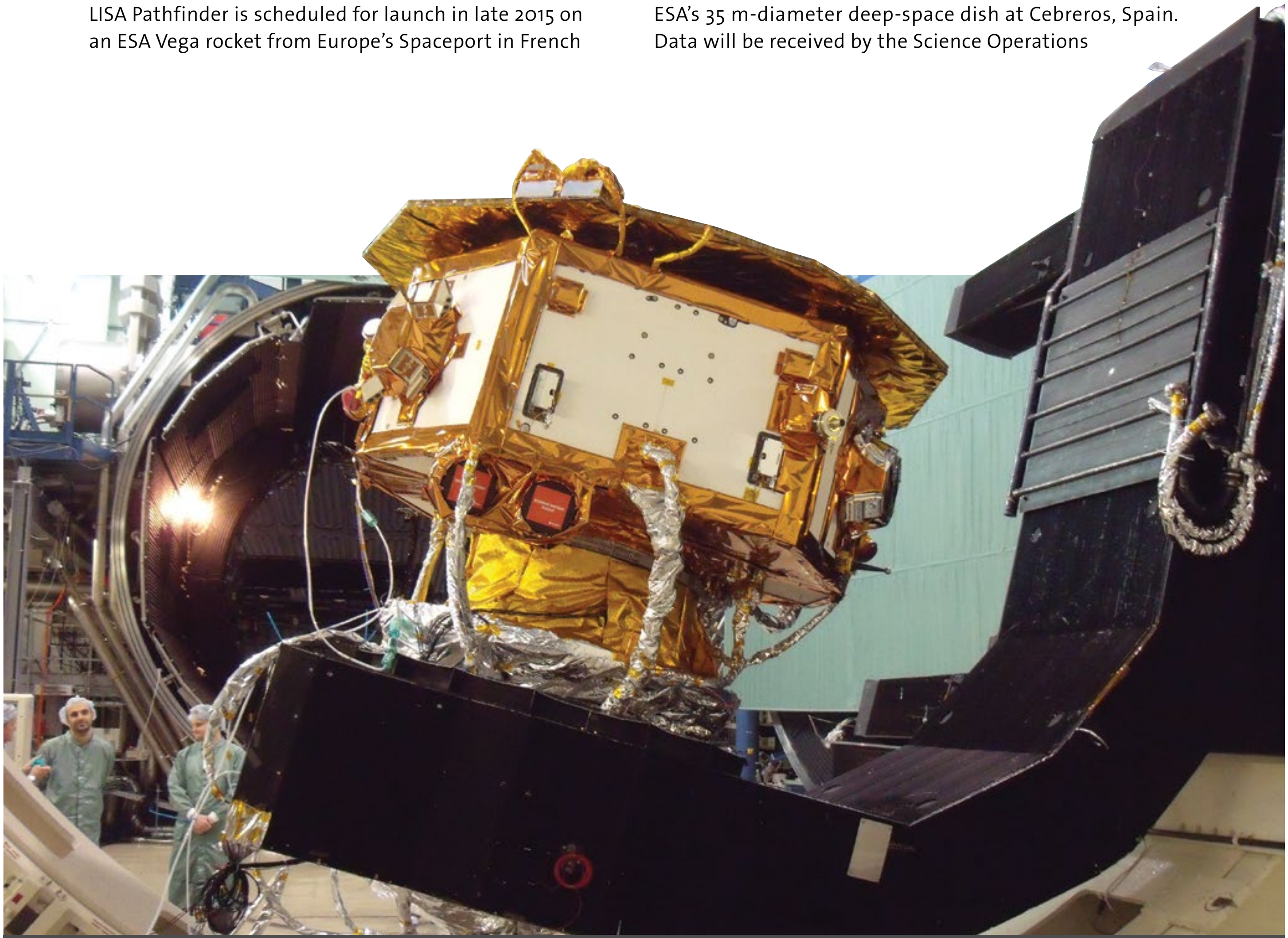
The journey to orbit

LISA Pathfinder is scheduled for launch in late 2015 on an ESA Vega rocket from Europe's Spaceport in French Guiana. The satellite 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.

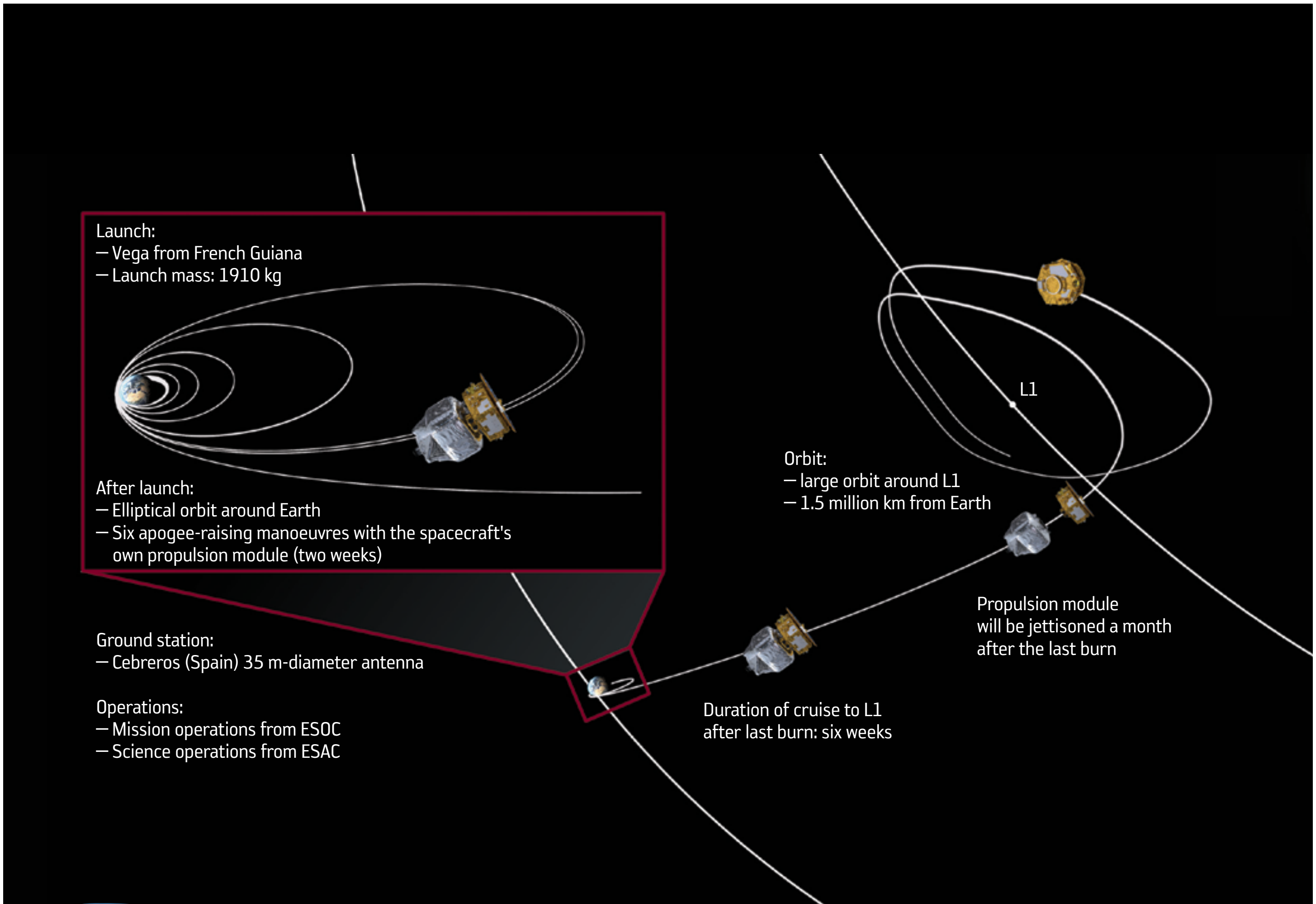
This orbit around L1 has been chosen because it fulfils the mission's stringent requirements on thermal and gravitational stability: it is an intrinsically 'quiet' place in space, far from massive bodies that would induce tidal forces on the spacecraft; it enjoys constant illumination from the Sun; and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

The ultimate physics laboratory

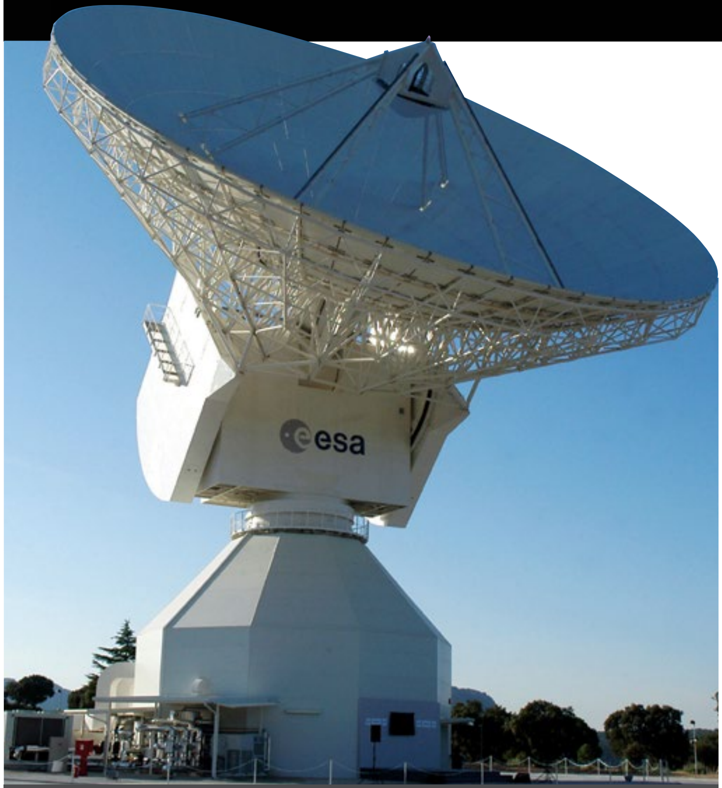
During science operations, LISA Pathfinder will communicate with Earth for 6–8 hours per day using ESA's 35 m-diameter deep-space dish at Cebreros, Spain. Data will be received by the Science Operations



↑ LISA Pathfinder about to enter the space environment vacuum chamber at IABG facilities in Ottobrunn, Germany, in 2011 (Astrium UK)



↑ LISA Pathfinder's transfer and operational orbits



↑ The Cebreros deep-space antenna near Avila, Spain

Centre at ESAC near Madrid, Spain, which will interface with the scientific community and the Mission Operations Centre at ESOC, taking care of scheduling, data processing and archiving.

Normal operations 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 designation 'LISA' in the mission's name stands for Laser Interferometer Space Antenna, an earlier concept for a space observatory for gravitational waves. This is now used to describe a class of missions based on the original LISA concept. Though not actually detecting gravitational waves, this Pathfinder will prove the key technology for future LISA-like space missions to study the gravitational Universe. ■

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