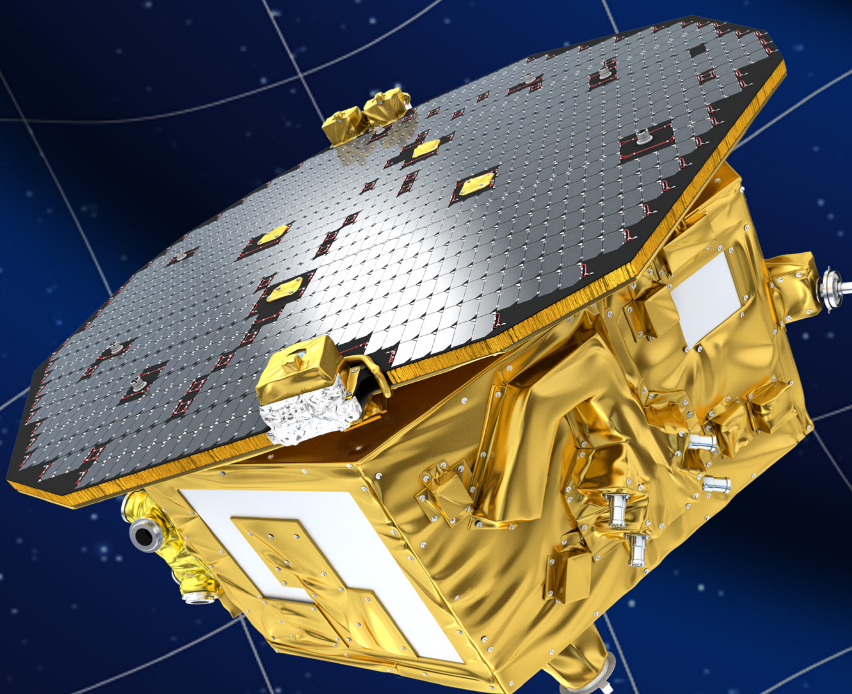
esa

lisa pathfinder

→ FIRST STEPS TO OBSERVING GRAVITATIONAL WAVES FROM SPACE

Media kit

June 2016



LISA Pathfinder is giving astronomers the equivalent of a new sense with which to study the Universe. Until now, we have mostly relied on sight and its technological equivalents to see celestial objects.

LISA Pathfinder is a new breed of spacecraft that will allow us to study the gravitational Universe. This can be imagined as an invisible landscape of contours and valleys that define the natural movement of celestial objects. Known as the spacetime continuum, it was described mathematically by Albert Einstein 100 years ago, in his celebrated General Theory of Relativity.

Beyond investigations into gravity, the technology developed for LISA Pathfinder opens the way for other missions, once thought almost impossible. This could eventually include the detailed investigation of the interiors of the planets and moons in our own Solar System, and even the atmospheric analysis of Earth-like worlds around other stars using formation-flying telescopes.

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➔ Why LISA Pathfinder?

Gravity remains the great cosmic mystery. Although it was the first force to be described mathematically, by Isaac Newton in 1687, we still do not know how it works. Our best modern description is Albert Einstein's General Theory of Relativity.

LISA Pathfinder was launched on 3 December 2015, on the day after the 100th anniversary of Einstein's publication in which he presented the final form of his equations that describe a gravitational field. These ten 'field equations' are the heart of general relativity. They describe a four-dimensional mathematical landscape known as the spacetime continuum.

General relativity is successfully used in maintaining the accuracy of satellite navigation signals, describing the motion of the inner planet, Mercury, and providing clues about some of the strangest of all celestial objects, black holes. But there is one huge prediction of general relativity that has only just this year come within our ability to detect: gravitational waves.

These are minuscule ripples in the spacetime continuum that are produced by all accelerating objects. They are analogous to the ripples on a pond made by the drop of a pebble. As they pass, they change the distance between points in space.

Now that we have the technology to detect gravitational waves, we will see the Universe as never before. It will be like the difference between going from silent movies to our modern cinema experience with surround sound.

Now that we have the technology to detect gravitational waves, we will see the Universe as never before.

As we refine our detection techniques, we will have the ability to peer into the hearts of colliding stars. We will see black holes forming at the edge of the known Universe. And we will truly be able to test whether general relativity works in the realm of extreme gravitational fields.

In order to feel these gravitational ripples and do these amazing things, one must first be sure that all other forces can be isolated and removed. Otherwise they will swamp the signal. No one can detect the pebble's ripple on a stormy ocean.

In February 2016, the international collaboration of scientists working on the Laser Interferometer Gravitational-Wave Observatory (LIGO) proved it was possible to detect gravitational waves from the ground. Now LISA Pathfinder is demonstrating that it will be possible from space too.

LISA Pathfinder's mission is proving that it can shield two metal cubes, which form the core of the payload, from all internal and external forces better than any other spacecraft ever flown. This means flying in space to within an accuracy of a few billionths of a metre (nanometre), and being able to sense the relative positions of the metal cubes to within a trillionth of a metre (picometre) over the bandwidth of interest.

The metal cubes are floating freely inside the spacecraft. This is why the technology cannot be tested on Earth – our planet's gravity would pull them toward the ground, ending the experiment after a few seconds at most. In space, however, the masses float freely for a long time, shielded from other influences by the spacecraft. This is allowing them to move only as gravity dictates. The spacecraft manoeuvres around them, sensing their motion using lasers and adjusting its own to compensate.

In short, LISA Pathfinder is the most perfect fundamental physics laboratory ever flown in space – and it is only the start. In 2013, ESA designated its L3 mission – the third large mission in the Cosmic Vision programme – to be an investigation of the gravitational Universe. Set for launch in 2034, a call for missions will follow the inflight demonstration of the LISA Technology Package performance.

One mission being considered by the science community is the evolved Laser Interferometer Space Antenna (eLISA). This would use the technology developed for LISA Pathfinder to build a multiple spacecraft mission that could directly observe gravitational waves and start the era of space-borne gravitational-wave astronomy.

→ Mission at a glance

Launch: 3 December 2015 at 04:04 UTC, on Arianespace flight VV06 on a European small Vega launcher, from Europe's spaceport at Kourou in French Guiana.

Launch mass: 1910 kg for science plus propulsion modules, includes 1200 kg propellant, 435 kg science module of which 141 kg is the payload.

Payload/experiment: In contrast to most space missions, LISA Pathfinder's payload and spacecraft act as a single unit, with the spacecraft being part of the experiment itself.

At the heart of the mission is the LISA Technology Package (LTP) core assembly, consisting of two inertial sensors around independent test masses, and an optical bench between them. LISA Pathfinder will monitor these test masses – two identical gold-platinum cubes measuring 46 mm on each side and weighing 1.96 kg each – as they free fall through space, measuring their positions and attitude via a laser interferometer.

The spacecraft surrounds the two test masses without touching them and shields them from outside influence by adjusting its position using several sets of thrusters that are capable of extremely fine adjustments.

In addition to the LTP, LISA Pathfinder also carries a US-contributed experiment – the Disturbance Reduction System payload – that contributes to the mission by validating additional technology for isolating the payload inside the spacecraft.

Orbit: LISA Pathfinder will arrive at its operational orbit, a Lissajous-type orbit at the L1 Lagrange point, 1.5 million km from Earth in the direction of the Sun, six weeks after launch.

Ground communications: ESA's 35-m-diameter X-band deep-space antenna at Cebreros, Spain, is the primary ground station during science operations. Other stations in the ESTRACK network may be used at other periods or in the event that Cebreros is not available.

Operations: LISA Pathfinder is operating as a physics laboratory in space. The nominal operations phase lasts six months: three months for the experiment involving the full LISA Technology Package and three months for the Disturbance Reduction System. Mission scientists are working 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.

Operational milestones: Following launch on 3 December 2016, the LISA Pathfinder mission has achieved a number of operational milestones.

- 13 January: The laser in the LTP was activated for the first time in space.
- 22 January: LISA Pathfinder arrived at the L1 point and jettisoned its propulsion module.
- 3 February: The 'launch lock fingers' were retracted from the test masses. This left the metal cubes in the hands of the Grabbing, Positioning and Release Mechanism (GPRM).
- 15 & 16 February: The GPRM released the test masses (one on each day), which were then held in place only by electrostatic forces.
- 22 February: The electrostatic forces were turned off, allowing the test masses to float completely freely.
- 1 March: LISA Pathfinder's scientific mission began.
- 7 June: First results are announced.

Mission lifetime: Nominal operations will last six months; an extension of six months is possible.

Mission cost: Total cost for ESA is 430 M Euro. This does not include national contributions or NASA contribution.

Industrial contributions: The prime contractor, Airbus Defence & Space Ltd, led the industrial team building the LISA Pathfinder spacecraft, while Airbus Defence & Space GmbH was responsible for providing the integrated LISA Technology Package payload. The technical team included more than 40 companies and research institutes from 14 European countries and the US.

Mission name: The designation 'LISA' in the mission's name stands for Laser Interferometer Space Antenna, an earlier concept for a space-borne 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.

➔ A challenging build

To explore the gravitational Universe requires an object – referred to as a test mass – to be in free fall. This is because in free fall an object will move solely as gravity pulls it. The place where an object can remain in free fall for long periods of time is space. But in our Solar System, the Sun makes this difficult.

Sunlight carries enough energy to push the object around in the frictionless environment of space. This is known as radiation pressure and spacecraft navigators have been aware of its effects since the early days of the space era. It would easily prevent a test mass from following the precise path that gravity dictates.

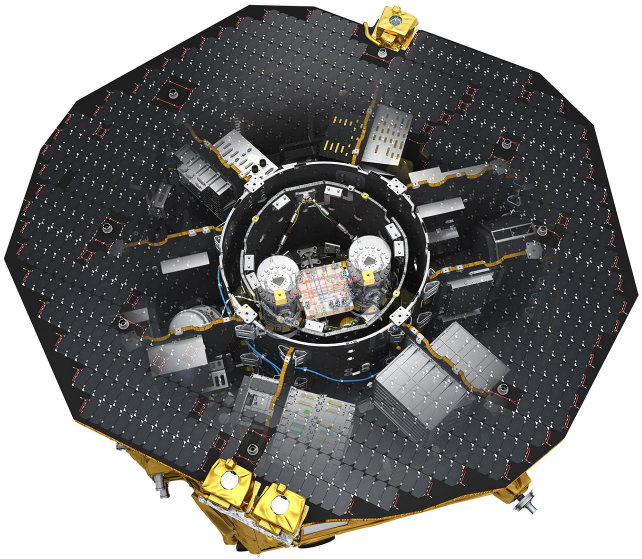
So to protect the object from the radiation pressure and other effects, engineers have no option but to build a spacecraft around it. This spacecraft will also contain all the equipment necessary to measure the movement of the test mass.

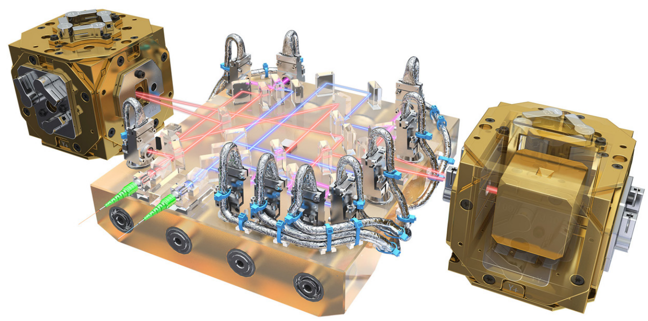
The trouble is, the spacecraft itself will generate forces capable of moving the test mass. These could be magnetic or electric forces, or indeed the gravitational field created by the spacecraft itself. It seems like catch-22 but that is where LISA Pathfinder comes in.

The mission holds two test masses and was designed to show that a spacecraft can be built to isolate such objects from all other forces except gravity. To do this, painstaking considerations must be taken into account.

Firstly, no magnetic material were planned to be used in the spacecraft. In the event, the lasers and thrusters needed some very small magnets to be used but these were positioned on the outer wall of the spacecraft, as far from the test masses as possible. Then, the test masses themselves were made of a special combination of gold and platinum. The metals were chosen and combined in such a way that the magnetic susceptibility of the finished alloy was virtually zero.

Secondly, the spacecraft has had to be balanced so that it does not pull on the test masses with its own gravitational field. This is what makes the construction of LISA Pathfinder one of the most ambitious space projects ever attempted. Everything that was fitted to the spacecraft had to have its mass and position accurately recorded.





A component on the outside of the spacecraft, about a metre away from the test masses, had to have its position measured to within a millimetre. Something placed close to the test masses, had to be placed to within a few tens of millionths of a metre.

Just moving a wire a few millimetres to one side could throw the spacecraft out of balance because of the mass of copper in the cable. The engineers building the spacecraft had to keep unprecedentedly meticulous records of everything that went on or came off the spacecraft. The mass logs run to hundreds of pages.

At the end of the build, a final compensating mass was placed near the test mass. Then smaller, fine-tuning masses were applied near the outside of the spacecraft as needed. According to the computer model of the spacecraft's gravitational field, based on the mass logs kept by the engineers, LISA Pathfinder will generate an internal gravitational force, at the position of the test masses, of just one tenth of a billionth of Earth's gravity.

But this cannot be verified on Earth. Only by sending LISA Pathfinder into a free fall environment, can the success of the engineering be tested. It is for this reason, that the mission had to be launched into space. We have to test if we can actually build spacecraft capable of protecting test masses from everything except the natural pull of gravity.

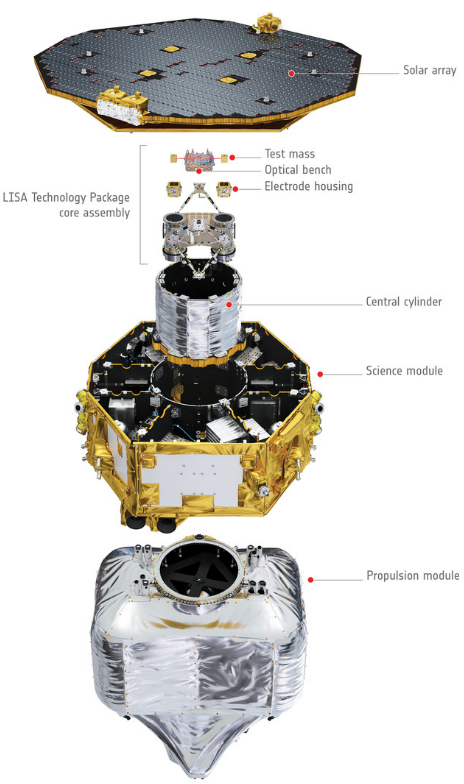
➔ What LISA Pathfinder is doing and how

Every object that has mass or energy produces gravity. In Albert Einstein's monumental description of gravity, the General Theory of Relativity, the combined gravitational fields of all the celestial objects create an invisible landscape of depressions, referred to as gravitational or potential wells. The steeper the sides of these wells, the stronger the gravitational field.

These invisible contours define how matter moves through space, rather like train tracks guiding a locomotive. In the case of general relativity, the paths are called geodesics.

For LISA Pathfinder to work it must detect this motion. The spacecraft is therefore equipped with two test masses, which float inside its body, and the spacecraft senses their motion relative to each other.

The test masses will naturally follow geodesics. If the spacecraft manages to isolate them from all other influences as hoped, then the motion will be purely geodesic and the two test masses will move in perfect synchrony.



If there is an external force acting then the test masses will appear to move differently from one another and the spacecraft will measure an acceleration between them.

The spacecraft keeps track of the test masses by using an ultrastable laser interferometer. A laser beam is split in two, bounced off the surfaces of the test masses and then recombined. Changes in the interference signal between the beams betray any movement between the two test masses down to a trillionth of a metre (a picometre).

Understanding what this relative motion means and making sure that it is coming solely from gravity is the job of the analysis team.

The Mission Operations Centre is at the European Space Operations Centre (ESOC), Darmstadt, Germany, where the spacecraft controllers are based. During the science operations phase, when the LISA Technology Package experiments are being run, the Science and Technology Operations Centre (STOC, usually based at the European Space Astronomy Centre - ESAC, Villafranca, Spain) and the scientists will also be at ESOC because of the need for constant interaction between the scientists running the experiment and the people 'flying' LISA Pathfinder.

LISA Pathfinder will be in touch with the ground for approximately 8 hours every day. It will downlink primarily through ESA's Cebreros and Malargüe tracking stations in Spain and Argentina, respectively. The first data to be transmitted every day tell the controllers and scientists about the health of the spacecraft and the experiment.

The rest of the day is spent downloading the actual scientific data. This will usually be complete by about 18:00, and then the data are transferred and formatted for the scientists' computers, a process called 'ingestion'. So it is the evening before any analysis can take place.

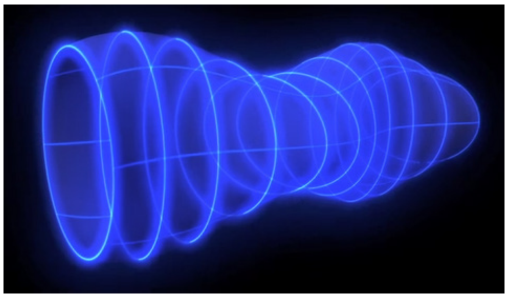
The first analysis is just a quick look to make sure the data look sensible. This takes until the late evening to complete. If everything checks out, the full analysis will begin first thing the next day. It can take days to analyse the data and document the results. Therefore to keep up with the data acquisition two teams must work in shifts. Because of the experimental nature of the mission, the scientific data are essential to inform what else needs doing with the spacecraft. New experiments will be based upon the results of the previous ones. In this way, ESA is learning how to control and make use of a gravitational-wave observatory.

ESA is learning how to control and make use of a gravitational-wave observatory

The scientists and operators at ESOC are also responsible for turning these follow-on scientific requests into command sequences that LISA Pathfinder's main computer will understand. The requests are tested in a computer simulation to make sure that they are safe to perform and then coded for transmission to the spacecraft. And the analysis cycle starts all over again.

➔ Paving the way for gravitational-wave observatories in space

Gravitational waves are fluctuations in the fabric of spacetime caused by accelerating masses. They are predicted by Albert Einstein's General Theory of Relativity. Indirect evidence for their existence has been observed in a system of two dead stars spiraling into tighter and tighter orbits. Discovered in 1974, the two stars are losing energy as expected from the emission of gravitational waves. But, until this year, gravitational waves had not yet been detected directly.



During the past half-century, numerous ground-based experiments have been gradually refined to finally achieve the exquisite sensitivity needed to capture these cosmic ripples. Modern detectors use laser beams to monitor tiny changes in the length of two perpendicular arms, each extending up to several kilometres. Variations in the length of the two arms could be caused by a variety of phenomena on Earth, both natural and artificial, but also by the passage of a gravitational wave.

The most sensitive gravitational-wave detectors are currently the pair that form the Laser Interferometer Gravitational-Wave Observatory (LIGO) in the United States. Recently upgraded, it started operations as Advanced LIGO in September 2015. Within days it detected a fleeting 20 millisecond signal that when analysed was clearly a gravitational wave signal. It had been produced by the collision of black holes 1.3 billion years ago. Each black hole contained about 30 solar masses.

Other detectors are the Virgo interferometer, operated by the European Gravitational Observatory in Italy, GEO600 in Germany and KAGRA in Japan. Many more discoveries are now expected.

Like light, gravitational waves should span a wide range in frequencies (or wavelengths). Different types of astrophysical objects are expected to emit in different regions of this gravitational-wave spectrum.

A supernova explosion or the coalescence of a pair of orbiting stellar remnants, such as neutron stars or black holes, are sources of high-frequency gravitational waves (over 1 Hz). In contrast, the merging of supermassive black holes in large galaxies would be a source of low-frequency gravitational waves (between 0.1 and 0.0001 Hz). Gravitational waves at even lower frequencies (around 10^{-16} Hz) may also exist. If so, they would have been produced during inflation, a theorised phase of accelerated expansion in the first moments of the Universe.

Different instruments will be needed to detect the full spectrum of gravitational waves. Ground-based experiments are sensitive to high frequencies, while observatories in space would be able to catch lower frequencies. The extremely-low-frequency gravitational waves from the early Universe would imprint their signature on the cosmic microwave background.

In space, a gravitational-wave observatory could use laser beams on a much longer baseline than between any pair of locations on Earth, making it sensitive to lower frequency gravitational waves. And, it would not be affected by the nuisance vibrations near the surface of Earth that plague ground-based detectors.

LISA Pathfinder is a new breed of spacecraft, testing technology to extend the quest for gravitational waves to space. It is providing the gravitational-wave community with the confidence needed to build the first gravitational-wave observatory operating in space.

Future space-borne observatories will be able to explore the Universe to distances and epochs that cannot be accessed even with the most sensitive telescopes operating today. They will yield information about the distribution of matter and the formation of cosmic structure a mere hundred million years after the Big Bang.

However, the most exciting findings from the study of gravitational waves might be the discovery of new celestial objects and phenomena.

→ 100 years of general relativity

Just over a hundred years ago, Albert Einstein debuted his revolutionary General Theory of Relativity in the form of four papers delivered to the Prussian Academy of Sciences in Berlin on 4, 11, 18 and 25 November 1915. One hundred years later, general relativity remains our most complete theory of gravity.

General relativity remains our most complete theory of gravity

Prior to general relativity, the leading theory was Isaac Newton's law of universal gravitation. While Newton's theory is still accurate in many situations, Einstein's novel approach achieved a more complete account of gravity's behaviour, especially in extreme cases.

In 1905, he had developed special relativity, showing that space and time are not independent or absolute. They are intertwined into 'spacetime' and appear to shrink or dilate according to the observer's speed. In 1907, Einstein started working towards a theory that would encompass gravity too, but he could not find a way to address it in the 'flat' spacetime of special relativity. Eventually, he realised that he needed to extend the description of spacetime so that it could be curved.

Using the sophisticated mathematics of non-Euclidean geometry, developed by Bernhard Riemann and other mathematicians in the 19th century, Einstein describes spacetime in a more flexible way, identifying curvature as the source of gravity. Spacetime is curved by the presence of mass and this curvature tells other objects how to move, which we perceive as gravity in action.

At the turn of the twentieth century, Mercury's orbit could not be explained. Its closest point to the Sun moved slightly each orbit. Newton's theory could not fully account for this precession but general relativity could. In addition, it predicted a number of unanticipated physical phenomena.

In the curved spacetime of general relativity, photons, the massless particles of light, can have their trajectories bent if they pass close to a massive object. As seen by a distant observer, this is similar to the focussing of light by an ordinary glass lens, and is thus known as gravitational lensing.

In 1919, an expedition led by Arthur Eddington to Príncipe, a small island off the west coast of Africa, measured the positions of stars in a patch of the sky near the eclipsed Sun. The stars appeared to be shifted with respect to their usual position by the amount that Einstein had predicted. It confirmed the validity of Einstein's theory of gravity.

General relativity also predicted black holes, celestial bodies so dense that nothing, not even light, can escape their gravitational pull. These objects were purely theoretically for many decades, until the weight of observational evidence became overwhelming in the 1970s.

The publication of general relativity also marks the birth of modern cosmology. Einstein and other physicists, including Alexander Friedman, Willem de Sitter and Georges Lemaître, started to apply the equations of general relativity to the Universe as a whole. These calculations revealed an unstable Universe, either shrinking or expanding.

Although Einstein tried to modify his equations to produce a stationary Universe, in 1929 the observations of distant galaxies by Vesto Slipher, Milton Humason and Edwin Hubble proved that the Universe was expanding – just as general relativity had predicted a few years earlier.

But there was still one major prediction from general relativity yet to be measured: the emission of gravitational waves. These ripples in spacetime emitted by an accelerating massive body remained undetected until this year. Thanks to the detection made at the Laser Interferometer Gravitational-Wave Observatory (LIGO), announced in February 2016, we know they exist.

Now, as a result of the LISA Pathfinder technology tests, space-borne observatories can in the future join the search.

→ LISA Pathfinder in the context of great physics experiments

By investigating gravity, LISA Pathfinder continues a grand tradition. Some of the greatest physics experiments ever performed have been linked to the investigation of gravity.

In the sixteenth century, the Italian physicist Galileo Galilei began his investigation of falling objects. By rolling spheres down inclined plains he showed that the action of gravity is to constantly accelerate falling bodies. He then showed that objects of different mass and composition are accelerated by gravity in exactly the same way.

He is said to have performed the experiment to prove this by dropping differently-sized objects off the leaning tower of Pisa. The famous location is probably not true, however, and was an embellishment of Galileo's student Vincenzo Viviani, who included the detail in a biography of his master. But in 1971, the experiment was performed in a spectacular setting.

American astronaut Dave Scott took a hammer and a feather to the Moon during the Apollo 15 mission. In the absence of air pressure, both fell to the floor at exactly the same time. "How about that," said Scott to the camera, "Mr Galileo was correct."

In 1687, British polymath Isaac Newton produced a mathematical masterwork when he showed that the gravitational force generated between two objects depended upon the combination of the two masses and their distance apart. If the distance between them doubled, the force dropped to a quarter of its original value – a behaviour known as an inverse square law.

One hundred and eleven years later, British physicist Henry Cavendish calculated the density of the Earth using an incredibly precise set of scales, known as a torsion balance. It worked by measuring the force of gravity between two small masses, then comparing this to the weight of one of those masses, which gave the gravitation force between it and the Earth.

The torsion balance was a large piece of apparatus, spanning almost two metres in width. It had to be placed in a large crate, in a shed, to stop the measurement being ruined by air currents. Cavendish found that Earth's average density was

5400 kg/m^3 (5.4 times that of water), a remarkably accurate result – the accepted value today is 5500 kg/m^3 – even by today's standards.

In the 19th century, physicists recast Newton's work as an equation that required a mathematical constant to work. Known as Big G, the constant quantifies the intrinsic strength of gravity. It can only be measured, rather than calculated theoretically. It is set during the Big Bang by means we do not yet understand.

Using Cavendish's density of the Earth, they calculated the value of this constant to be $6.74 \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$. The accuracy to which we know Big G hasn't changed much ever since. Modern measurements are within one percent of this first value because it is incredibly difficult to measure in the Earth's overwhelming gravitational field.

In the early 20th century, British astrophysicist Arthur Eddington made his own great gravitational observation. He was on the African Island of Príncipe, in the midst of a total solar eclipse, to test Albert Einstein's General Theory of Relativity.

According to the German-born physicist, the gravitational field of the Sun would bend light rays as they passed by twice the value predicted by Newton's theory. During the eclipse, Eddington photographed nearby stars and compared their positions to night-time shots when the Sun was nowhere near.

He found changes in the positions of the stars as predicted by Einstein's theory. It was a stunning vindication of the esoteric theory that described gravity as an invisible landscape of contours and valleys.

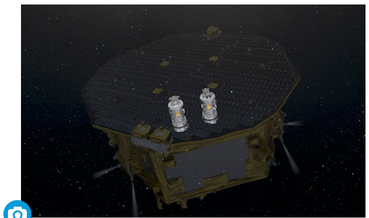
Now we can add the Laser Interferometer Gravitational-Wave Observatory (LIGO) to this list of great physics experiments. Their discovery of gravitational waves has proven not only that Einstein's theory is our best description of gravity yet, but that a whole new Universe of discoveries is waiting for us out there.

The technology being tested in LISA Pathfinder will help unlock those breakthroughs and lead to new great experiments in gravity as modern researchers look for ways to extend Einstein's theory so that it can be used to understand the moment of the Big Bang and the internal workings of black holes.

Appendix 1: Selected images and videos

A full selection of images and videos is available at http://sci.esa.int/lisa-pathfinder-gallery/

First science results
http://sci.esa.int/lisa-pathfinder/57869


LISA Pathfinder: operating in space
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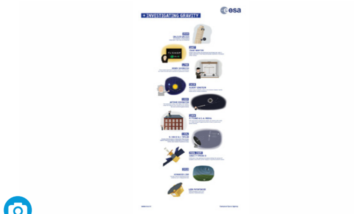
Investigating gravity - a timeline
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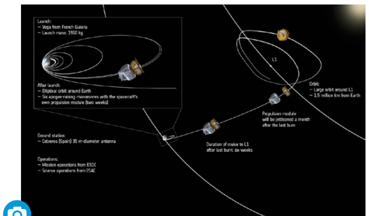
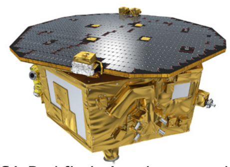

LISA Pathfinder's journey through space – annotated
http://sci.esa.int/lisa-pathfinder/56410


LISA Pathfinder: science and propulsion modules
http://sci.esa.int/lisa-pathfinder/56412


LISA Pathfinder's science module and solar array
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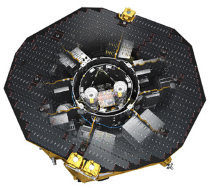
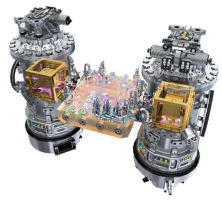

Inside the LISA Pathfinder science module
http://sci.esa.int/lisa-pathfinder/56421


An exploded view of LISA Pathfinder
http://sci.esa.int/lisa-pathfinder/56425


LISA Technology Package core assembly and inertial sensors
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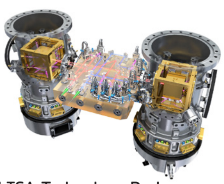
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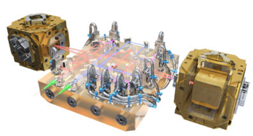
LISA Technology Package core assembly – without vacuum enclosures
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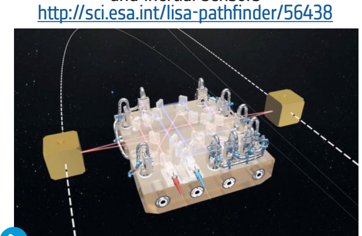
Inside LISA Pathfinder
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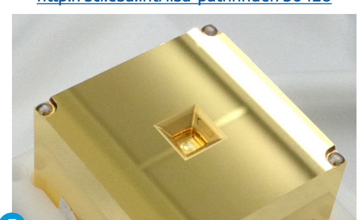
Photograph of the test masses
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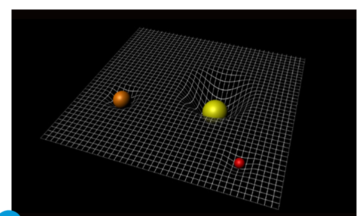
Spacetime curvature
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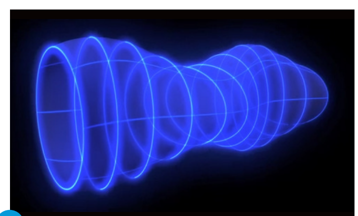
Gravitational waves
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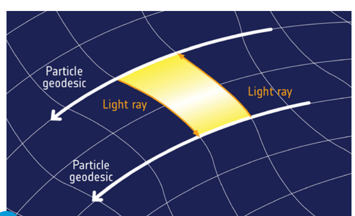

Measuring spacetime curvature
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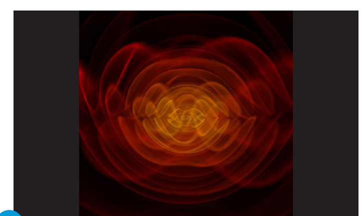
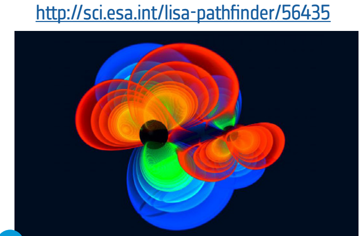
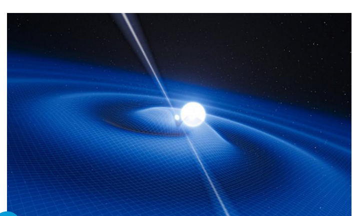

If we could see gravitational waves – I
http://sci.esa.int/lisa-pathfinder/56865


If we could see gravitational waves – II
http://sci.esa.int/lisa-pathfinder/56866


Colliding galaxies
http://sci.esa.int/hubble/29873


Merging galaxies
http://sci.esa.int/hubble/42651


Pulsar and white dwarf binary system
http://sci.esa.int/lisa-pathfinder/56867

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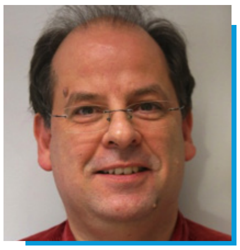

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