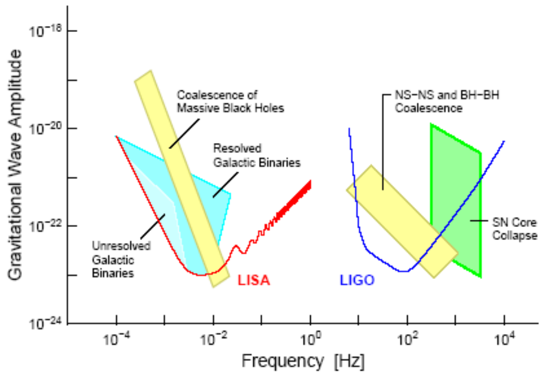
LISA Pathfinder

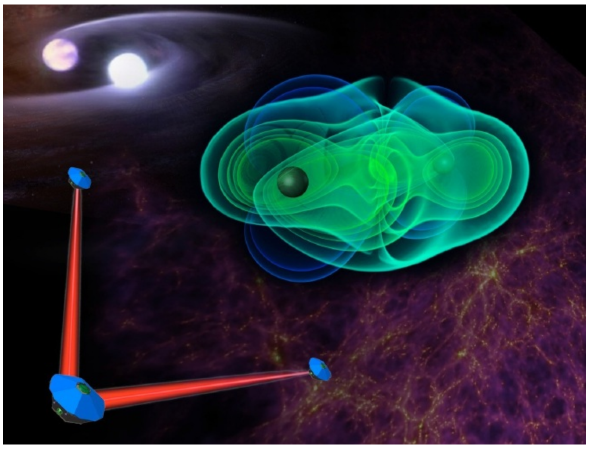
LISA Pathfinder and LISA: Mission Goals

LISA Pathfinder (LISA-PF) represents the essential technology demonstration mission in preparation of the ESA Science-Mission LISA (Laser Interferometer Space Antenna). LISA is planned to be launched presumably in 2034 as the L3 mission of ESA's Cosmic Vision 2015 – 2025 programme to observe low-frequency gravitational waves of cosmic objects in the frequency range from 0.1 mHz to 0.1 Hz from space. Thus, LISA will be operated to complement earth-bound gravitational wave observatories like Advanced LIGO (USA), GEO 600 (Germany / Great Britain), VIRGO (France / Italy), KAGRA (Japan) and their follow-up experiments, all of which will take measurements in the frequency range from about 10 to 10^4 Hz. According to the predictions of the General Theory of Relativity, accelerated masses cause periodic distorsions of the space-time continuum, also called gravitational waves. These distorsions of space-time in turn lead to alterations of the distances between two acceleration-free test masses. In reality, however, the distorsions are so small that only the effects of strong accelerations of very large masses can be detected.

Cosmic sources of gravitational waves that will be detected in the above mentioned frequency range by LISA are short-period binaries, close and collapsing systems of stars, neutron stars and black holes respectively, supermassive black holes in the centers of galaxies, as well as a stochastic background of sources within and outside of our Galaxy. Typical gravitational wave amplitudes, i.e. relative alterations in length, $h = \Delta L / L$, of the interferometrically measured distances, which are required to be detected by the gravitational wave detectors, are of the order of 10^{-18} to 10^{-24} depending on the nature of the objects and the frequencies and durations of the signals emitted. For a long time the existence of gravitational waves could only be indirectly inferred from observations of a few pulsars. However, in September and December 2015 Advanced LIGO succeeded in the first direct detections of gravitational waves emitted by coalescent stellar black holes (GW150914 and GW151226).



LISA will presumably consist of a cluster of three spacecraft placed at the corners of a (nearly) equilateral triangle with side lengths of about 2.5 million km. The center of gravity of the triangle will follow the Earth at a distance of approx. 50 million km. Each of the spacecraft will contain two free-flying test masses which are kept virtually free of external disturbances. The mutual distances of these masses between the spacecraft are measured by means of high precision heterodyn laser interferometry with the goal to identify the very small distance changes triggered by the passage of a gravitational wave. The required measurement accuracy of the test-mass distances typically amounts to about a few 100th of the diameter of a hydrogen atom at the distance of 2.5 million km (i.e. 10^{-12} m). The minute corrections of orbital-parameters and attitude necessary for each satellite to be always centered on the test masses are deduced from frequent measurements of inertial sensors by a Drag-Free Attitude Control System (DFACS), and are converted into small correcting motions of the spacecraft via micro-Newton- (μN-) thrusters (cold gas and colloid thrusters).



However, owing to the large disturbing effects (mainly caused by the gravity of the Earth) that have to be controlled, the required freedom of the test masses from disturbing forces cannot be entirely verified on Earth. Therefore, LISA-PF, as the necessary precursor mission for LISA, followed the goal to test in space the key technologies of the system consisting of

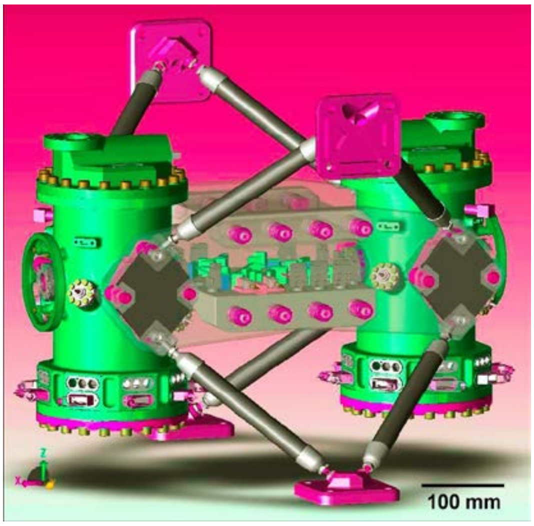
- the inertial sensors to determine the positions of the test masses relative to their spacecraft,
- the Drag-Free Attitude Control System to compensate the disturbing forces by means of μN-thrusters, and
- the laser interferometry.

The goal of the LISA-PF mission is to meet the relevant specifications for the LISA level-of-disturbances (the maximum spectral energy density of the disturbing accelerations of the test masses being $< 3 \times 10^{-15}$ ms^{-2} Hz$^{-1/2}$ in the frequency range from 0.1 mHz to 1 mHz) to less than one order of magnitude. This goal has been followed by the LISA Technology Package (LTP) developed under the responsibility of ESA. The development of the Disturbance Reduction System (DRS, Space Technology 7), which was intended to be supplied by the NASA Jet Propulsion Laboratory (JPL) complementary to the LTP, was cancelled in the meanwhile. Only the colloid thrusters have been supplied by JPL.

Besides ESA as the responsible space agency for the overall LISA-PF mission, the LTP team is joined by scientists and engineers from Germany, Italy, Great Britain, Spain, France, the Netherlands und Switzerland. The industrial main contractor responsible for providing the LTP payload integrated from the national subsystem deliveries was EADS Astrium GmbH (Friedrichshafen, Germany; now Airbus Defence & Space GmbH), while the LISA-PF spacecraft was built by EADS Astrium Ltd. (Stevenage, Great Britain). In Germany the Albert-Einstein-Institut (AEI) in Hannover was leading the development of the interferometer which is at the heart of the science payload of LISA Pathfinder.

The LISA Pathfinder Mission and its Measurement Principle

After its launch on December 3, 2015, LISA-PF was first injected into an elliptical transfer orbit. The apogee of this orbit was then gradually lifted by means of a dedicated propulsion module during several burning phases to finally reach a **halo orbit around Lagrange point L1**, about 1.5 million km from the Earth. Just before reaching its final destination, and before starting the science (drag-free) operation under the lowest disturbance level possible, the propulsion module was separated from the payload module in order to avoid disturbances exerted on the test masses. The halo orbit around L1 has been selected to fulfil the stringent requirements of the LTP with respect to its thermal stability (constant solar irradiation and temperature), and the lowest possible gravitational disturbances that are accessible near the equilibrium point between the Earth und the sun.



The **LISA Technology Package** basically consists of an optical bench (LTP Core Assembly, LCA) which carries inside of each of two separate vacuum enclosures a test mass manufactured from a gold-platinum alloy, the inertial sensors, and the so called caging mechanism (CM). The task of the inertial sensors is to determine the position and orientation of the test mass by electric capacitance changes, and to transfer the measurement data to the drag-free control system to perform the attitude control of the spacecraft. The CM protected the test masses during launch and the transfer phase to L1, and released it in a controlled way at the beginning of the scientific (drag-free) measurement phase.

The laser interferometer is arranged between the vacuum enclosures. It measures, complementary to the inertial sensors, the distances between the two test masses and their accelerations at the highest possible accuracy. The light of the necessary Nd:YAG laser (wavelength 1.064 μm) is produced, and modulated outside the LCA by two acousto-optical modulators, and is feed into the LCA via glas fibers. Another important part of the LTP is the unit to determine the phase difference of the interfering laser beams (the phasemeter) which also delivers a feedback for the frequency stabilization and the stabilization of the optical path difference (OPD) of the beams. A number of additional sensors and systems to monitor and control the LTP environmental conditions like temperature sensors, a magnetometer, a radiometer, magnetic field coils, heaters and an electrical charge management unit for the test masses, as well as a dedicated data processing and control unit (Data Management Unit) are completing the LTP.

The measurements of the inertial sensors at both test masses delivered 10 positions per second during operation. These positional data serve as the basis to control the μN-thrusters via the Drag-Free Attitude Control System, in order to center the LISA-PF spacecraft on the test masses. Moreover, the laser interferometer allowed the scientists to obtain positional data of the test masses independently (at a rate of 100 Hz) which has been used with a subsequent scientific data analysis to identify and determine the residual disturbances, and review the mission success. At the end of the mission the LTP will have been successfully operated in drag-free mode for at least 15 months in total.

To a certain extent, the LTP simulates one arm of the later LISA interferometer which is thus being reduced from about one million km to about 38 cm, in order to accommodate the most essential technological tests for LISA into a conventional (and cost effective) satellite platform.

The German contribution to the LTP comprised the performance of system tasks for the LTP development (industrial architect), and the provision of the optical bench (interferometer) and the laser system (laser and laser assembly). These tasks were carried out by EADS Astrium GmbH (Friedrichshafen, now Airbus Defence & Space GmbH), Kayser-Threde GmbH (Munich, now OHB), and Tesat-Spacecom GmbH & Co. KG (Backnang) under a contract of the Albert-Einstein-Institute (MPI für Gravitationsphysik, Hannover), and funded by DLR.

Characteristics of LISA Pathfinder and the LTP

- Start of development: September 2001
- Start of mission: December 3, 2015, 5:04 CET
- Launcher: Vega
- Launch site: Kourou, French Guiana
- Duration of mission: 19 months (incl. extension) (15 months drag-free operation)
- Orbit characteristics: halo orbit around L1 (dist. to Earth ~1.5 million km)
- Space operations center: ESOC (Darmstadt, Germany)
- Mass of spacecraft: 475 / 1900 kg (payload mod. / launch mass)
- Dimensions of spacecraft: ∅ 2.1 m x 1.0 m (payload mod.)
- Mass of LTP: 140 kg
- Dimensions of LTP: 64 x 37.5 x 37.5 cm^3
- El. power consumpt. (LTP): 150 W (typ.)
- Telemetry rate (spacecraft): 1.7 kbit/s (X-band)

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