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Extract of LISA Pathfinder section

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4.4 LISA Pathfinder

Introduction

LISA Pathfinder (formerly known as SMART-2, the second of the ESA Small Missions for Advanced Research in Technology), is a dedicated technology demonstrator for the Laser Interferometer Space Antenna (LISA) mission. LISA, a joint ESA/NASA mission to detect low-frequency gravitational waves, is expected to observe hundreds of merging massive black hole binaries out to redshifts of z~20, tens of thousands of close compact binary systems in the Milky Way, merging intermediate-mass black hole binaries, tens of stellar-mass black holes falling into supermassive black holes in galactic centres, and possibly other exotic sources.

The technologies required for LISA are many and extremely challenging. This, coupled with the fact that some flight hardware cannot be tested in a 1-g environment, led to the LISA Pathfinder (LPF) mission being implemented to test the critical LISA technologies in space. The scientific objective of the LISA Pathfinder mission is thus the first inflight test of gravitational-wave detection metrology.

LISA Pathfinder mimics one arm of the LISA constellation by shrinking the 5-million-km arm length down to a few tens of centimetres. The experimental concept is to measure the relative separation between two test masses, nominally following their own geodesics, and thereby determine the relative residual acceleration between them near 1 mHz, about a decade above the lowest frequency required by LISA.

To implement such a concept, disturbances on the test masses are kept very small through several design features, but chiefly by 'drag-free' flight. A drag-free spacecraft follows a freefalling test mass, which it encloses but has no mechanical connection to. The spacecraft senses its orientation and separation with respect to the test mass, and its propulsion system is commanded to keep the spacecraft centred about the test mass. Thus, the spacecraft shields the test mass from most external influences, and minimises the effects of force gradients arising from the spacecraft and acting on the test mass. LISA Pathfinder will compare the geodesic of one test mass against that of the other.

LISA Pathfinder will carry two payloads, the European-provided LISA Technology Package (LTP), and the NASA provided Disturbance Reduction System (DRS), part of NASA's New Millennium Programme.

Mission goals

LISA Pathfinder will test in a space experiment that free falling bodies do follow geodesics in space–time, by more than two orders of magnitude better than any past, present, or planned mission (with the exception of LISA itself). The concept that a particle falling under the influence of gravity alone follows a geodesic in space–time is at the very foundation of General Relativity (GR).

LISA Pathfinder's experiment concept is to improve the uncertainty in the proof of geodesic motion. This is achieved by tracking, using picometre resolution laser interferometry, two test-masses nominally in freefall, and by showing that their relative parasitic acceleration, at frequencies around 1 mHz, is at least two orders of magnitude smaller than anything demonstrated or planned so far. The LISA Pathfinder spacecraft as an inertial platform, free of spurious accelerations, will be the best laboratory ever created for Fundamental Physics experiments.

LISA Pathfinder is a mission in both General Relativity and Precision Metrology, pushing these disciplines several orders of magnitude beyond their current state of the art. In doing so it opens new ground for an entire class of new missions in General Relativity, in Fundamental Physics at large, and in Earth Observation. The high resolution optical readout of test-mass motion allows test-mass-to-test-mass tracking even when they are located in different spacecraft, at great distance and in

For further information, see http://sci.esa.int/lisapathfinder

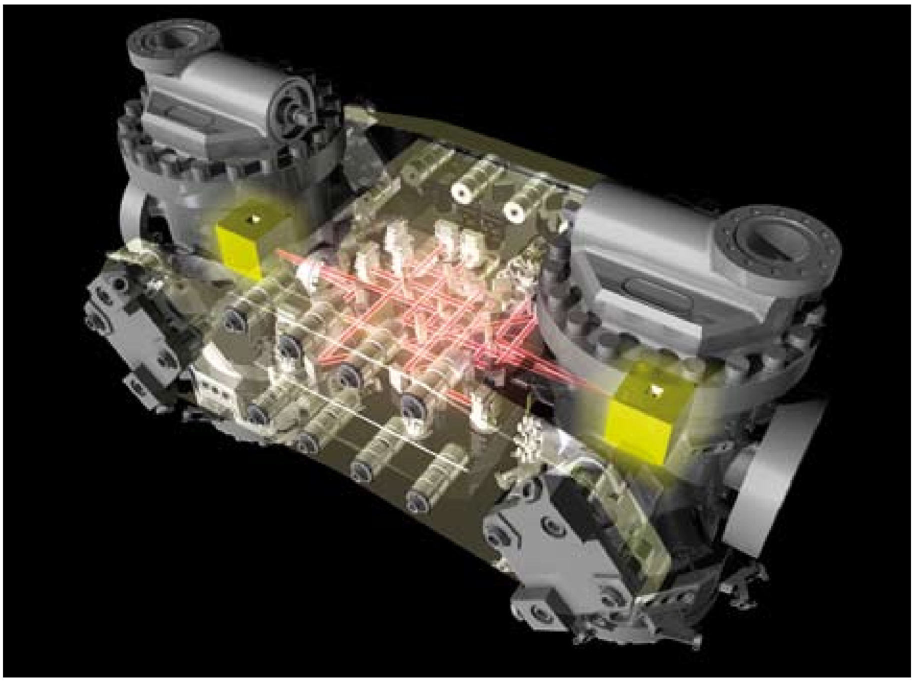

Figure 4.4.1. Drawing of the LISA Technology Package, showing the test masses inside the vacuum enclosures and the metrology interferometer.

interplanetary space, e.g. LISA, or at a short distance in low Earth orbit, as in future geodesy missions.

However, the true objective of LISA Pathfinder is not to develop hardware, but to confirm the overall physical model of the forces that act on a test-mass in interplanetary space. To fulfil this programme, the mission is not just going to make a measurement of acceleration but will implement a full menu of measurements: at the end of this set of measurements, the residual acceleration noise model will be verified in painstaking detail.

The performance goals of LISA Pathfinder can be summarised as follows:

— to demonstrate that a test-mass can be put into pure gravitational freefall within one order of magnitude of the requirement for LISA. The one order of magnitude rule applies also to frequency. Thus the flight test is considered satisfactory if freefall of one test-mass is demonstrated to within 3×10^{-14} $ms^{-2}/\sqrt{Hz}$, rising as f^2 between 3 mHz and 30 mHz;

— to demonstrate laser interferometry with a freefalling mirror (the LTP test-mass) with displacement sensitivity meeting the LISA requirements over the LTP measurement bandwidth. Thus the flight test of LTP is considered satisfactory if the laser metrology resolution is demonstrated to within 9×10^{-12} $m/\sqrt{Hz}$ between 3 mHz and 30 mHz, rising as $1/f^2$ down to 1 mHz;

— to assess the lifetime and reliability of the µN thrusters, lasers and optics in a space environment.

LISA Technology Package

The basic idea behind the LTP is to reduce the size of one arm of LISA from 5×10^6 km to a few centimetres and place it onboard a single spacecraft. The key elements are two nominally free-flying test-masses and a laser interferometer to read the distance between the test-masses (Fig. 4.4.1).

The two test-masses are surrounded by position-sensing electrodes. These provide the information to a drag-free control loop that, via a series of μN thrusters, keeps the spacecraft centred with respect to some fiducial point.

In LISA, as in LPF, each spacecraft hosts two test-masses. This has an important consequence for the spacecraft control logic. The baseline for LISA foresees a control logic whereby the spacecraft is simultaneously centred on both test-masses. The spacecraft follows each test-mass only along the axis defined by the incoming laser beam, however; the remaining axes have to be controlled by a capacitive suspension (or by some other controlled actuation scheme). On LPF, in order to be able to measure differential acceleration, the sensitive axes of the two test-masses have to be aligned. This requires the development of a capacitive suspension scheme that carries one or both test-masses along with the spacecraft (including along the measurement axis), while ensuring the meaningfulness of the test.

In LISA, the proper distance between the two freefalling test-masses at the end of the interferometer arms is measured via a three-step process: by measuring the distance between one test-mass and the optical bench (known as the local measurement); by measuring the distance between optical benches (separated by 5 million km); and finally by measuring the distance between the other test-mass and its optical bench. In LPF, the optical metrology system essentially makes two measurements: the separation of the test masses; and the position of one test-mass with respect to the optical bench. The latter is identical to the LISA local measurement interferometer, thereby providing a flight demonstration of precision laser metrology directly applicable to LISA.

In both LISA and LPF, charging by cosmic rays is a major source of disturbance. Each test-mass therefore carries a non-contact charge measurement and neutralisation system based on UV photoelectron extraction. A flight test of this device is a key element of the overall LPF test.

Disturbance Reduction System (DRS)

The DRS is a NASA-provided payload. When proposed, the DRS payload closely resembled the LTP in that it consisted of two inertial sensors with associated interferometric readout, as well as the drag-free control laws and microNewton (μN) thrusters, though the technologies employed were different from the LTP.

Owing to budgetary constraints, the DRS was de-scoped, and now consists of the μN colloidal thrusters, drag-free and attitude control system (DFACS), and a microprocessor. The DRS will now use the LTP inertial sensors as its drag-free sensors.

The primary goal of the DRS is to maintain the position of the spacecraft with respect to the test-mass to within 10 nm/√Hz over the frequency range of 1–30 mHz.

Launch & orbit

LISA Pathfinder is scheduled to be launched in 2010 on board a dedicated launch vehicle. The spacecraft (Fig. 4.4.2) and expendable propulsion module are injected into a low Earth orbit (200x900 km), from which, after a series of apogee-raising manoeuvres, they will enter a transfer orbit towards the first Sun-Earth Lagrange point (L1). After separation from the propulsion module, the LPF spacecraft will be stabilised using its μN thrusters, entering a Lissajous orbit around L1 (500 000 km by 800 000 km orbit).

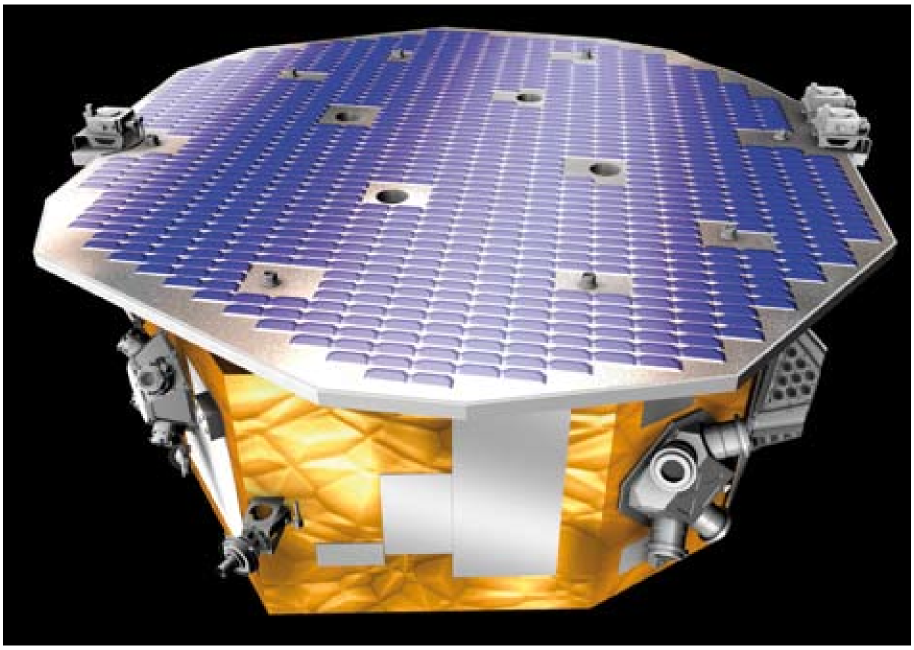

Fig. 4.4.2. Drawing of the LISA Pathfinder spacecraft.

Following the initial on-orbit check-out and instrument calibration, the inflight demonstration of the LISA technology will take place. The nominal lifetime of the science operations is 180 days: this includes the LISA Technology Package operations, the Disturbance Reduction System operations, and a period of joint operations when the LTP will control the DRS thrusters.

Status

LISA Pathfinder is in Phase C/D: the Implementation Phase. During the previous two years, all LTP subsystem Critical Design Reviews (CDRs) have taken place, culminating in the successful LTP System CDR in November 2007. Several spacecraft subsystem CDRs have taken place, with the remaining subsystem reviews occurring in 2008. The LISA Pathfinder System CDR is scheduled to take place in October 2008.

The previous two years have also seen the delivery of the first flight hardware units of the mission, including the digital Sun sensors, separation system, and spacecraft structure. Other units are awaiting their Delivery Review Board prior to shipment. Most flight units will be delivered to the Prime Contractor and LTP Architect in 2008.

The DRS Pre-shipment Review is scheduled to take place during the second quarter of 2008, with flight units being shipped to ESA shortly thereafter.