LISA Pathfinder and the LTP

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LISA Pathfinder (formerly known as SMART-2) is an ESA mission designed to pave the way for the joint ESA/NASA Laser Interferometer Space Antenna (LISA) mission by validating in flight the critical technologies required for space-born gravitational wave detection: it will put two test masses in a near-perfect gravitational free-fall and control and measure their motion with unprecedented accuracy. This is achieved through technology comprising inertial sensors, high precision laser metrology, drag-free control, and an ultra precise micro-Newton propulsion system.

This paper gives an overview of the mission, focusing on the scientific and technical goals.

1 Introduction

LISA Pathfinder (LPF), the second of the European Space Agency's Small Missions for Advanced Research in Technology (SMART), is a dedicated technology validation mission for the joint ESA/NASA Laser Interferometer Space Antenna (LISA) mission.

LISA, a mission to observe low frequency gravitational waves, has continually been ranked as one of the most scientifically important missions under study. However the very concept of low frequency gravitational wave detection, i.e. that a particle falling under the influence of gravity alone follows a geodesic in spacetime, has never been demonstrated to the required precision. This is the most basic assumption of Einstein's General Relativity: LISA Pathfinder has been designed to test this hypothesis with unprecedented accuracy.

The LISA Pathfinder mission essentially mimics one arm of the LISA constellation by shrinking the 5 million kilometre armlength down to a few tens of centimetres. The distance between the two test masses is measured using a laser interferometric technique similar to one aspect of LISA interferometry system.

LISA Pathfinder is due to be launched in 2011 on-board a dedicated launch vehicle. The spacecraft and expendable propulsion module are injected into a low earth orbit (200 km x 1600 km), from which, after a series of apogee raising manoeuvres, 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 micro-Newton thrusters, entering a Lissajous orbit around L1 (500,000 km by 800,000 km orbit). Following the initial on-orbit check-out and instrument calibration, the in-flight validation of the LISA technology will take place.

*http://www.rssd.esa.int/index.php?project=LISAPATHFINDER&page=Author_List
LISA Pathfinder Mission Concept

LISA Pathfinder will test in a space experiment that free falling bodies do follow geodesics in spacetime 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).

In GR, gravity is not considered as an external force: instead gravity is the source of spacetime curvature. Therefore, in a universe devolved of mass (a flat spacetime) free-falling test masses will move in straight lines with uniform velocity (Newton’s 1st Law). In the real (as described by General Relativity) Universe, the presence of mass, hence gravity/curvature, modifies Newton’s 1st Law to state that in the absence of any external force, test masses move along geodesics.

All experiments aimed at directly measuring curvature caused by celestial bodies, or to test subtle effects of GR, e.g., frame-dragging, detection of gravitational waves, or to probe its very foundation - the Equivalence Principle, invariably search for violation of geodesic motion.

The difficulty of achieving high purity geodesic motion is that any parasitic forces compete with spacetime geometry to set masses into motion, perturbing them away from their geodesic lines. As gravity is by far the weakest of all fundamental interactions, achieving the required extremely low level of non-gravitational acceleration requires the understanding, reduction and control of the disturbances produced by a wide range of physical phenomena.

LISA Pathfinder’s experiment concept is to improve the uncertainty in the proof of geodesic motion. This is achieved by tracking, using pico-meter resolution laser interferometry, two test-masses nominally in free-fall, 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, where the conditions hypothesised by Einstein will be realised in the real world.

LISA Pathfinder is both a mission in General Relativity and in 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 large distance and in interplanetary space. e.g. LISA, or at short distance in low Earth orbit, like in future geodesy missions.

It must be stated that 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 program, the mission is not going to just 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 down to painstaking detail.

3 Mission Goals

The mission goals of LISA Pathfinder can be split into three categories, covering the performance of the inertial sensor, the performance of the laser interferometer, and the demonstration of the flight readiness of the technologies critical for a successful LISA mission. The mission goals can be summarised as follows (for a full description of the mission goals, the reader is directed to1):

- demonstrate that a test mass can be put in a pure gravitational free-fall within approximately one order of magnitude of the LISA requirement. The one order of magnitude applies also
to the measurement bandwidth. Therefore, the differential acceleration noise requirement of LISA Pathfinder is stated quantitatively as:

$$\Delta a \leq 3 \times 10^{-14} \left[ 1 + \left( \frac{f}{3 \text{mHz}} \right)^2 \right] \text{ms}^{-2}/\sqrt{\text{Hz}}$$  \hfill (1)

over the frequency bandwidth, $f$, of 1-30 mHz. This is the top-level science requirement of the mission.

- demonstrate laser interferometry with free-falling mirrors (test masses of the LISA Technology Package) with a displacement sensitivity equal to the LISA requirements. Therefore, the flight test is considered successful if the laser metrology resolution is demonstrated to within:

$$\Delta r \leq 9 \times 10^{-12} \left[ 1 + \left( \frac{3 \text{mHz}}{f} \right)^2 \right] \text{m}/\sqrt{\text{Hz}}$$

over a frequency bandwidth of 1-30 mHz with a dynamic range on the order of one millimetre.

- assess the lifetime and reliability of the micro-Newton thrusters, lasers and optics in a space environment.

4 The LISA Technology Package

Unlike traditional observatory or planetary missions, the payload in LISA Pathfinder cannot be considered as a discrete piece of hardware carried by the spacecraft. Instead, during science operations, the payload and the spacecraft act as a single unit: the attitude control of the spacecraft is driven by the payload. LISA Pathfinder will carry two payloads: the LISA Technology Package (LTP), and the Disturbance Reduction System (DRS). The LISA Technology Package is provided by a consortium of European national space agencies (France, Germany, Italy, Spain, Switzerland, The Netherlands, and the United Kingdom) and ESA, while the DRS is provided by NASA. Only the LTP will be described here.

The LTP consists of two major subsystems: the Inertial Sensor Subsystem, and the Optical Metrology Subsystem. Both subsystems are described in further detail in the following sections.

4.1 Inertial Sensor Subsystem

The Inertial Sensor Subsystem (ISS) is at the heart of the LISA Pathfinder mission; the development and on-orbit testing of this subsystem are the main reasons for ESA implementing the mission. The ISS of LISA Pathfinder is the ISS of LISA - the relaxation in the requirements of LPF comes from the relaxation in the environmental conditions of the LPIF spacecraft as compared to LISA.

The inertial sensor subsystem comprises the test masses and all systems interacting directly with the test masses, i.e. the electrode housing, front-end electronics, vacuum system, charge management, and caging mechanism. This section will describe each of these subsystems in turn.

The test masses consist of a 1.96 kg cube of Gold-Platinum mono-phasic alloy of dimension 46 mm on a side. The alloy is formed from 73% gold and 27% platinum, chosen as this alloy has an extremely low magnetic susceptibility ($\chi_m \approx 10^{-5}$) and high density $\approx 2 \times 10^3 \text{ kgm}^{-3}$. The combination of both greatly reduces the effect of external forces on the test mass.

The test masses' position is readout by two means: high resolution laser interferometry, and electrostatic (capacitive) sensing. The former only senses the test mass position along the
sensitive axis (the line joining the two test masses) and the angles of rotation around the axes perpendicular to the sensitive axis, whereas the capacitive sensor measures the position of the test mass in all six degrees of freedom. The capacitive sensor comprises a hollow cubic molybdenum housing with gold coated sapphire electrodes mounted in the faces (see Figure 1). The housing is sized to allow for a ≈4 mm gap between the electrode faces and the test mass. The size of the gap is a trade off between reducing the effects of noise sources, e.g. from uncontrolled potentials on the electrodes, and being able to meet the capacitive sensing requirement of 1.8 nm/√Hz over the measurement bandwidth.

The capacitive readout system, known as the Inertial Sensor Subsystem Front End Electronics (ISS FEE), is arranged such that electrodes facing opposing faces of the test mass are combined via a capacitive bridge. A change in the position of the test mass gives a differential, bi-polar, signal at the output of the bridge, which is used as an input to the drag-free control system. As well as sensing the position of the test masses, the ISS FEE can also be used to actuate (force) the test mass.

The test mass and electrode housing are mounted inside a dedicated vacuum enclosure. To meet the mission requirements, the vacuum around the test mass must be maintained, throughout the mission lifetime, to less than 10⁻⁵ Pa. In order to limit the pressure increase due to outgassing or virtual leaks within the vacuum enclosure, the enclosure will be vented to space once the spacecraft reaches its operational science orbit. As with all equipment used in LISA Pathfinder (with the exception of a few components mounted on the outer wall of the spacecraft as far as possible from the test masses) only non-magnetic materials are permitted to be used in the system, forcing the vacuum chamber to be manufactured from titanium as opposed to the standard stainless steel construction techniques.

As there is no physical contact between the test mass and the surrounding environment, one issue that must be dealt with is charging of the test mass due to cosmic ray and solar energetic particle impacts. A build up of charge on the test mass, coupled with the potentials on the electrodes, creates a force, resulting in additional noise in the test mass position. The charge is controlled using a non-contact discharge system based on the photo-electric effect. UV light from Mercury vapour lamps is channelled to the electrode housing via fibre optic cables. Depending on the sign of the charge on the test mass, the light is either shone onto the test mass or the
electrode housing, thereby extracting electrons from either surface, providing bi-polar charge management.

A further challenge which is unique to space flight hardware is the need for a launch-lock device to prevent hardware being damaged during the extreme vibration conditions experienced during launch. In LISA Pathfinder, this is especially true for the test masses - the most sensitive part of the experiment must survive a random load of \( \approx 50g_{\text{rms}} \), requiring a holding force of \( \approx 1200 \text{N} \), while not damaging the gold coated surface of the cube. In addition to the launch load requirement, when on-orbit, the device must release the test mass within an error box of 200 \( \mu \text{m} \), with a velocity of less than 5 \( \mu \text{m/s} \). These requirements are met by the Caging Mechanism Assembly. This device consists of three actuators: a first stage launch lock mechanism providing a 1200N preload; a second stage positioning actuator, which is used to break the adhesion of the launch lock and position the test mass to the desired location; and finally, the release actuator, a small diameter pin which is used to break the adhesion of the positioning plunger and release the mass with the required accuracy.

Several other challenges must also be solved in order to meet the requirements of the LTP. These include: balancing of the differential gravitational force and gradient at the test mass positions - achieved by mounting compensation masses inside, and external to, the vacuum enclosure; creating a thermally quiet environment around the test mass - a temperature stability of \( 10^{-5} \text{K/\sqrt{Hz}} \) over the measurement bandwidth; associated with the thermal stability requirement is the need to have thermometers with a resolution better than \( 10^{-5} \text{K/\sqrt{Hz}} \); and as mentioned earlier, no magnetic materials can be used - this makes the design of several of the subsystem units especially difficult (e.g. vacuum chamber, mounting brackets, bolts, etc).

4.3 Optical Metrology Subsystem

The Optical Metrology Subsystem (OMS) is the high resolution laser interferometric readout of the test masses' positions. The OMS comprises several subsystems, namely: the reference laser unit, the laser modulator, the optical bench interferometer, the phasemeter, and the data management unit (Figure 1).

The Reference Laser Unit (RLU) comprises a 40 mW Nd:YAG non-planar ring oscillator of the same design commonly used in metrology labs around the world. This laser design is ideal for space applications due to its small size, high electrical to optical efficiency and inherent low noise operation. The challenges for space applications come from the need for a robust design which can survive both the launch loads and thermal environment, as well as having a sufficient lifetime to guarantee the life of the mission. All of these challenges have been overcome and similar lasers are now flying in space on optical communication satellites. The RLU is baselined as the master oscillator in the LISA laser system.

The RLU output is fibre coupled using single-mode, polarisation-maintaining (sm/pm) fibre. The fibre couples the light to the subsequent component in the optical chain, the Laser Modulator (LM). The LM consists of a beam splitter, two acousto-optic modulators, and optical pathlength actuators. The light from the laser is split into two paths, each path is passed through an acousto-optic modulator. One modulator is driven at 80 MHz, while the other is driven at 80 MHz + 1.2 kHz, thereby creating two beams with a frequency difference of 1.2 kHz. The beams are then passed through the optical pathlength difference (OPD) actuator which consists of a fibre optic cable wrapped around a cylindrical piezo-electric transducer. The OPD is used to stabilise the optical pathlength of the fibre optic cables leading to the optical bench. After the OPD, the beams are transmitted, again via sm/pm fibre, to the Optical Bench Interferometer (OBI).

The main function of the OBI is to direct the beams to the relevant positions in 3-dimensional space, without adding any significant noise to the measurement path. The primary optical bench
requirement is that the pathlength noise induced by the components on the optical bench should not exceed $1 \mu m/\sqrt{Hz}$ over the measurement bandwidth. The optical bench is constructed from a block of Zerodur ceramic glass with fused silica mirrors and beamsplitters bonded to the bench using hydroxy catalysis bonding \textsuperscript{6}. The mirrors and beamsplitters are used to direct the two beams to form four interferometers: the $x_2 - x_1$ interferometer which measures the differential motion of the two test masses - this is the primary science measurement of the mission: $x_1$ interferometer which measures the position and angles of test mass 1 with respect to the optical bench (and therefore, the spacecraft) - equivalent to the LISA local test mass interferometer; the Frequency interferometer which is an unequal arm Mach-Zehnder interferometer, the output of which is sensitive to laser frequency fluctuations, and therefore can be used to stabilise the laser frequency; and the Reference interferometer which is a rigid equal arm interferometer which provides the system noise floor, and is used to stabilise the optical pathlengths via the OPD. The light from each fibre is also sent directly to a photodiode which is used to monitor the laser intensity noise. The signal from these photodiodes is used to stabilise the intensity of both beams by feeding back to the acousto-optic modulator drive signal.

The signals from the (quadrant) photodiodes of each interferometer (each interferometer has two quadrant photodiodes for redundancy) are sent to the Phasemeter Assembly. The phasemeter samples the data at 50 kHz and performs a Single Bin Discrete Fourier Transform \textsuperscript{7} to measure the phase of the signal at the heterodyne frequency. This technique is used due to the efficiency of the algorithm. The phasemeter not only outputs the longitudinal phase from the respective interferometers, but also outputs the angles between the wavefronts interfering on the photodetectors - commonly known as differential wavefront sensing (DWS) - at 100 Hz. The DWS signals from the $x_1$ and $x_2 - x_1$ interferometers are used to align the test mass to the interferometer. The longitudinal signals from the interferometers are used to stabilise the laser frequency, the optical pathlength, and (with the DWS signals) as inputs for the Drag-Free and Attitude Control System (DFACS) \textsuperscript{8}.

As mentioned above, the phasemeter outputs the data at 100 Hz. However, the 100 Hz samples are not required for routine operation, and so the data is downsampled to 10 Hz prior to transmission to the on-board computer (and hence the DFACS). The downsampling is performed inside the Data Management Unit (DMU) - a 12 MHz ERC32 processor. The DMU is also responsible for the interface to the LTP subsystems, routing telecommands and timing information to the units, and collecting and transmitting telemetry to the on-board computer.

### 4.3 Micropropulsion

The LISA Pathfinder Micro-Propulsion Subsystem (MPS) is based on Field Emission Electric Propulsion (FEEP) technology. An extensive account can be found in \textsuperscript{9} and \textsuperscript{10}. In field emission electrical propulsion, positive ions are directly extracted from liquid metals (for LISA Pathfinder, Caesium has been chosen as the liquid metal source) and accelerated by means of electrostatic force in high vacuum. This function is carried out by applying a high voltage to a suitable electrode configuration, which is able to create and enhance very high electrical fields (up to $10^9$ V/m). An additional external source of electrons, the neutraliser, needs to be included to maintain the balance of the overall electrical charge of the system (ions$^+ = e^-$).

The LISA Pathfinder MPS is composed of three main parts: a FEEP Cluster Assembly; a Power Control Unit (PCU); and a Neutraliser Assembly (NA). The FEEP Cluster Assembly consists of a self-contained unit of 4 FEEP Thruster Assemblies, which include propellant reservoir, mounted on a support structure. The four thrusters are devoted to provide thrust to the required vector directions and are commanded individually and work in hot redundancy.

The Neutralizer Assembly consists of a self-contained unit of two neutraliser units necessary to null the spacecraft charge imbalance due to ion thruster operations. The neutralisation func-
Figure 2: The LISA Pathfinder launch composite being in the vacuum chamber in preparation for the Transfer Orbit Thermal Balance test. The test was performed at the IABG, Germany.

The Power Control Unit consists of an electronic unit interfacing to the spacecraft for power supply and telecommand and telemetry tasks and provides power and control to both the FEEP Cluster and Neutraliser assemblies.

5 Spacecraft

The spacecraft platform structure provides the mechanical support for the hardware of the other spacecraft subsystems. The spacecraft has a shape of an octagonal prism, with outer diameter of 231 cm and height of 96 cm. One of the two bases is covered by a sunshield panel supporting an array of triple-junction GaAs solar cells of 2.8 m², providing at end-of-life 650 W of power, while the other base interfaces with the propulsion module (Figure 2). A large central cylinder accommodates the LTP core assembly, while the rest of the payload equipment and the spacecraft units are mounted as far away as possible on shear walls connecting the central cylinder to the outer panel forming the octagonal structure. The cylinder and all structural panels are constructed from sandwich panels or shells with carbon fibre laminate skins bonded to aluminium honeycomb core. Aluminium items are limited to structural rings, cleats, inserts and minor brackets.

The Thermal Control Subsystem must guarantee the very stable thermal environment required by the science measurements. Together with the stringent thermal stability required at LTP level, a stable thermal environment of $10^{-4} \text{K/}\sqrt{\text{Hz}}$ is also required at the LTP interface, in order to minimise the thermo-elastic distortions. Passive means are used to control the upper temperatures of sensitive equipments, with electrical heaters to control the lower temperatures. The entire module is wrapped in Multi-Layer Insulation (MLI) except for designated radiator areas designed to reject to space the excessive heat. The minimum necessary heater power is applied in the cold cases so that the lower temperature of each unit is maintained towards the bottom of their allowable range. By using the full design temperature range of each unit in this way, the heater power requirement is minimised. Heater switching is not permitted during the science operations as the transient variations in temperature that happen as heaters switch can interfere with the payload measurements. On the sensitive equipment, different combinations of trimming heaters are used to obtained the required temperatures.
6 Conclusions

Throughout the history of the LISA mission, the science return has never been in doubt - LISA will observe the Universe in a way which has never been possible before. This has captured the imagination of the science community, but at the same time has cast doubt on the probability that such a mission can be realised. Together, this prompted the European Space Agency to adopt the LISA Pathfinder mission - the science return of LISA easily justifies the technology development mission.

The final return of LISA Pathfinder is not only related to the development of the critical technologies for LISA - in the process of implementing the mission, the industrial experience required to build a mission like LPF (and LISA) has also been acquired, as has the knowledge of the ground segment required by a LISA-like mission.

In conclusion, LISA Pathfinder is on track to demonstrate the first in-flight test of low frequency gravitational wave detection metrology. Launch is scheduled for 2014, with first results available to the science community approximately three months thereafter.

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