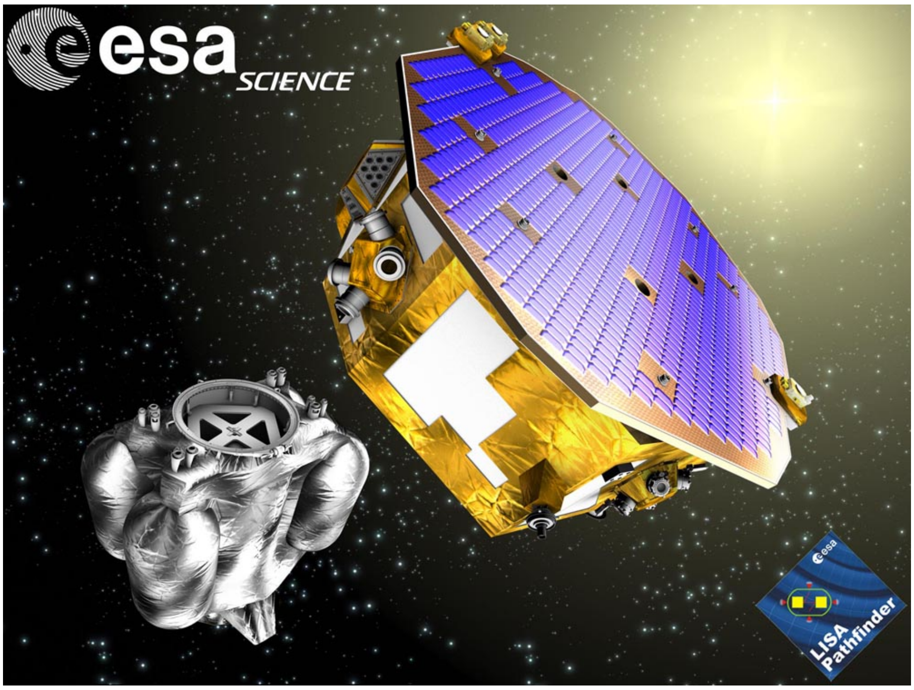
Introduction to LISA Pathfinder



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Contents

1 Introduction

LISA Pathfinder, the second of the European Space Agency's Small Missions for Advanced Research in Technology (SMART), is a dedicated technology demonstrator for the joint ESA/NASA Laser Interferometer Space Antenna (LISA) mission [1].

The technologies required for LISA are many and extremely challenging. This coupled with the fact that some flight hardware cannot be fully tested on ground due to Earth-induced noise, led to the implementation of the LISA Pathfinder mission to test the critical LISA technologies in a flight environment.

LISA Pathfinder essentially mimics one arm of the LISA constellation by shrinking the 5 million kilometre armlength down to a few tens of centimetres, giving up the sensitivity to gravitational waves, but keeping the measurement technology: the distance between the two test masses is measured using a laser interferometric technique similar to one aspect of the LISA interferometry system.

The scientific objective of the LISA Pathfinder mission consists then of the first in-flight test of low frequency gravitational wave detection metrology.

LISA Pathfinder was first proposed in 1998 as ELITE (European LIsa Technology Experiment) [2]. This mission consisted of a single spacecraft in geostationary orbit with a differential acceleration goal of $10^{-14}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ over a frequency range of 1-100 mHz. This original proposal was refined and proposed to ESA in 2000 in response to the SMART-2 announcement of opportunity. At the time, the proposal called for a joint LISA and Darwin[1] pathfinder mission, consisting of two free-flying spacecraft, with three payloads (LISA Technology Package, Darwin Technology Package, and a NASA provided LISA Technology Package). The goal of the mission was to demonstrate drag-free control (for LISA) and formation flying (for Darwin). The mission was approved by the Science Programme Committee (SPC) in November 2000. After an initial industrial study, the mission was descoped to a single spacecraft (the Darwin Pathfinder was cancelled) and renamed LISA Pathfinder (LPF). At the time, LPF carried two payloads, the European built LISA Technology Package (LTP) [3], and the NASA provided Disturbance Reduction System (DRS) [4]. Both payloads consisted of two inertial sensors, a laser metrology system, micro-Newton thrusters and drag free control software. However, the DRS was descoped and now consists of micro-Newton thrusters and a dedicated processor running the drag-free and attitude control software, and will rely on the LTP for its inertial sensing.

LISA Pathfinder is due to be launched in 2011 on-board a dedicated small launch vehicle. The launcher selected is the new ESA VEGA launcher, which will launch LPF from the European spaceport of Kourou (French Guyana) into a parking orbit with perigee at 200 km, apogee at 1620 km, and an inclination to the equator of 5.3°. After a series of apogee raising manoeuvres using an expendable propulsion module, LISA Pathfinder will enter a transfer orbit towards the first Sun-Earth Lagrange

[1]Darwin is a proposed mission consisting of a flotilla of four or five free-flying spacecraft that will search for Earth-like planets around other stars and analyse their atmospheres for the chemical signature of life [5].

point (L1). After separation from the propulsion module, the LPF spacecraft will be stabilised using the micro-Newton thrusters, entering a 500,000 km by 800,000 km Lissajous orbit around L1.

Following the initial on-orbit check-out and instrument calibration, the in-flight demonstration of the LISA technology will then take place. The nominal lifetime of the science operations is 180 days; this includes the LTP and DRS operations, and a period of operations when the LPF DFACS will use the DRS thrusters.

2 LISA Pathfinder Science Case

The main aim of the LISA Pathfinder mission is to demonstrate, in a space environment, that free-falling bodies 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) [9].

In Einstein's General Theory of Relativity, 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). However, 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, free-falling test masses move along geodesics. 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; all experiments aimed at demonstrating a prediction of GR require the use of particles that are, to varying accuracies, in geodesic motion.

Examples of such experiments include; MICROSCOPE [10], STEP [11] and GG [12] which are designed to test the weak equivalence principle; Viking [13] and Cassini [14] which have made measurements of the Shapiro time delay; LATOR [15] and ASTROD [16], both of which propose to measure to high accuracy post-Newtonian parameters; GP-B [17] a mission to directly measure the effects of frame-dragging, and finally LISA [18], and the ground-based gravitational wave detectors (LIGO [19], VIRGO [20], GEO 600 [21] and TAMA [22]). In all these experiments, curvature is studied through its effect on some aspect of the motion of particles along geodesics.

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. The LISA Pathfinder experiment concept is to improve the uncertainty in the proof of geodesic motion. This is achieved by tracking, using pico-metre resolution laser interferometry, two test-masses nominally in free-fall, and by showing that their relative parasitic acceleration, at frequencies around 1mHz, is at least two orders of magnitude smaller than anything demonstrated or planned so far.

To reach its goals, LISA Pathfinder will have to achieve many firsts simultane-

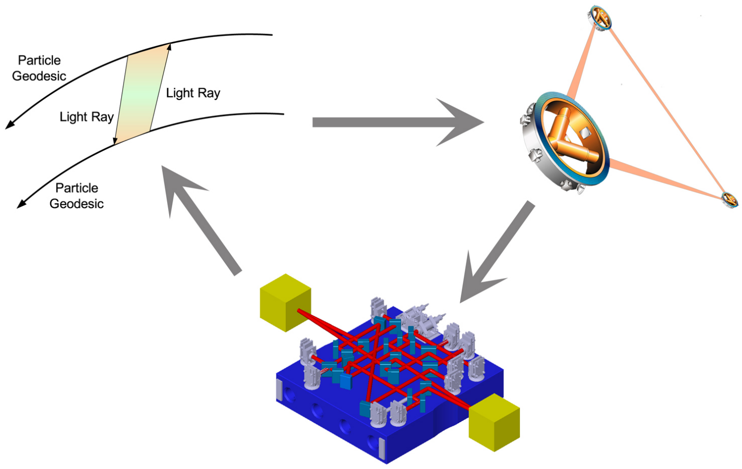


Figure 1: LISA Pathfinder experiment concept. The top left image shows the classical Einstein thought experiment to measure spacetime curvature. This is the basis for all gravitational wave detectors, *e.g.* LISA (top right). LISA Pathfinder will not only pave the way for LISA, but will also demonstrate the main assumption of the thought experiment: that free particles follow geodesics.

ously. Its test masses will be the first large-mass high-purity metal test bodies flown freely in space at a distance of several millimetres from their immediate surroundings and with no mechanical contact to them. With its test mass to test mass and test mass to spacecraft interferometric motion readout, it will realize the first high precision laser interferometric tracking of orbiting bodies in space. With its nanometer spacecraft to test-mass control and its pico-metre test mass to test mass control, it will realize the first nano and sub-nanometer formation flight of bodies in orbit. And with its sub nano-g self-gravity suppression at both test masses locations, it will be the first high-quality orbiting gravitational laboratory for Fundamental Physics experiments.

The concept of LISA Pathfinder is derived from the classical Einstein *Gedanken* experiment depicted in Figure 1. In this thought experiment, the curvature of spacetime can be measured by exchanging a photon between two free-falling particles moving along geodesics. The rate of change of the frequency of the photon then gives a direct measure of the spacetime curvature between the particles according to following relationship:

$$\frac{1}{\omega_{light}} \frac{d\omega_{light}}{dt} \approx c\, R^1_{010}\, \Delta x^1 \tag{1}$$

where ω_{light} is the angular frequency of the photon, Δx^1 is the separation between the particles (along x^1) and $R^\eta_{\alpha\beta\gamma}$ is the Riemann-Christoffel tensor, which represents the real effect of matter-energy on spacetime geometry.

This thought experiment is the basis for all gravitational wave detectors; the passage of a gravitational wave appears as a change in the curvature of the spacetime between the particles. In LISA, the free-particles are gold-platinum cubes located in the spacecraft at the ends of the 5 million kilometre arms, while in the ground based detectors, the free-particles are represented by the suspended mirrors at the end of the interferometer arms. However, in LISA Pathfinder, the goal is *not* to measure the curvature of spacetime, instead the goal is to demonstrate the underlying assumption of the *gedanken* experiment: free-particles move along geodesics. As such the armlength between the test masses is significantly reduced compared to LISA (in this case to 38 cm), thereby minimising the effects of spacetime curvature on the frequency of the light.

Unfortunately, in a real experiment, not only spacetime curvature or the tidal effect of the passage of a gravitational wave affect the frequency of the light; the frequency also changes due to many other effects, most notably due to secular variations of the orbital motion inducing Doppler shifts in the signal. However, this effect is normally at a timescale much longer than those at which the curvature is being observed (days for Cassini, hours to minutes for LISA).

Much worse is the effect of non-gravitational forces that push the particles away from their geodesics. For slow particles these induce a frequency variation with time of:

$$\frac{1}{\omega_0}\frac{d\omega}{dt} \approx \frac{1}{c}\left[\left(\frac{\vec{F}}{m}\right)_{em} - \left(\frac{\vec{F}}{m}\right)_{rec}\right] \cdot \hat{n}_{ray} \tag{2}$$

where $\vec{F}$ is the ordinary, non-gravitational force, m is the mass of the particle, *em* stands for the particle emitting the light ray, *rec* for the one receiving it and finally $\hat{n}_{ray}$ is the unit vector in the ray's direction. Thus stray forces, or accelerations, will mimic curvature signals.

This is not the only source of error when measuring curvature. Any instrumental frequency fluctuation directly spoils the measurement by mimicking a relative acceleration. This is the reason that normally null measurements are performed by comparing the change to a reference in an interferometer or taking the difference between two arms. Thereby, in order to measure curvature, two essential ingredients are required:

- free-falling test mass pairs with very low relative acceleration of non-gravitational origin,
- the ability of tracking these test masses with light-beams with very small instrumental fluctuations.

LISA Pathfinder aims at demonstrating both of these at an unprecedented level. In particular, LISA Pathfinder will demonstrate immunity from relative accelerations of non-gravitational origin to

$$\Delta a \leq 3 \times 10^{-14} \sqrt{1 + \left(\frac{f}{3\,\mathrm{mHz}}\right)^2}\ \mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}} \tag{3}$$

over the frequency bandwidth of 1 - 30 mHz. *This is the top-level science requirement of the mission.* It should be noted that this requirement is a factor of ten less stringent than LISA, in a frequency bandwidth roughly a factor of ten higher than LISA. However, as seen in Figure 2, the current best estimate of the performance we can achieve from LISA Pathfinder is significantly better than the requirements. The final step to the required LISA performance will be performed via extrapolation.

In addition, LISA Pathfinder will demonstrate the ability of tracking free-floating test masses by laser interferometry with a resolution of

$$\Delta x \leq 9 \times 10^{-12} \sqrt{1 + \left(\frac{3\,\mathrm{mHz}}{f}\right)^2}\ \mathrm{m}/\sqrt{\mathrm{Hz}} \tag{4}$$

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

Here the main challenge is the low frequency at which this performance is required. Achieving low stray accelerations and low displacement noise becomes increasingly difficult at the lowest frequencies. Resolutions of better than $10^{-18}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ are routinely achieved by the LIGO, VIRGO and GEO 600 ground-based interferometers [19][20][21], but at frequencies above 100 Hz. However, all effects of interest for space missions are comparatively slow processes as they involve the motion of large bodies.

Several other missions have been flown, or are under development, which will use tracking of the relative motion of nearly free-falling artificial bodies. A comparison of the expected performance of these missions versus LISA Pathfinder is shown in Figure 2. It is important to stress that LISA Pathfinder is not a mission mainly aimed at demonstrating drag free control. Drag-free control is just one of the many tools used to achieve test mass geodesic motion. *The main difference is that geodesic motion is the lack of relative acceleration between free test masses other than due to spacetime curvature, while drag free motion is the lack of acceleration of the spacecraft relative to a local inertial frame.*

However, LISA Pathfinder also improves drag-free performance by more than two orders of magnitude relative to any other flight mission (See Table 1).

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 [23].

Also, it must be stated that the final 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 fulfill 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 Description

The main requirements for the LISA Pathfinder mission have been described in Section 2, but the most important of all is the level of free fall purity as expressed

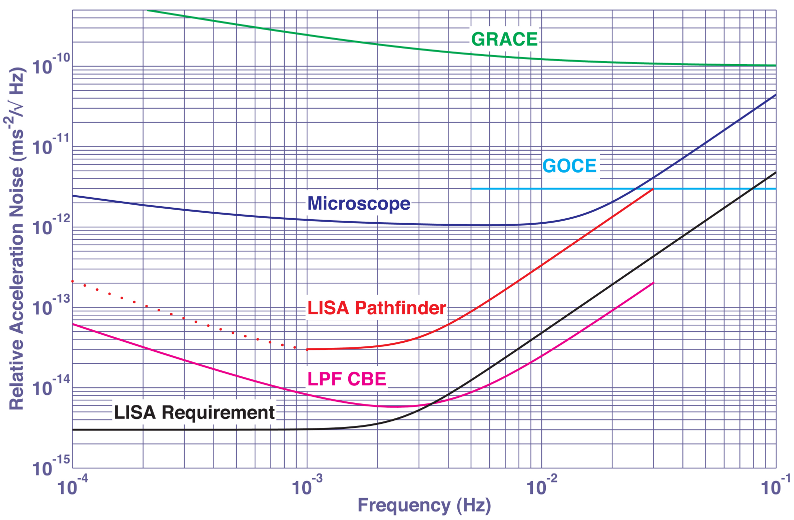


Figure 2: Comparison of the performance of several missions. The line labeled *LPF CBE* is the current best estimate of the expected performance of LPF, the line labeled *LISA Pathfinder* is the LPF science requirement.

Table 1: Comparison of main features of missions requiring geodesic motion. (a) see [24] for more details. (b) Single Test mass acceleration specified at $\approx 2 \times 10^{-12}$ above 5 mHz (Source: GOCE Project)

Mission	Test Mass	Test Mass Environment	Tracking Method	Orbit	Test Mass Geodesic Motion performance (ms^{-2}/rtHz at 1mHz)	Drag-free (Residual Acceleration) (ms^{-2}/rtHz at 1mHz)
GRACE	Accelerometer test masses (<100g)	<200μm gaps from electrodes. Mechanical contact via grounding wire	Radio-link plus capacitive sensing	Low Earth Orbit	$\sim 10^{-10}$	No
Microscope	Differential Accelerometer test masses (<500g)	~200μm gaps from electrodes. Mechanical contact via grounding wire	Capacitive Sensing relative to s/c	Low Earth Orbit. Drag-Free	2×10^{-12} (a)	3×10^{-10}
GOCE	Accelerometer test masses (<320g)	~300μm gaps from electrodes. Mechanical contact via grounding wire	Capacitive Sensing relative to s/c	Low Earth Orbit. Drag-Free	3×10^{-12} (b)	3×10^{-8}
LISA Pathfinder	Gravity Reference Sensor test masses (~2000g)	4mm gaps from electrodes. No Mechanical Contact	High resolution (test-mass to test-mass) interferometry	Interplanetary (L1). Drag-Free	3×10^{-14}	3×10^{-13}

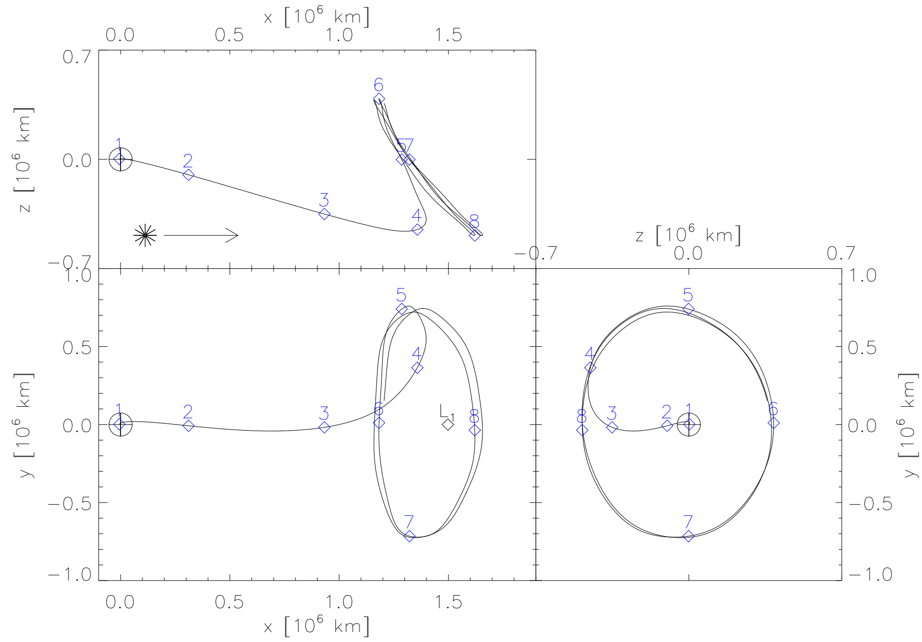


Figure 3: Reference trajectory for LISA Pathfinder. The trajectory is shown in synodic (co-rotating) frame with the Earth at the origin, the x-axis pointing into the Sun direction, and the x-y plane being the plane of the ecliptic. The z-axis (out-of-plane axis) is chosen to form a right-handed coordinate system. The markers show the positions of the spacecraft at different epochs.

by Equation 3. This requirement dictates some fundamental constraints to the mission. Financial constraints prevented from baselining a similar orbit as LISA for LISA Pathfinder, as the launch energy and communication requirements would imply a large launcher and a complex and heavy platform. On the other hand, the requirements of LISA Pathfinder are not as demanding as those of LISA. A small launcher can easily bring a satellite into an earth orbit, however the required orbit for LISA Pathfinder should be as far as possible free from eclipses in order to maintain a stable thermal environment. In addition the earth must be distant enough to avoid gravitational and magnetic disturbances. All these considerations and other more detailed ones, led to the choice of a Lissajous orbit around the first Sun-Earth Lagrangian point (L1). This orbit, depicted in Figure 3, maintains a stable environment, and with the distance from the Earth ranging between 1.2 to 1.8 million km, does not require sophisticated communication equipment.

The use of a small launch vehicle requires that the spacecraft is deployed into a relatively low Earth orbit, from where the spacecraft with its own means must travel to the operational orbit around L1. This transfer costs, in terms of ΔV, about 3100 $\mathrm{ms^{-1}}$ and can be performed by means of several perigee burns (around 12) with a chemical bi-propellant engine of about 400 N thrust (see Figure 4). The amount of propellant needed is considerable (see Table 2) and requires large tanks which at the end of the burn will still contain some residual fuel which might cause gravitational disturbance to the LTP experiment (see Section 4). The consequence is therefore that the propulsion module used for the transfer must be jettisoned from the sciencecraft where the LTP is accommodated before the science operational orbit is reached. The LISA Pathfinder spacecraft is therefore made of two modules as shown in Figure 5.

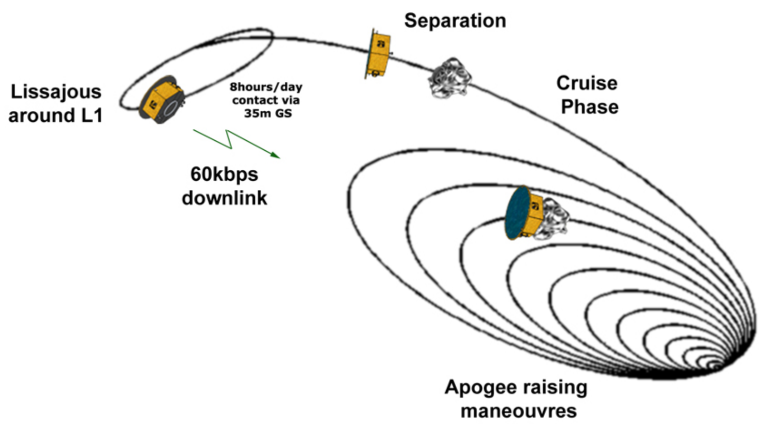


Figure 4: Schematic of the LISA Pathfinder orbit from launch to science operational orbit.

The small launch vehicle selected is the new ESA small launcher VEGA, which will launch LISA Pathfinder into a parking orbit with perigee at 200 km, apogee at 1620 km and an inclination to the equator of 5.3°[2].

The mission consists of five distinct phases, namely:
– **Launch and Early Operations**: The first phase consists of the launch and apogee raising manouevres. It lasts approximately 21 days.
– **Transfer Phase**: The Transfer Phase begins after the last perigee burn and concludes with the launch composite reaching L1. The Transfer Phase lasts approximately 20 days.
– **Separation/Despin** After reaching the L1, the launch composite is spun up to a maximum rate of 5° per second, before the propulsion module is separated from the sciencecraft. After separation, the sciencecraft is de-spun/de-nutated using the micro-Newton propulsion system. The separation/despin phase will last approximately 15 days.
– **Commissioning Phase** Once the sciencecraft is stabilised and under AOCS control, the spacecraft, propulsion system and payload will be commissioned. The commissioning performed during this phase will focus primarily on the micro-Newton propulsion system. Ten days has been each allocated to the platform, the LTP and DRS for commissioning, although half of the DRS commissioning will likely be post-

[2]Since the VEGA launcher is still under development a back-up launch possibility is maintained with the Russian vehicle, Rockot, which could launch LISA Pathfinder from Plesetsk (Russia) into a parking orbit with perigee at 200 km, apogee at 900 km and an inclination to the equator of 63°.

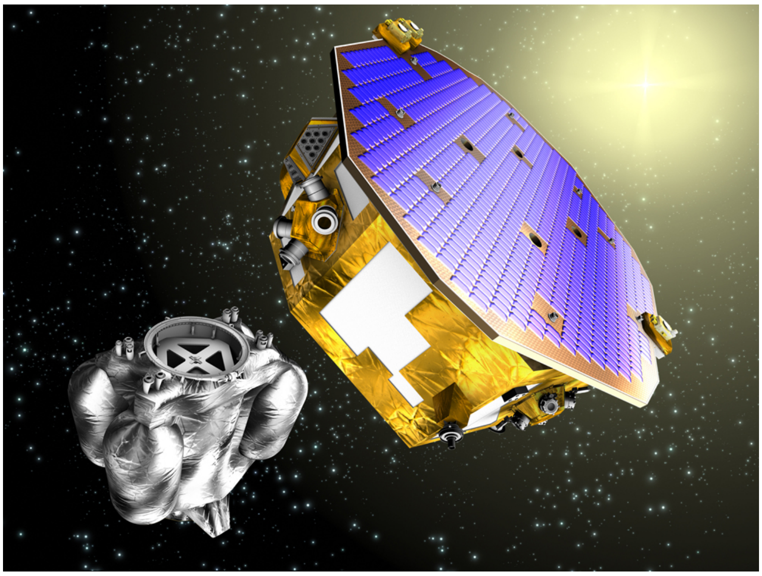


Figure 5: Artist impression of LISA Pathfinder after separation of the science module from the propulsion module before reaching the operational orbit around L1

Table 2: LISA Pathfinder mass budget

Item	**Maximum mass [kg]**
Data Handling	15.4
Power subsystem	63.1
XBand comms subsystem	8.3
AOCS	17.5
Structure	83.0
Thermal subsystem	8.8
Micropropulsion subsystem	43.8
Balance mass	17.5
LISA technology Package	150
Disturbance Reduction System	43
Science Spacecraft Dry Total	450.4
Structure	81.4
Main Engine	100.3
Thermal subsystem	10.6
Harness	8.5
Separation system	8.5
Propulsion Module Dry Total	209.3
Propellant	1214.0
Launch Composite Wet Total	1873.7
Launch vehicle capability	1910.0
Wet Mass Margin	36.3

poned until after the LTP operations.
–**In-Orbit Operations Phase** After commissioning, the science operations will take place. The science operations are split into two blocks of 90 days - the first block is reserved for the LTP operations, while the latter block of 90 days is reserved for the DRS operations.

During IOOP, orbit maintenance manoeuvres are required once per month, with each manoeuvre lasting 2-3 days. Full details of the LISA Pathfinder mission analysis can be found in [25].
Figure 6 shows the pictorial view of the mission timeline.

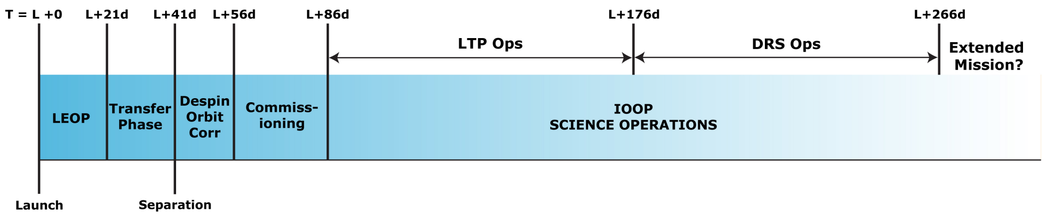


Figure 6: Schematic of the LISA Pathfinder mission timeline.

Ground station coverage is scheduled for 8 hours every day, with a downlink rate of 52.3 kbps. The ground station used will be ESA's 35 m dish at Cebreros in Spain. Mission operations will be conducted by the European Space Operations Centre (ESOC) in Darmstadt (Germany), while the science operations are coordinated from the European Space Astronomy Centre (ESAC) in Villafranca (Spain).

4 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). Only the LTP will be described here.

The LISA Technology Package is provided by a consortium of European National Space Agencies and ESA. Table 3 lists the countries, institutes/industries, and responsibilities, involved in the manufacture of the LTP.
As described earlier in this paper, the main aim of LISA Pathfinder is to demonstrate the principle of geodesic motion to more than two orders of magnitude better than has been previously achieved. In order to meet this goal, all external forces acting on the test mass must be reduced to level below which the relationship in Equation 3 can be met. LTP has been designed to meet these stringent requirements. The main role of the LTP is to house the test masses and provide the position information of the test masses to the Drag-Free and Attitude Control System (see section 5.2). However, due to the resolution required, coupled with the proximity

Table 3: Responsibilities in the manufacture of the LISA Technology Package

Country	Institute/Industry	Responsibility
France	APC, Paris, Oerlikon (CH)	Laser Modulator
Germany	AEI, Hannover Astrium GmbH Tesat	Co-PI, Interferometer design LTP Architect Reference Laser Unit
Italy	University of Trento Carlo Gavazzi Space Thales Alenia Space	PI, Inertial Sensor Design Inertial Sensor Subsystem Test Mass Electrode Housing
The Netherlands	SRON	ISS Check Out Equipment
Spain	IEEC/Uni of Barcelona	Data Management Unit Data Diagnostic System
Switzerland	ETH Zurich/Oerlikon	ISS Front End Electronics
United Kingdom	University of Birmingham University of Glasgow Imperial College London	Phasemeter Assembly Optical Bench Interferometer Charge Management System
ESA	Thales Alenia Space Astrium GmbH	Caging Mechanism LTP Architect

of hardware to the test masses, the performance and environmental requirements levied on the LTP subsystems is extremely demanding.

Figure 7 shows an artists impression of the LTP. The LTP consists of two major subsystems; the Inertial Sensor Subsystem, and the Optical Metrology Subsystem. Both subsystem are described in further detail in the following sections.

4.1 Inertial Sensor Subsystem

The inertial sensor subsystem consists of 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.

In LISA Pathfinder, 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 material can have an extremely low magnetic susceptibility ($\chi_m \approx 10^{-5}$) and high density $\approx 20\,\text{kgm}^{-3}$. The combination of both greatly reduces the effect of external forces on the test mass. A detailed description of the noise sources affecting the test masses is beyond the scope of this document. The reader is directed to [26] for the full error budget of the noise sources affecting the performance of the mission.

The position of the test masses 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

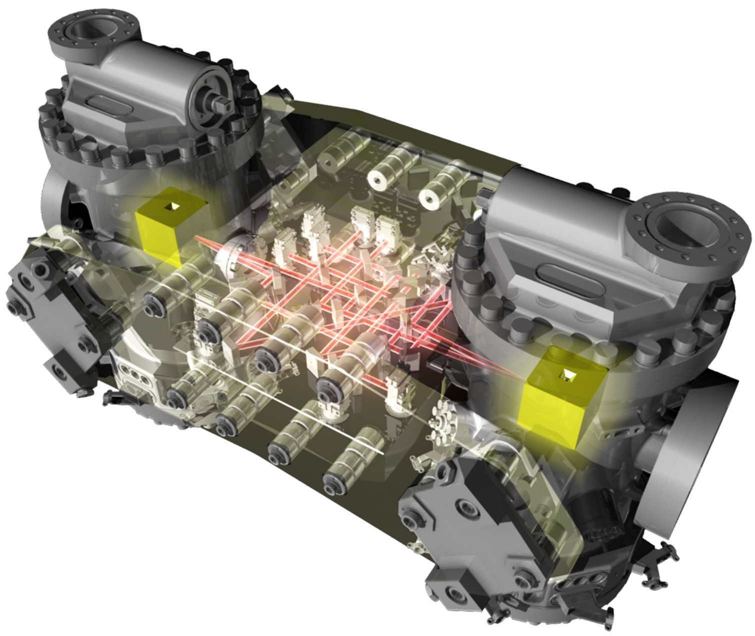


Figure 7: Artists impression of the LISA Technology Package.

freedom. The capacitive sensor comprises a hollow cubic molybdenum housing with gold coated sapphire electrodes mounted in the faces (see Figure 9). 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 $2\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ 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 which is used as an input to the drag-free control system (see Figure 8 for a schematic of the functionality of the ISS FEE). As well as sensing the position of the test masses, the ISS FEE can also be used to actuate (force) the test mass. In the basic operational mode of LISA Pathfinder, one test mass can be considered drag free, *i.e.* the position of this test mass with respect to the spacecraft is fed back to the thrusters such that the *spacecraft* is forced to follow the test mass. However, in this case, any unbalanced external force acting on the second test mass will cause a differential motion between the drag-free mass and the second test mass, which, if uncontrolled, will lead to a collision with the electrode housing after a period of time. For this reason, the ISS FEE must force the second test mass back to the optimum location within the electrode housing. However, this feedback loop only acts at frequencies below the measurement bandwidth, in order to minimise any spurious noise at the frequencies of interest.

The test mass and electrode housing are mounted inside a dedicated vacuum

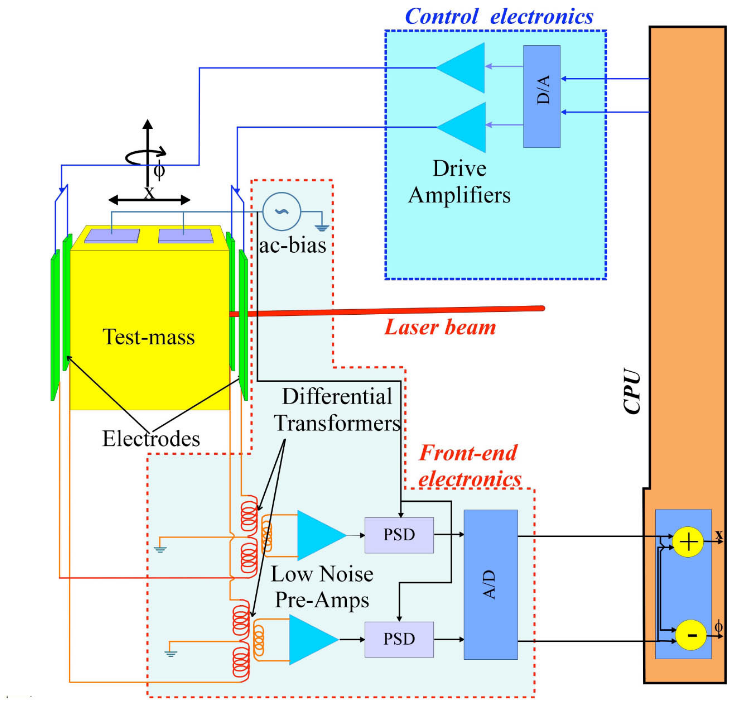


Figure 8: Schematic diagram of the operation of the inertial sensor capacitive readout and actuation electronics.

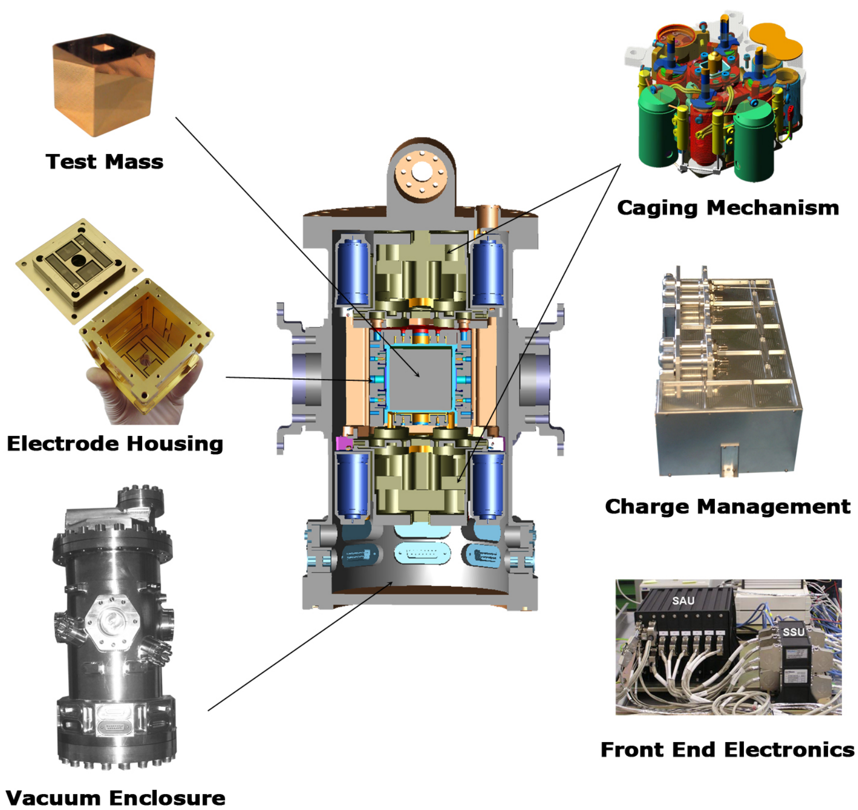


Figure 9: The Inertial Sensor. The centre graphic shows a cut-away of the Inertial sensor vacuum enclosure. The photographs around the side show engineering models of the ISS subsystems (with the exception of the drawing of the caging mechanism which is shown for clarity)

enclosure. In order to meet the instrument requirements, the vacuum around the test mass must be maintained, throughout the mission lifetime, to less than 10^{-5} Pa. While inter-planetary space is an exceptionally good vacuum environment, the space inside, and around, a spacecraft is considerably more dirty (due to outgassing) than can be tolerated by the LISA Pathfinder inertial sensor, hence the need for a dedicated vacuum chamber. As with all equipment used in LISA Pathfinder, only non-magnetic materials can be used in the system, forcing the vacuum chamber to be manufactured from titanium as opposed to the standard stainless steel construction techniques. Also, in order to limit the pressure increase due to outgassing or virtual leaks within the vacuum enclosure (see Figure 9), a getter pump assembly is required to keep the vacuum at the required level.

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, will lead to additional noise in the test mass position. The actual charge on the test mass is measured by commanding the test mass to rotate with a given amplitude and looking at the corresponding actual displacement of the mass. The difference between the commanded and actual motion provides a measure of the test mass charge. The charge is then 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. The system has two modes of operation: rapid discharge, were the science run is stopped, the charge measured, and the UV lamps set to near maximum intensity to discharge the mass in as quick a time as possible; and a continuous discharge mode, where the science measurement is not interrupted, the mass is forced to rotate around the x-axis (direction θ in Figure 12) and the UV lamps are set to a low intensity such that the charging rate is balanced, preventing charge build-up on the mass. Both schemes will be tested on LISA Pathfinder.

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 at 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 $\approx 50\,\mathrm{g_{rms}}$, requiring a holding force of $\approx 2000\,\mathrm{N}$, 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 micron, with a velocity of less than $5 \times 10^{-6}\mathrm{ms}^{-1}$. These requirements are met by the *Caging Mechanism Assembly*. This device consists of three actuators: a first stage hydraulic actuator to provide the 2000 N preload (the launch lock); 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. The caging mechanism is shown in Figure 9.

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 $10^{-5}\,\mathrm{K}/\sqrt{\mathrm{Hz}}$ over the measurement bandwidth is required; associated with the thermal stability requirement is the need to have thermometers with a resolution better than $10^{-5}\,\mathrm{K}/\sqrt{\mathrm{Hz}}$; 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/pumps, mounting brackets, bolts, etc).

4.2 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, optical bench interferometer and the phase meter.

The *Reference Laser Unit* (RLU) employed on LISA Pathfinder is a 35 mW Nd:YAG non-planar ring oscillator [27] 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 [28]. The RLU of LISA Pathfinder is baselined as the master oscillator in the LISA laser system.

The RLU output is fibre coupled using single-mode, polarisation-maintaining 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 (also known as a frequency shifter). 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 fibre optic paths 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 Optical Bench Interferometer 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 can be stated that the pathlength noise induced by the components on the optical bench should not exceed $1\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ [3] over the measurement bandwidth. The optical bench is constructed from a block of Zerodur ceramic glass measuring $200 \times 212 \times 22.5$ mm. Fused silica mirrors and beamsplitters are used to reflect the two beams to form four interferometers on the bench: 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, sensitive to laser frequency fluctuations - the output of this interferometer is 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 fibre 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. Figure 10 shows the optical layout of the optical bench with each of the interferometers labelled.

The signals from the (quadrant) photodiodes of each interferometer (each in-

[3] pm = pico-metre ($\equiv 10^{-12}$ m)

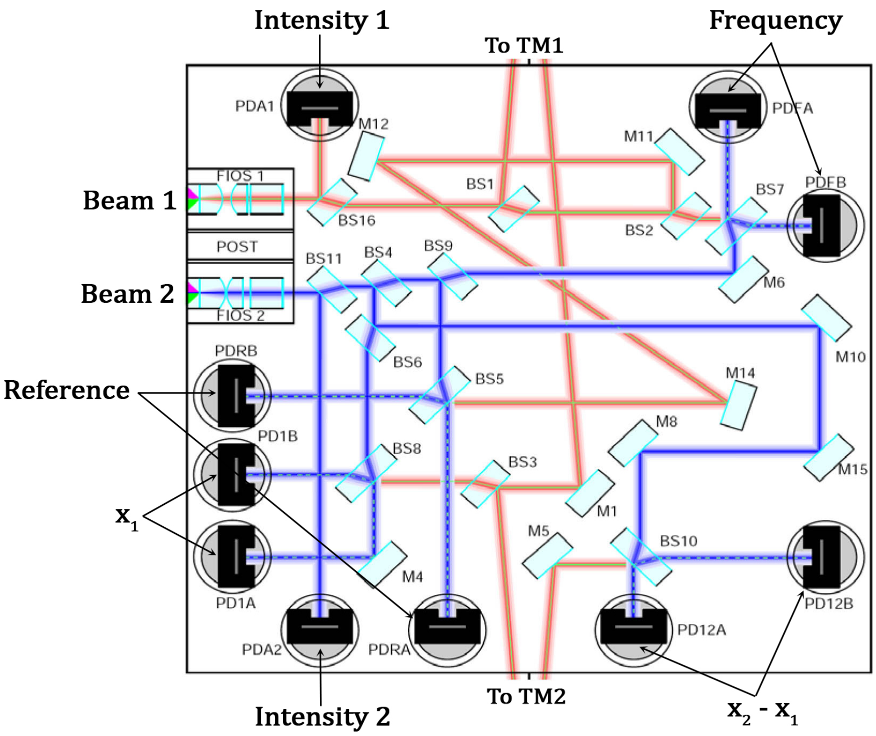


Figure 10: Optical Bench Interferometer layout. The labels *To TM1* and *To TM2* indicate the positions of the test masses (not shown).

terferometer has two quadrant photodiodes for redundancy) are sent to the *Phase Meter Assembly*. The phase meter samples the data at 100 Hz and performs a Single Bin Discrete Fourier Transform to measure the phase of the signals at the heterodyne frequency. This technique is used due to the efficiency of the algorithm. The phase meter 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). The latter 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).

As mentioned above, the phase meter samples 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. The DMU also controls the diagnostic subsystems, consisting of heaters/ thermometers, coils/magnetometers, and a radiation monitor. The diagnostic items are required to isolate particular noise sources in the LTP.

5 Spacecraft

The science module carries all the necessary subsystems required to support the performance of the scientific experiments. In addition this module is also supporting with power and command and data handling the operations of the propulsion module until separation. The science module moreover physically hosts the LTP and the NASA provided payload, the Disturbance Reduction System (DRS). The DRS replicates some of the functions of the DFACS, including using the LTP as the inertial sensor. The science module also hosts a US provided microproplusion system, the Colloidal Micro-Newton Thrusters (CMNT). This document will emphasise the technology associated with the spacecraft, and thereby in the following, a general overview is given on the *standard* platform followed by a more detailed description of the micropropulsion system and the drag-free attitude control system.

5.1 Spacecraft Platform

The Science Spacecraft platform structure provides the mechanical support for the hardware of the other spacecraft subsystems. The spacecraft has a shape of an octagonal prism (see Figure 11). The outer diameter is 2.31 m and the height 0.96 m. One of the two bases is covered by a sunshield panel supporting an array of triple-junction GaAs solar cells of 2.8 m^2, providing at end-of-life 650 W of power, while the other base interfaces with the propulsion module. 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

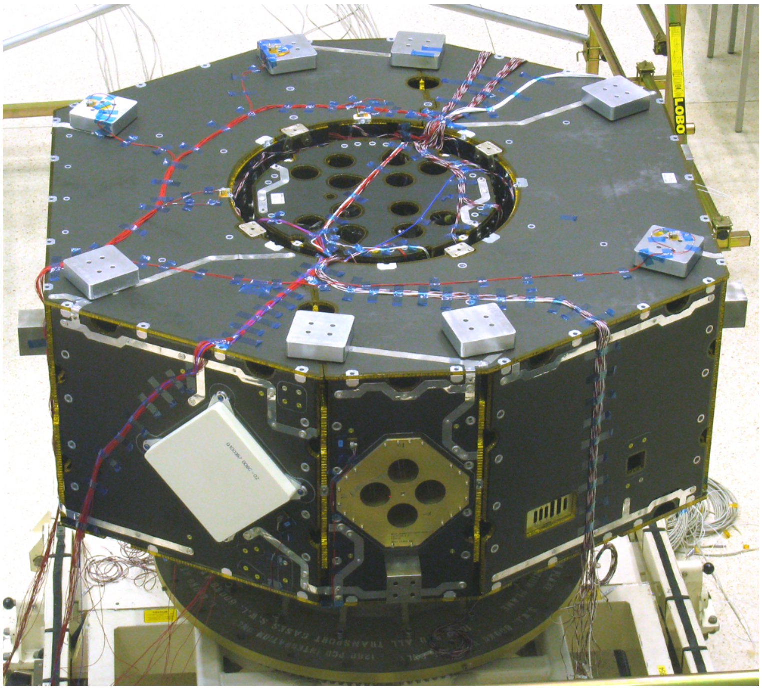


Figure 11: LISA Pathfinder flight structure being prepared for the first of the environmental test campaigns.

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, as seen in Section 4.1, a stable thermal environment of $10^{-3}\,\mathrm{K}/\sqrt{\mathrm{Hz}}$ 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 (see Figure 5). 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 nominal 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. On the micropropulsion systems (both FEEP and CMNT) a high frequency pulse width modulation control of the heaters is used. Heat pipes are avoided as they too would interfere with the measurements due to gravitational disturbance caused by the transfer of mass through the pipes.

The Science Module is a three-axis controlled spacecraft. Apart from the DFACS, which is described in Section 5.2, an Attitude and Orbit Control Subsystem (AOCS) is needed in order to control the Launch Composite (when the propulsion module is attached to the science module) and for the on-station phases when the drag-free conditions cannot be maintained. The AOCS uses as sensors two Autonomous Star Trackers, two Digital Sun Sensors (DSS) for sun acquisition and in safe mode and two Fibre-Optic Gyroscopes Units, required for certain phases where the optical sensors are inoperable due to high rates or eclipse. They are also needed to provide high bandwidth data during the main engine burn. The AOCS actuators are 4 pairs of 10 N bi-propellant thrusters located on the propulsion module and three clusters of 4 FEEP thusters each located on the sides of the science module.

The power subsystem provides a stable regulated bus, with voltage regulation at 28 VDC. During the technology demonstration phase the spacecraft will be sun pointing, therefore all electrical power can be generated by the solar array. Battery power is only required during launch and early operations (LEOP), for eclipse periods during the transfer, during slews to and from engine firing attitude, while firing the engine, and for any anomalies during the on-station phase. For a nominal mission the battery is only required during the initial phases of the mission, therefore because of its low mass, and simple management, a Li-ion battery providing 400 Wh is used.

The On-Board Computer (OBC) is the central control unit for all on board data handling activities, the attitude and orbit control subsystem (AOCS), the DFACS and the management of the platform and payload equipments. Data Handling functions mainly constitute of command distribution, telemetry acquisition and timing facilities during all phases of the mission. Furthermore the OBC performs monitoring functions and depending the detection of failures provides safe system reconfiguration capabilities. The OBC consists of several independent redundant modules: two processor modules, each based on a single chip ERC32 central processing unit working at 22.5 MHz with 6MB RAM, 1.5 MB EEPROM and 64 KB PROM; two telecommand, telemetry and reconfiguration units containing 400 KB safeguard memory; four actuator and sensors interface modules and two mass memory units of 12.5 Gb.

The OBC interfaces with the spacecraft units and the LTP through a MIL-bus 1553B, while the internal backplane link uses the Space-Wire standard. The OBC hosts the On-Board Software (OBSW) which performs all the spacecraft and most of the LTP functions. Only the interferometric optical measurement and the diagnostic functions are performed inside the LTP Data Management Unit (DMU) as described in Section 4.2.

The communications subsystem works at X-band frequency (7230 MHz uplink and 8495 MHz downlink) and provides for commanding and housekeeping telemetry during LEOP, transfer and on-station and also transmits science data telemetry whilst on-station. For LEOP, some phases of transfer and during on-station anomalies, omni directional coverage is required. Two hemispherical antennas are used for the omnidirectional coverage allowing a maximum data rate of 60 ksymbols/s during LEOP and 1 ksymbols/s at L1. However to achieve the required telemetry data rate

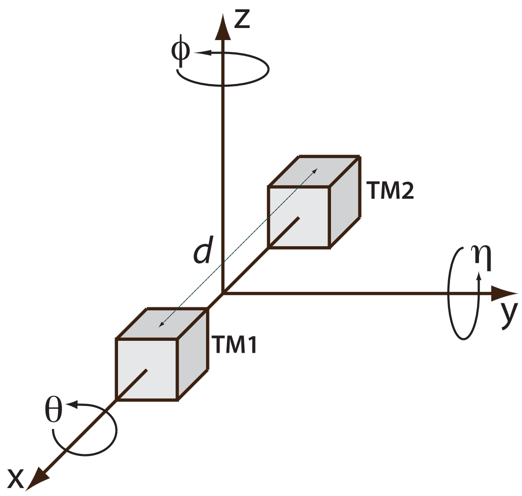


Figure 12: LTP Test Masses layout schematic and axis rotation angles notation

on-station at L1 distance, a medium gain horn antenna is used capable to transmit 120 ksymbols/s. Two X-band transponders are present for redundancy, with coherent ranging. Additional amplification is required at the output of the transponders to achieve the required telemetry margins.

5.2 Drag-Free Attitude Control System

The Drag-Free Attitude Control System (DFACS) is probably the single most important subsystem on board. The main objective of the DFACS is to control the spacecraft dynamics is such a way that the main requirement on the residual acceleration, expressed by Equation 3 is met. Like any control system, DFACS makes use of sensors and actuators. The spacecraft attitude is sensed by means of a pair of star trackers with a measurement error of 32 arcsec/$\sqrt{\text{Hz}}$. With refererece to Figure 12, the test masses position (x_i, y_i, z_i with $i = 1, 2$) and attitude (θ_i, η_i, ϕ_i with $i = 1, 2$) with respect to their housing inside the inertial sensor, are sensed through two different means:

- **electrostatic readout** based on capacitance electronic measurement (see section 4, with a measurement noise of 1.8 nm/$\sqrt{\text{Hz}}$ for x, y, z and 200 nrad/$\sqrt{\text{Hz}}$ for θ, η, ϕ over the measurement bandwidth.
- **optical readout** based on laser interferometric measurement, with a noise of 9 pm/$\sqrt{\text{Hz}}$ for x_1 and $x_1 - x_2$ and 20 nrad/$\sqrt{\text{Hz}}$ for $\eta_1, \phi_1, \eta_{1-2}, \phi_{1-2}$ over the measurement bandwidth.

The actuation on the spacecraft attitude is performed by the set of micropropulsion thrusters, described in Section 5.3, with a noise of 0.1 μN/$\sqrt{\text{Hz}}$. The forces and torques on the test masses are provided by the inertial sensor **electrostatic**

actuation. During the science modes, the maximum differential acceleration noise allowed on the TM's is $10^{-14}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$.

The DFACS tasks is to control the 15 degrees of freedom (DOF) present on-board (6 DOF per test mass and 3 DOF for the attitude of the spacecraft) to fulfill the following objectives:

- to shield one test mass - the *drag-free* or *free floating* test mass - from external disturbances along its sensitive axis in the measurement bandwith [1 mHz to 30 mHz]. The spacecraft is therefore controlled to follow the drag-free test mass, which is free to float in its housing, only subject to the forces that directly impact on the test mass (*e.g.* thermal radiation pressure, magnetic field interaction with TM), called internal forces f_i and to the non contact coupling with the electrodes housing (*e.g.* due to electrostatic field and gravity gradient), called parasitic stiffness ω_i^2.

- to measure by laser interferometer the differential acceleration between the drag-free test mass and the second test mass maintained centred in its housing using electrostatic capacitive forces.

- to keep the spacecraft pointed to the sun and the fixed communication antenna pointed to Earth.

This is realised by careful selection of the drag-free degrees of freedom and frequency band separation. The drag-free DOF conditions are not belonging to one TM, but on 6 DOF's of the two TM's: $x_1, y_1, z_1, \theta_1, y_2, z_2$. Below the measurement bandwith the test masses drag-free DOF's $\theta_1, z_1 - z_2, y_1 - y_2$ are controlled using capacitive suspension control in order to maintain the attitude of the spacecraft according to the star tracker measurements and attitude guidance law (Table 4 lists the control degrees of freedom). Above the measurement bandwidth, the spacecraft is controlled by means of the microproplusion system.

The drag-free controller design is not described in this document but can be found in the literature (e.g. [29], [30], [31]). The DFACS has several modes of operation, which are not described here in detail, and are used during the on station operations after release of the TM from the caging mechanism. One particular science mode, dubbed M3, is particularly interesting for the characterisation of the spurious acceleration noise acting on the TM's. In the M3 mode, the distance between the two TM's, measured by the interferometer, is used by the controller as the main signal to control the position of the spacecraft and of the suspended test mass. Neglecting the thermoelastic deformation of the inertial sensors and optical bench and the cross-talk terms, the interferometer readout measurement equation is the following:

$$S = \frac{1}{s^2 + \omega_2^2 + \omega_{lfs}^2} \left[\frac{f_2 - f_1}{m_{TM}} + x_{nl}(s^2 + \omega_2^2) + \frac{\omega_2^2 - \omega_1^2}{s^2 + \omega_1^2 + \omega_{fb}^2} \left(\frac{F_{SC}}{M} + \omega_{fb}^2 x_n - \frac{f_1}{m_{TM}} \right) \right] \tag{5}$$

Table 4: Drag Free and Attitude Control System degrees of freedom

DoF	Name of Loop	Sensor	Actuator
Test Mass 1			
x_1	drag-free	IS1 x_1 or IFO x_1	FEEPs
y_1	drag-free	IS1 y_1	FEEPs
z_1	drag-free	IS1 z_1	FEEPs
θ_1	drag-free	IS1 θ_1	FEEPs
η_1	suspended	IS1 η_1 or IFO η_1	IS1 electrostatic suspension torque along η_1
ϕ_1	suspended	IS1 ϕ_1 or IFO ϕ_1	IS1 electrostatic suspension torque along ϕ_1
Test Mass 2			
x_2	suspended	IFO $(x_2 - x_1)$	IS2 electrostatic suspension force along x_2
y_2	drag-free	IS2 y_2	FEEPs
z_2	drag-free	IS2 z_2	FEEPs
θ_2	suspended	IS2 θ_2	IS2 electrostatic suspension torque along θ_2
η_2	suspended	IS2 η_2 or IFO η_2	IS2 electrostatic suspension torque along η_2
ϕ_2	suspended	IS2 ϕ_2 or IFO ϕ_2	IS2 electrostatic suspension torque along ϕ_2
Spacecraft			
$x_{s/c}$	uncontrolled		
$y_{s/c}$	uncontrolled		
$z_{s/c}$	uncontrolled		
$\theta_{s/c}$	attitude	Star Tracker	IS1 electrostatic suspension torque along θ_1 below the mbw
$\eta_{s/c}$	attitude	Star Tracker	IS1 and IS2 electrostatic suspension force along z_1 and z_2 below the mbw
$\phi_{s/c}$	attitude	Star Tracker	IS1 and IS2 electrostatic suspension force along y_1 and y_2 below the mbw

$S = x_1 - x_2 + x_{nl}$	is the interferometer differential measurement signal
x_i	is the displacement of the test mass i with respect to the inertial frame
$s = j\omega = 2j\pi f$	is the complex frequency
ω_i^2	is the parasitic stiffness of the test mass i
f_i	are the disturbance forces acting directly on the test mass i
F_{SC}	are the disturbance forces acting directly on the spacecraft
ω_{fb}^2	is the open loop drag free gain
ω_{lfs}^2	is the open loop electrostatics suspension gain
x_{nl}	is the noise of the differential laser interferometer
x_n	is the readout noise of the sensor used for the drag free (either electrostatic or interferometer)
m_{TM}	is the mass of the test mass
M	is the mass of the spacecraft

From Equation 5, it can observed that there are three main contributions to the measured signal, which should be as low as possible, as it is directly related to the residual differential acceleration. The first is a combination of the direct internal forces acting on the test masses, the second is a term proportional to the differential interferometer noise and the third is the so-called spacecraft jitter noise, the physical movement of the TM along the measurement axis. It is instructive to examine these terms one by one. The first term, the internal forces contribution, enters into the equation without multiplying factor, so it cannot be minimised, with respect to other contributors, by tuning system parameters. This means that the term has to be minimised by design and by proper selection of TM material and inertial sensor construction. The multiplying term of Equation 5 can indeed reduce the effect of all the contributions, however at a given frequency band, one can only tune the gain of the electrostatic suspension ω_{lfs}^2, which cannot be increased indefinitely. In other words, if the internal forces term is too large by LTP and system construction, it cannot be mitigated by system tuning. The second term is due to the interferometer noise. This is more important at high frequencies and at large ω_2^2. However the intrinsic noise of the interferometer given by Equation 4 makes this term rather small. The third contribution is dominated by the disturbance forces on the spacecraft (*e.g.* solar pressure fluctuations and micropropulsion force noise) and by the noise of the measurement system used for the drag free control. In the case where the interferometer is used, the term x_n is small and the only remaining term is F_{SC}. This term can be minimised by tuning two system parameters: the difference between the parasitic stiffness $\omega_2^2 - \omega_1^2$ and the drag free gain ω_{fb}^2. The first term must be minimised, while the second maximised.

The above illustrates the basis upon which the on-board calibration and scientific runs will be performed and how the system will be tuned for optimal performance.

5.3 Micropropulsion

The LISA Pathfinder Micro-Propulsion Subsystem (MPS) is based on Field Emission Electric Propulsion (FEEP) technology. An extensive account can be found in [32] and [33]. In field emission electrical propulsion, positive ions are directly extracted

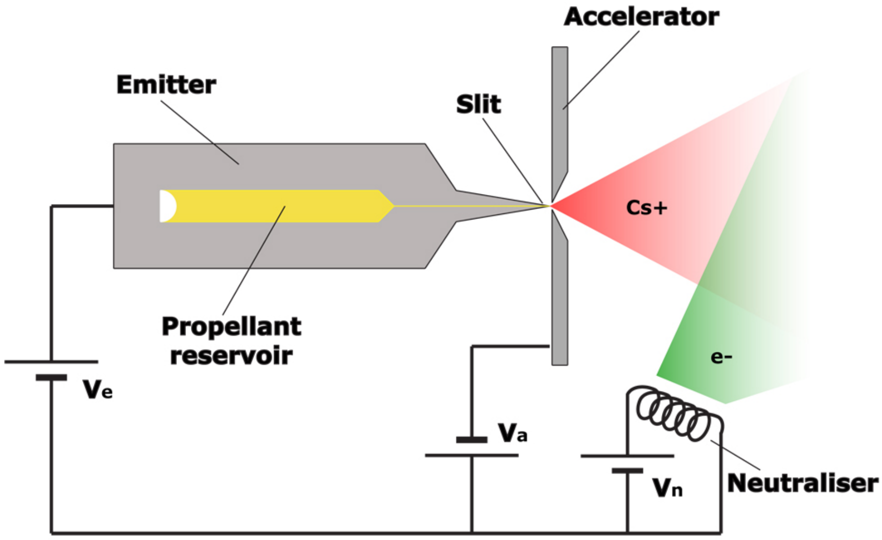


Figure 13: FEEP propulsion concept

from liquid metals (for LISA Pathfinder, Caesium has been chosen as the liquid metal source, however a back-up option of using Indium is also being developed in Europe) and accelerated by means of electrostatic force in high vacuum. This function is carried out by applying a very high voltage to a suitable electrode configuration, which is able to create and enhance very high electrical fields (up to 10^9 V/m). The FEEP working principle is given in Figure 13. An additional external source of electrons, the neutraliser, needs to be included to maintain the balance of the overall electrical charge of the system ($\text{ions}^+ = e^-$).

The main performance requirements of the micro-propulsion system for LPF are shown in Table 5. The main difference between the LPF FEEP requirements and the LISA micro-propulsion system is in the thruster lifetime. The LPF FEEP is designed for mission lifetime of 6,000 hours, with the propellant tank sized for a total impulse of 2,000 Ns, whereas LISA requires 40,000 hours of continuous operation, and total impulse of 4,000 Ns[4].

In addition to the performance requirements, the MPS once initialised and operating in orbit, must not have moving parts, nor gas leaks that could result in spacecraft disturbance and to avoid magnetic disturbance the thruster does not make use of ferromagnetic materials.

The LISA Pathfinder MPS is composed of three main parts, called Micro Propulsion Assembly (MPA): each one consisting of one FEEP Cluster Assembly, one Power Control Unit (PCU) and one Neutraliser Assembly (NA). The FEEP Cluster Assembly (Figure 14) consists of a self-contained unit of 4 FEEP Thruster Assemblies, which include propellant reservoir, mounted on a support structure. The four

[4] LPF requires a large total impulse (2,000 Ns) as the micro-propulsion system is used for station keeping manoeuvres (requiring maximum thrust of 150 μN), while in LISA, the maximum thrust is derived from the need to cancel the solar radiation pressure on the spacecraft (30 μN).

Table 5: FEEP micro-propulsion main requirements. For comparison, the colloidal micro-Newton thruster requirements are also shown.

Propulsion parameter	FEEP Req	Colloid Req
Thrust range	0.1 to 150 μN	5 to 30 μN
Thrust resolution	$\leq$ 0.1 μN	$\leq$ 0.1 μN
Thrust noise	$\leq 0.1\,\mu\mathrm{N}/\sqrt{\mathrm{Hz}}$	$\leq 0.1\,\mu\mathrm{N}/\sqrt{\mathrm{Hz}}$
Thrust response time	$\leq$ 340 ms	$\leq$100 sec
Specific Impulse	$\geq$ 4,000 sec	$\geq$150 sec
Cluster power consumption (@ 30 μN)	55 W	25 W
Cluster Mass	13.7 kg	14.6 kg
Lifetime (Thruster ON)	250 days	90 days
Total Impulse	2,000 Ns	300 Ns

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 unbalance due to ion thruster operations. Also the neutralisation function is implemented by means of cold redundant hardware.
The Power Control Unit consists of an electronic unit interfacing the spacecraft for power supply and telecommand and telemetry tasks and provide power and control to both FEEP Cluster and Neutraliser assemblies.
Each MPA is mounted at 120° with respect to the others. The PCU is located inside the spacecraft while the FCA and NA are mounted externally.

In order to characterise the thruster performance on ground, a complex instrument called the *Nanobalance* (NB) has been devised. The NB is based on a thrust stand with a dual pendulum balance where the plate deflection is measured by a Fabry-Perot interferometer. Designed to be able to measure accurately the full thrust range required down to a resolution fractions of micronewton, the NB has recently been upgraded to be able to measure the thrust noise required (see Table 5). The system is based on multi-stage passive and active noise filtering array. A Thrust Stand a Vacuum System, a Laser Metrology System and a Digital Control Unit basically compose the NB. More details and NB performance can be found in [34]

6 Science Operations

Being a technology demonstration mission, the *nominal* science operations of LISA Pathfinder are more akin to the commissioning phase of a standard science observatory. In fact, the LISA instrument commissioning plan will be optimised using the knowledge gained in the LPF nominal mission.

The operations of the platform and payload will be driven via a mission timeline (MTL) stored on-board the satellite. Real-time commanding of LPF is possible, however this functionality to restricted to initial commissioning of the hardware and

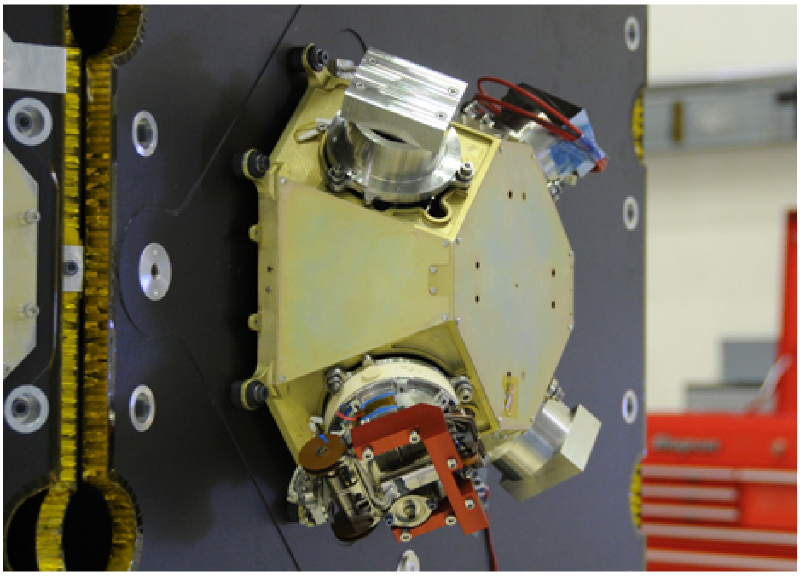


Figure 14: Engineering Model of the Slit FEEP Cluster Assembly mounted on the spacecraft during the acoustic test at system level. The cluster shown consists of one FEEP thruster EQM (bottom) and three mass dummies. The four thrusters are in the launch configuration of lids closed. A lid opening mechanism is operated before the thusters can be used in orbit.

AOCS/DFACS, and during contingency operations. At any time, a minimum of three days of MTL will be stored on board, with the possibility of storing up to 6 days for autonomous operations. Due to the nature of the mission, data analysis will be performed on a near-real time basis: data from a given day is used to plan the operations for three days in the future. In certain situations, the data from one day can be used to replan the activities of two days henceforth, however, this is not foreseen to be the standard operational scenario.

The ground segment of LPF is composed of two operational centres, both provided by ESA:

- The *Mission Operations Centre* (MOC) is responsible for the LEOP, the transfer phase, and the execution of the in-orbit operations and is in contact with the spacecraft for a maximum of 8 hours per day through the 35 m Cebreros ground stations. It is located at the European Space Operations Centre (ESOC) in Darmstadt, Germany

- The *Science and Technology Operations Centre* (STOC) is the point of interface to the scientific community, and is responsible for the payload scheduling (both long and short-term), quick-look data analysis, data processing and archiving. The STOC will also take a leading role in the analysis of the mission data. Development of the STOC is run from the European Space Astronomy Centre (ESAC) in Villafranca, Spain, however, during the science operations of the LTP, the STOC will be re-loacted to ESOC. This is to enable the required close contact between the science operations planing and the mission operations.

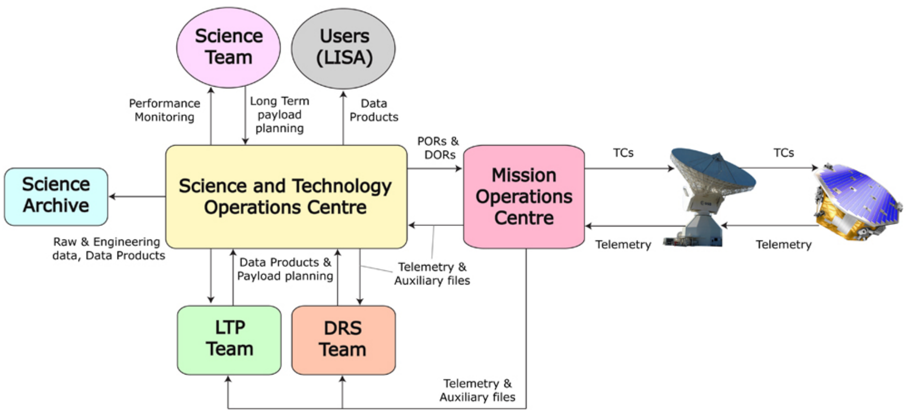


Figure 15: Overview of the LISA Pathfinder Ground Segment diagram showing the data flow.

Figure 15 shows the overall data flow between the various elements of the ground segment.

The section will focus primarily on the Science Operations Ground Segment, and hence the activities of the STOC.

The main activities of the STOC fall into the following classes:

- **Long-term payload planning (LTPP)**: This activity is concerned with the high-level planning of the 90 days of the mission operations. In particular, in defining the experiments to be performed, and the creation of a strawman operational plan. The results of the LTPP are contained in the Experiment Master Plan (EMP) [35]

- **Medium-term payload planning (MTPP)**: This activity concerns the validation of the payload operational requests (POR). A POR is a time-tagged list of telecommand sequences to be executed autonomously. One POR is required for each day of operations.

- **Short-term payload planning (STPP)**: This activity deals with the delivery of validated PORs to the MOC for generation of the Mission Timeline.

- **Data Ingestion (DI)**: The main purpose of the STOC Data Ingestion System is to retrieve telemetry data during each of the ground passes and to make it available to the STOC Quick-Look and Data Analysis and to the archive system for future usage by LTP and DRS.

- **Quick Look (QL)**: The aim of the QL subsystem is to monitor the LTP operations taking place and to provide an alert in case something is not as expected.The QL uses a subsystem of full science telemetry which is directed to a specific packet-store n board, and is telemetred with high priority at the start of the ground station pass. Following the QL activities, the STOC may:
  - Issue a warning for a deeper investigation as part of the Data Analysis.

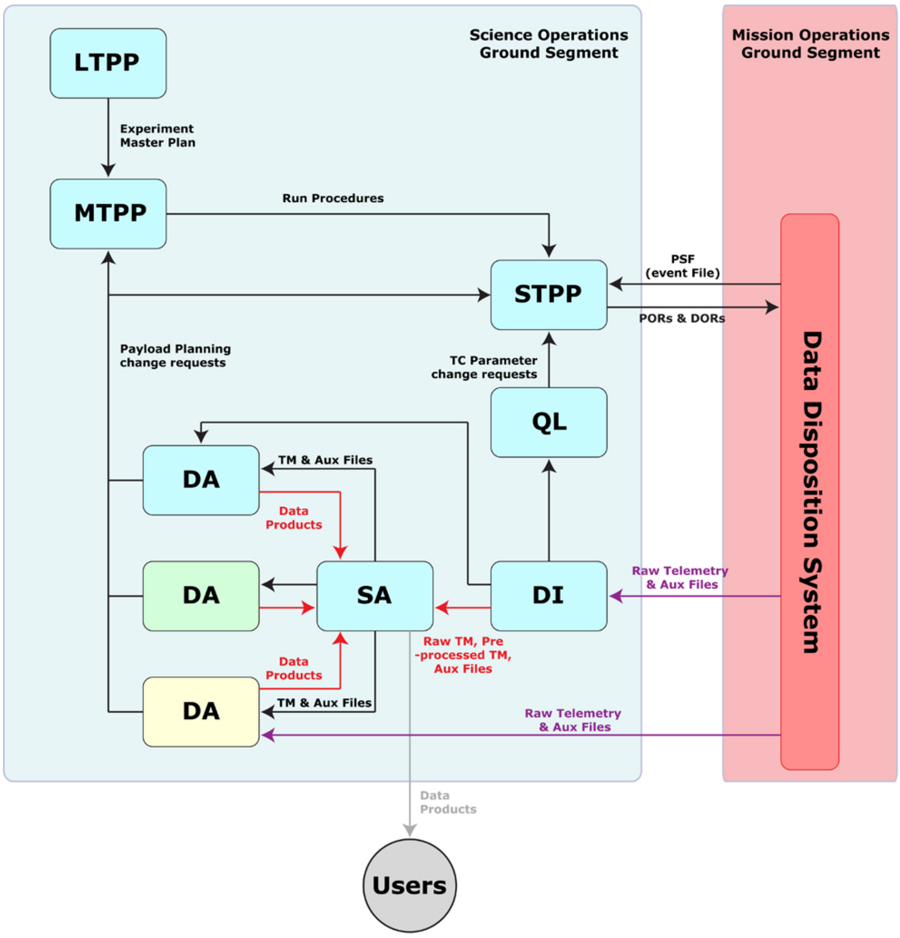


Figure 16: Overview of the science operations ground segment showing the data flow between the various subsystems.

  - Request to MOC a change of TC parameter to be applied to the next run if an immediate action is needed.
  - Request to MOC to immediately command the LTP into Standby mode.

- **Data Analysis (DA)**: The DA is a joint effort of the STOC, LTP and DRS teams and will use the telemetry and auxiliary files available in the STOC archive.
- **Science Archive (SA)**: The SA will make all the data accumulated by LPF and a subset of the data analysis products available to the wider scientific community. The LTP team have priority rights to the data for the first three months, after which the archive goes live on the public domain.

Figure 16 shows an overview of the science operations ground segment during the operational phase of the mission phase.

Table 6: Development milestones of the LISA Pathfinder mission.

Passed Milestones	**Date**
Systems Requirements Review	November 2004
Technology Readiness Review	June 2005
Preliminary Design Review	September 2005
LTP Preliminary Design Review	August 2005
Ground Segment Requirements Review	November 2005
DRS Delta-CDR/Risk Review	January 2006
Mission Preliminary Design Review	February 2006
Hardware Design Review	October 2007
LTP Critical Design Review	November 2007
Ground Segment Design Review	June 2008
DRS Pre-Ship Review	June 2008
Platform Critical Design Review	November 2008
Future Milestones	**Date**
Mission Critical Design Review	September 2009
Ground Segment Implementation Review	December 2009
LTP Core Assembly Delivery	October 2010
Launch	mid 2011

7 Current Status

LISA Pathfinder is in the implementation and testing phase of the mission. The LISA Technology Package Critical Design Review (CDR) was successfully held in November 2007, while the Platform CDR was held November 2008. The overall Mission CDR will be held in September 2009. Table 6 lists the major milestones of the project. Launch is scheduled for mid-2011.
The following sections detail the current status of the spacecraft and the payload.

7.1 Spacecraft

The spacecraft flight hardware has either been delivered and is being used in system testing, or is under subsystem testing prior to shipping (with the exception of the FEEPs which are at EQM testing). Table 7 shows the current delivery dates for the main spacecraft flight articles. In addition to unit deliveries, the launch composite structures (spacecraft and propulsion module) are also under test. In the latter half of 2008, the launch composite underwent the environmental acoustic test (see Figure 17), and separation shock tests (both the separation of the launch composite form the launcher, and also the separation of the sciencecraft from the propulsion module). Testing of the structures and flight hardware is ongoing.

The FEEP thruster hardware is also under test. Several Thruster Assembly Priming Tests (TAPT) have been performed to test the repeatability of the priming of the thruster. The priming of the thruster requires several steps to be performed,

Table 7: Scheduled delivery dates of the LISA Pathfinder platform flight units [36]

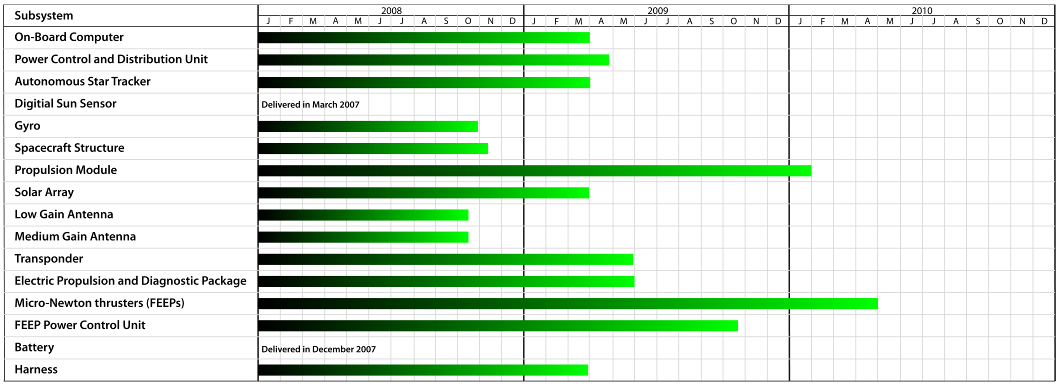
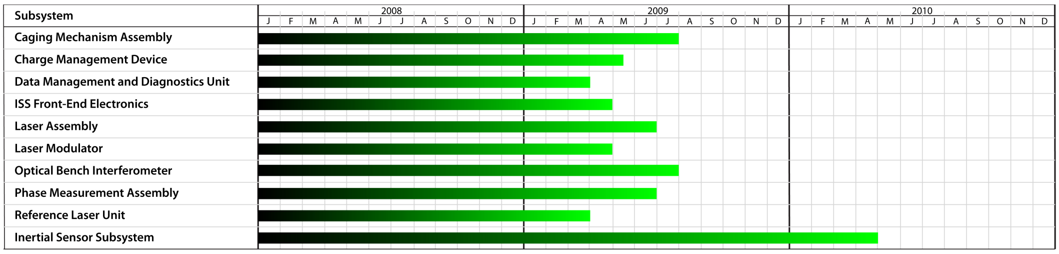


Figure 17: Photograph of the LISA Pathfinder launch composite being prepared for the environmental acoustic test campaign.

Table 8: Scheduled delivery dates of the LISA Technology Package flight units [37].



and hence can only be fully tested at system level (the TAPT tests), namely: propellant reservoir tank rupture, capillary flow of Cs to slit emitter, and finally emission of ions under accelerating field. The TAPT tests have been used to demonstrate the nominal (capillary flow) and back-up (forced flow by heating the Cs) operational priming scenarios, with both sets of tests showing that the priming and firing functionality is repeatable. In addition, one of the TAPT tests was allowed to continue after the successful firing of the engine to demonstrate the endurance of the thruster over continuous use. This test was stopped after 3200 hours of operation and 862 Ns of accumulated total impulse.

The FEEP flight hardware deliveries are split across several units. The first Power Control Unit (PCU) is scheduled for delivery in August 2009, the neutraliser in October 2009, with all four thruster clusters scheduled for delivery in April 2010.

7.2 LISA Technology Package

The LISA Technology Package flight hardware is also being manufactured, with most flight articles due to be delivered and tested over the coming year. Table 8 shows the current delivery dates for the various subsystems.

The main focus of the AIT activities has been on environmental testing of the LTP structure and the system testing of the hardware using the Real-Time Testbed (RTB) and Software Verification Facility (SVF). The former, LTP structure testing, was essential due to the nature of the LTP and in particular the load bearing Zerodur parts. A structural dummy was constructed from FM-like zerodur parts, FM mounting struts, an FM equivalent mounting cylinder, and mass dummies for the inertial sensors (see Figure 18). This model was used for both subsystem vibration tests, and for the acoustic and separation shock tests listed in Section 7.1. The results of these tests showed that the system will survive the launch loads with adequate margin.

The main concern in the LTP development has been the caging mechanism, which is required to hold the test during launch, and then release it once on orbit such that the mass can be captured using the weak electrostatic suspension. This development has proven to be fraught with difficulty, mostly due to the softness of the gold-platinum material, and the extremely tight requirements on the positioning and release system. As of writing, the Engineering Qualification Units (EQM) of

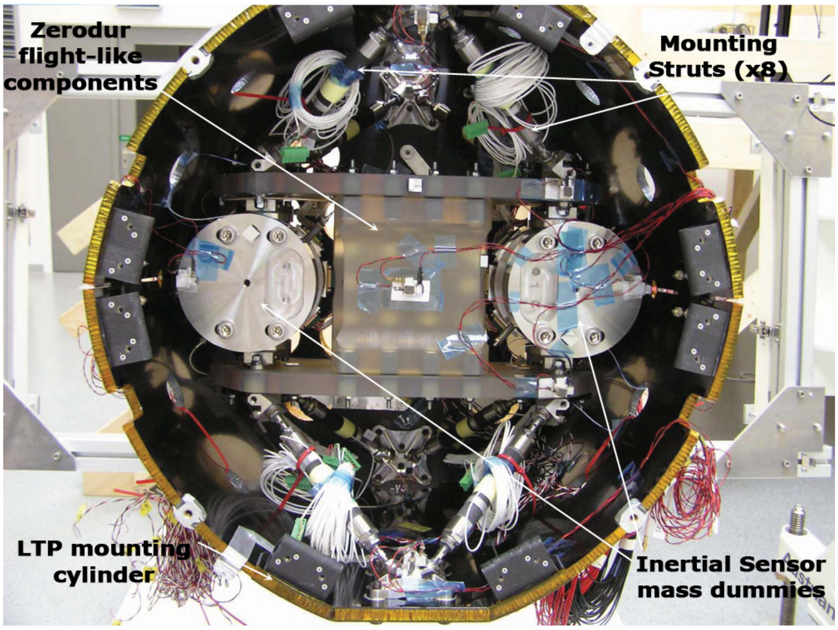


Figure 18: Photograph of the LISA Technology Package Core Assembly (LCA) in preparation for vibration testing.

the positioning and release mechanisms have been tested by the manufacturer, and have been delivered to the Inertial Sensor Subsystem integrator for system testing, and the first of the launch lock devices has been assembled at the manufacturer and is currently under test.

8 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 instigate the LISA Pathfinder mission - the science return of LISA easily justifies the technology development mission.

As expected, the development of the technologies for LISA has not proven to be an easy task, however *all technology development has now ceased, and all hardware development is at the EQM level or beyond.* The activities remaining in LPF are now focused on the testing of the hardware at the system level. The results of these tests goes a long way to providing the necessary knowledge for a successful LISA development.

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 built-up, 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 2011, with first results available to the science community approximately three months thereafter.

9 Bibiliography

References

[1] Bender, P., *et al.*, *LISA Pre-Phase A Report*, **MPQ 208**, Munich, unpublished (1998)

[2] Danzmann, K., *et al.*, *European LISA Technology: Demonstration Satellite for the LISA Mission in ESA's Space Science Programme*, unpublished proposal (1998)

[3] Vitale, S., *LISA Technology Package Architect Final Report*, ESTEC contract No. 15580/01/NL/HB (2002)

[4] O'Donnell, J., *et al.*, *The Space Technology 7 Disturbance Reduction System*, Proceedings of the 18th International Symposium on Space Flight Dynamics, (ESA SP-548), p 105 (2004)

[5] Kaltenegger, L., Fridlund, M., *The Darwin mission: Search for extra-solar planets*, Advances in Space Research, **36**, 6, 1114-1122 (2005)

[6] Vitale, S., *et al.*, *Science Requirements and Top-Level Architecture Definition for the LISA Technology Package (LTP) on board LISA Pathfinder (SMART-2)*, ESA Ref: LTPA-UTN-ScRD-Iss3-Rev1 (2005)

[7] McNamara, P., *et al.*, *LISA Pathfinder*, Classical and Quantum Gravity, **25**, 11, p114034 (2008)

[8] Anza, S., *et al.*, *The LTP experiment on the LISA Pathfinder mission*, Classical and Quantum Gravity, **22**, 10, p s125 (2005)

[9] Vitale, S., *et al.*, *LISA Pathfinder: Einstein's Geodesic Explorer*, ESA-SCI(2007)1

[10] Touboul, P, *et al.*, *MICROSCOPE, testing the equivalence principle in space*, Compte Rendus de L'Academie des Sciences Series IV Physics, 2, 1271-1286 (2001)

[11] Mester, J, *et al.*, *The STEP mission: principles and baseline design*, Classical and Quantum Gravity, 18, 2475 (2001)

[12] Nobili, A, *et al*, em Galileo Galilei flight experiment on the equivalence principle with field emission electric propulsion, Classical and Quantum Gravity, 13, A197, (1996)

[13] Resenberg, R.D., *et al.*, *Viking relativity experiment: verification of signal retardation by solar gravity*, Astrophysical Journal, 234, L219 (1979)

[14] B. Bertotti *et al.*, *A test of general relativity using radio links with the Cassini spacecraft*, Nature, 425, 374-376 (2003)

[15] Turyschev, S.G., *et al.*, *The laser astrometric test of relativity mission*, Nuclear Physics B, 134, 171 (2004)

[16] Ni, W-T, *ASTROD - an overview*, International Journal of Modern Physics, D11, 947 (2002)

[17] Buchman, S, *et al*, *The Gravity Probe B Relativity mission*, Advances in Space Research, 25(6), 1177 (2000)

[18] Shaddock, D, *Space based gravitational wave detection with LISA*, Classical and Quantum Gravity, 25(11) 114012 (2008)

[19] Abramovici, A, *et al*, *LIGO: The Laser Interferometer Gravitational-Wave Observatory*, Science, 256, 325 (1992)

[20] Acernesse, F, *et al*, *Status of VIRGO*, Classical and Quantum Gravity, 21, S385-S394 (2004)

[21] Danzmann, K, *et al.*, *The GEO Project: A long baseline laser interferometer for the detection of gravitational waves*, Lecture Notes in Physics, 410, 184-209 (1992)

[22] Takahashi, R, *et al*, *Status of TAMA300*, Classical and Quantum Gravity, 21, S403-S408 (2004)

[23] Drinkwater, M, *et al.*, *GOCE: ESA's first Earth explorer core mission*, Space Sciences Series of ISSI, 18, 419 (2003)

[24] Hudson, D., *et al.*, proceedings of the 9th ICATPP Conference, Villa Olmo 2005, (World Scientific 2006)

[25] Landgraf, M., *Consolidated Report on Mission Analysis: Issue 4*, ESA document reference: S2-ESC-RP-5001 (2008)

[26] Brandt, N., *LISA Technology Package Experiment Performance Budget: Issue 2.2*, ESA document reference: S2-ASD-RP-3036 (2008)

[27] Kane, T.J., and Byer, R.L., *Monolithic, unidirectional single-mode Nd:YAG ring laser*, Optics Letters, **10**, 2, 65-67 (1985)

[28] Lange, R, *et al.*, *BPSK Laser communication terminals to be verified in space*, MILCOM 2004 - IEEE Military Communications Conference (2004)

[29] Fichter, W., *et al.*, *Drag-Free Control Design with Cubic Test Masses*, In "Lasers, Clocks, and Drag-Free Control", Astrophysics and Space Science Library, Vol. 349, Dittus, H.J.; Lammerzahl, C.;Turyshev, S. (Eds.), December 2007, Springer, ISBN: 978-3-540-34376-9

[30] Fichter, W., *et al.*, *Closed Loop Performance and Limitations of the LISA Pathfinder Drag-Free Control System*, AIAA 2007-6732, AIAA Guidance Navigation and Control Conference, 20-23 August 2007, Hilton Head, South Carolina.

[31] Fichter, W., *et al.*, *LISA Pathfinder Drag-Free Control and System Implications*, Classical and Quantum Gravity, **22**, 10, s139-s148, (2005)

[32] Nicolini, D., *LISA Pathfinder Field Emission Thruster System Development Program*, 30^{th} International Electric Propulsion Conference, IEPC-2007-363, Florence, (2007)

[33] Ceruti, L., and Nicolini, D., *Power Processing Control Units for FEEP Micro-Propulsion Subsystems*, International Astronautic Congress, Glasgow, (2008)

[34] Canuto, E., and Rolino, A., *Nanobalance: An automated interferometric balance for micro-thrust measurement*, ISA Transactions 43, 169-187 (2004)

[35] Vitale, S., *et al.*, *LISA Pathfinder Experiments Master Plan*, ESA document reference: S2-EST-PL-5007 (2006)

[36] *LISA Pathfinder Current Schedule, v056*, ESA document reference: S2-ASU-CH-1001 (04/02/2009)

[37] *LISA Technology Package Summary Schedule, Iss8,.3*, ESA document reference: S2-ASD-CH-3003 (21/01/2009)

10 Acronym List

AEI	Albert Einstein Institute
AIT	Assembly, Integration and Test
AIV	Assembly, Integration and Verification
AOCS	Attitude and Orbital Control System
AOM	Acousto-Optic Modulator
APC	AstroParticule et Cosmologie
ASTROD	Astro-dynamical Test of Relativity using Optical Devices
Au	Gold
bps	bits per second
CBE	Current Best Estimate
CDR	Critical Design Review
CH	Switzerland (Confoederatio Helvetica)
CMNT	Colloidal Micro-Newton Thruster
CMSS	Caging Mechanism Support Structure
CPU	Central Processing Unit
Cs	Caesium
DA	Data Analysis
DFACS	Drag-Free and Attitude Control System
DI	Data Ingestion
DMU	Data Management Unit
DoF	Degree of Freedom
DOR	Direct Operations Request
DRS	Disturbance Reduction System
DSS	Digital Sun Sensor
DWS	Differential Wavefront Sensing
EEPROM	Electronically Erasable Programmable Read-Only Memory
ELITE	European LISA Technology Experiment
EM	Engineering Model
EMP	Experiment Master Plan
EOM	Electro-Optic Modulator
EQM	Engineering Qualification Model
ESA	European Space Agency
ESAC	European Space Astronomy Centre
ESOC	European Space Operations Centre
ETH	Eidgenössische Technische Hochshule
FCA	FEEP Cluster Assembly
FEE	Front-End Electronics
FEEP	Field Emission Electric Propulsion
FM	Flight Model

GaAs	gallium Arsenide
GP-B	Gravity Probe B
GG	Galilleo Galillei
GPRM	Grabbing, Position and Release Mechanism
GR	General Relativity
IEEC	Institut d'Estudis Espacials de Catalunya
IFO	Interferometer
IOOP	In-Orbit Operational Phase
ISS	Inertial Sensor Subsystem
L1	First Sun-Earth Lagrange point
LATOR	Laser Astrometric Test of Relativity
LEOP	Launch and Early Operations Phase
LIGO	Laser Interferometer Gravitational Wave Observatory
LISA	Laser Interferometer Space Antenna
LM	Laser Modulator
LPF	LISA Pathfinder
LTP	LISA Technology Package
LTPP	Long-Term Payload Planning
MLI	Multi-Layer Insulation
MOC	Mission Operations Center
MPA	Micro-Propulsion Assembly
MPS	Micro-Propulsion System
MTL	Mission Timeline
MTTP	Medium-Term Payload Planning
NA	Neutraliser Assembly
NB	Nano-Balance
NASA	National Aeronautics and Space Administration
Nd	Neodymium
nm	nano-metre
OBC	On-Board Computer
OBI	Optical Bench Interferometer
OMS	Optical Metrology Unit
OPD	Optical Pathlength Difference
OBSW	On-Board Software
PCU	Power Control Unit
PDR	Preliminary Design Review
PI	Principle Investigator
PLL	Phase-Locked Loop
POR	Payload Operations Request

pm	pico-metre
PROM	Programmable Read-Only Memory
Pt	Platinum
QL	Quick Look
RAM	Random Access Memory
RLU	Reference Laser Unit
rms	Root Mean Square
RTB	Real-Time Testbed
SA	Science Archive
SBDFT	Single Bin Discrete Fourier Transform
s/c	Spacecraft
SMART	Small Missions for Advanced Research in Technology
SPC	Science Programme Committee
SRON	Space Research Organisation of the Netherlands
STEP	Satellite Test of the Equivalence Principle
STOC	Science and Technology Operations Centre
STM	Structural Thermal Model
STTP	Short-Term Payload Planning
SVF	Software Verification Facility
TAPT	Thruster Assembly Priming Test
TC	Telecommand
TM	Telemetry
TM	Test Mass
UV	Ultra Violet
YAG	Yttrium Aluminium Garnet