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The LISA Pathfinder Mission

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Abstract. LISA Pathfinder (formerly known as SMART-2) is an European Space Agency mission designed to pave the way for the joint ESA/NASA Laser Interferometer Space Antenna (LISA) mission by testing in flight the critical technologies required for space-borne 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.

LISA Pathfinder (LPF) essentially mimics one arm of spaceborne gravitational wave detectors by shrinking the million kilometre scale armlengths down to a few tens of centimetres, giving up the sensitivity to gravitational waves, but keeping the measurement technology.

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

In this paper I will give a brief overview of the mission, focusing on scientific and technical goals.

1. Introduction

LISA Pathfinder, the second of the European Space Agency's Small Missions for Advanced Research in Technology (SMART), is a mission designed to pave the way for future spaceborne gravitational wave detectors[1], by testing, in a space environment, the basic assumption of General Relativity: that free particles follow geodesics. In doing so, LISA Pathfinder will demonstrate the proof of principle of low frequency gravitational wave detection, as well as demonstrating the core technologies required for spaceborne interferometric gravitational wave detectors.

LISA Pathfinder was first proposed in 1998 as ELITE (European LIsa Technology Experiment) (Danzmann (1998)). The original proposal was refined and proposed to ESA in 2000 in response to the SMART-2 announcement of opportunity. At the time,

[1]When originally proposed, LISA Pathfinder was a dedicated technology demonstrator for the joint ESA/NASA Laser Interferometer Space Antenna (LISA) mission (Bender et al. (1998)), however, since this time the LISA mission has been removed from the ESA Science Programme. Many of the currently proposed spaceborne interferometric gravitational wave detectors are based on the original LISA mission concept, and therefore still rely on the LPF flight demonstration.

the proposal called for a joint LISA and Darwin[2] 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) (Vitale (2002)), and the NASA provided Disturbance Reduction System (DRS) (O'Donnell (2004)). 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 on-board a dedicated small launch vehicle 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 point (L1). After separation from the propulsion module, the LPF spacecraft will be stabilised using 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 science operations phase of the mission will then take place. The nominal lifetime of the science operations is 180 days; this includes the LTP and DRS operations.

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.

The difficulty of achieving high purity geodesic motion is that any parasitic forces compete with spacetime geometry to set masses in 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 picometre 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.

To reach its goals, LISA Pathfinder will have to achieve many firsts simultaneously. 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

[2]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 (Kaltenegger & Fridlund (2005)).

and with no mechanical contact to them. With its test mass to test mass and test mass to spacecraft interferometric readout, it will realise 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 realise 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 quantitative mission goal of LISA Pathfinder is to demonstrate immunity from relative accelerations of non-gravitational origin to

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

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

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

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

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

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 (Albertella et al. (2002)).

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 (Brandt (2010)) will be verified down to painstaking detail.

3. 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 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 (DFACS).

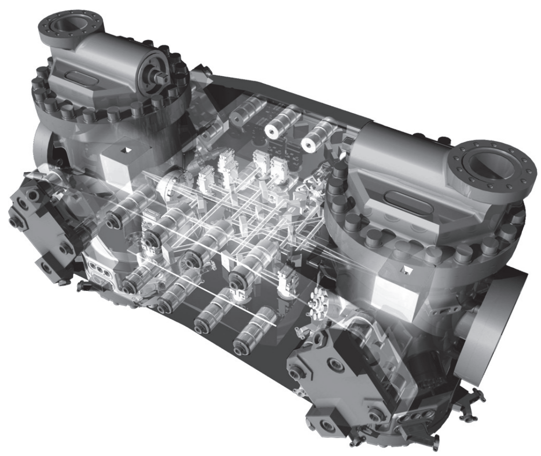

Figure 1. Artists impression of the LISA Technology Package Core Assembly (LCA).

However, due to the resolution required, coupled with the proximity of hardware to the test masses, the performance and environmental requirements levied on the LTP subsystems is extremely demanding.

Figure 1 shows an artists impression of the LTP Core Assembly. 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.

3.1. 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.

The LTP 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 $\approx 20\,\mathrm{kgm}^{-3}$. The combination of both greatly reduces the effect of external forces on the test mass.

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 freedom. The capacitive sensor comprises a hollow cubic molybdenum housing with gold coated sapphire electrodes mounted in the faces. 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. 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. 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; this is achieved by venting the vacuum chamber to space after LPF reaches its nominal science orbit. 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.

With 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 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.

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 $\approx 50\,g_{\rm rms}$, requiring a holding force of ≈ 1200 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 5×10^{-6}ms^{-1}. These requirements are met by the *Caging Mechanism Assembly*. This device consists of three actuators: a first stage single shot mechanism, based on a high-output paraffin, actuator to provide the 1200 N preload (the launch lock); a second stage piezo actuator, which is used to break the adhesion of the launch lock and position the test mass at the desired location; and finally, the release actuator, a small diameter, piezo actuated, 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 $10^{-5}\,\mathrm{K}/\sqrt{\mathrm{Hz}}$ 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, mounting brackets, bolts, etc).

3.2. 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, phasemeter, and data management unit.

The *Reference Laser Unit* (RLU) employed on LPF is a 35 mW Nd:YAG non-planar ring oscillator (Kane & Byer (1985)) 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 RLU output is fibre coupled using single-mode, polarisation-maintaining fibre 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 heterodyne frequency. The beams are then passed through the optical pathlength difference (OPD) actuators 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 with fused silica mirrors and beamsplitters bonded to the surface, forming 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); 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. Figure 2 shows the layout of the optical bench with each of the interferometers labelled.

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 100 Hz and performs a Single Bin Discrete Fourier Transform to measure the phase of the signals at the heterodyne frequency. 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). 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 phasemeter samples the data at 100 Hz. However, the 100 Hz samples are not required for routine operation, and so the data is downsam-

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

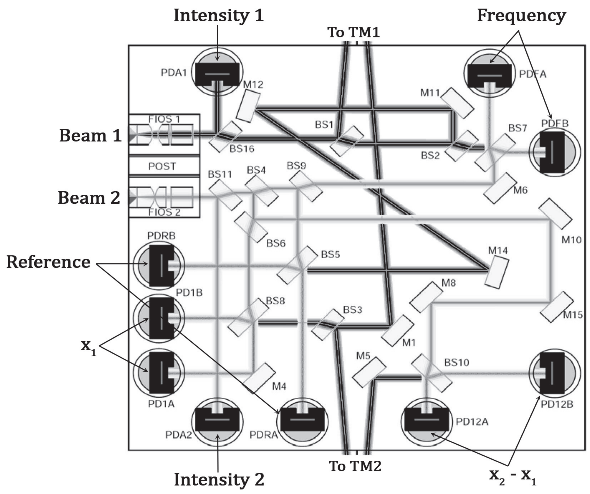

Figure 2. Optical Bench Interferometer layout. The labels *To TM1* and *To TM2* indicate the positions of the test masses (not shown).

pled 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.

4. Spacecraft

The spacecraft carries all the necessary subsystems required to support the performance of the scientific experiments. In addition this module also supports, 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).

4.1. Spacecraft Platform

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 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 disposable 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 the central cylinder to the outer panel form-

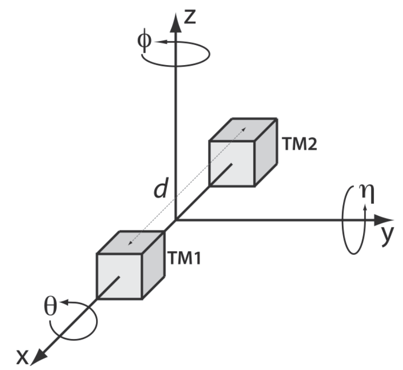

Figure 3. LTP Test Masses layout schematic with axis rotation angles notation

ing 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.

4.2. 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 in such a way that the main requirement on the residual acceleration, expressed by Equation 1 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 reference to Figure 3, 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 3), 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 of the spacecraft attitude is performed by the set of micropropulsion thrusters, described in Section 4.3, 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.

The DFACS task 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.

- to measure, by laser interferometer, the differential displacement between the drag-free test mass and the second test mass.
- 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 (DOF) and frequency band separation. In practice, the drag-free DOF conditions are not belonging to one TM, but on 6 DOF's of the two TM's: $x_1, y_1, z_1, \theta_1, y_2, z_2$. The remaining test mass coordinates are controlled electrostatically.

4.3. Micropropulsion

The LISA Pathfinder Micro-Propulsion Subsystem (MPS) is based on a Nitrogen Cold Gas thruster system, originally developed for the European Space Agency's GAIA mission (Lindegren et al. (2008)).

The main performance requirements of the LPF propulsion system are shown in Table 1.

Table 1. LPF micro-propulsion main requirements

Propulsion parameter	**Requirement**
Thrust range	0.1 μN to 150 μN
Thrust resolution	$\leq 0.1\ \mu$N
Thrust accuracy	$\leq 2\%$ at max thrust
Thrust linearity	$\leq 0.5\%$
Thrust response time	≤ 500 ms
Noise (from 10^{-3} Hz to 1 Hz)	$\leq 0.1\ \mu\mathrm{N}/\sqrt{\mathrm{Hz}}$

The LISA Pathfinder MPS is composed of three main parts: the thruster head assembly, the propellant tanks and feed system, and the power control unit. The thruster head assembly consists of three clusters of four thrusters per cluster, with each cluster mounted on the outside walls of the spacecraft, 120° apart. The thruster clusters are fed via a series of pipes and valves from the four Nitrogen tanks mounted on the inside walls of the spacecraft structure. Each tank holds a total of 8.3 litres of propellant, which is sufficient to meet the LPF lifetime with adequate margin, even in the event of the failure of one thruster. The main concern is the change in the gravitational balancing of the spacecraft as the fuel is depleted. For this reason, the spacecraft will be designed to be *unbalanced* at the start of operations, reaching the optimal gravitational balance towards the end of the LTP operations. The whole system is controlled from the power control units (PCU); one PCU can control up to six thrusters.

5. 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.

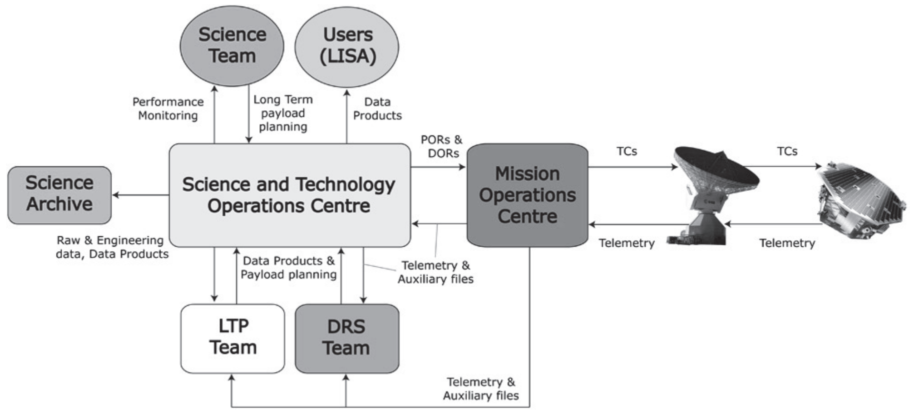

Figure 4. Overview of the LISA Pathfinder Ground Segment diagram showing the data flow.

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

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

- The *Mission Operations Centre* (MOC) is responsible for the launch and early operations, the transfer phase, and the execution of the in-orbit operations. The MOC 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.

Figure 4 shows the overall data flow between the various elements of the ground segment.

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