LISA Pathfinder: mission and status

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LISA Pathfinder: mission and status

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Abstract

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. 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 is due to be launched in 2013 on-board a dedicated small launch vehicle (VEGA). 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 stabilized using the micro-Newton thrusters, entering a 500 000 km by 800 000 km Lissajous orbit around L1. Science results will be available approximately 2 months after launch.

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(Some figures in this article are in colour only in the electronic version)

1. Mission goals

The mission goals of LISA Pathfinder can be split into three categories, covering the performance of the inertial sensor, the performance of the laser interferometer and the demonstration of the flight readiness of the technologies critical for a successful LISA mission. The mission goals can be summarized as follows (for a full description of the mission goals, the reader is directed to [1]).

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

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

  over the frequency bandwidth, f, of 1–30 mHz. *This is the top-level science requirement of the mission*.
- Demonstrate laser interferometry with free-falling mirrors (test masses of the LISA Technology Package (LTP)) with a displacement sensitivity within approximately a factor of 5 of the LISA requirements. Therefore the flight test is considered successful if the laser metrology resolution is demonstrated to within

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

  over a frequency bandwidth of 1–30 mHz with a dynamic range on the order of a millimetre.
- Assess the lifetime and reliability of the micro-Newton thrusters, lasers and optics in a space environment.

However, it must be noted 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 fulfil this program, the mission is not going to just make a measurement of acceleration but will implement a full menu of measurements: at the end of this set of measurements, the residual acceleration noise model [2] will be verified down to painstaking detail.

2. The LISA Technology Package

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

Figure 1 shows an artists impression of the LTP. The LTP consists of two major subsystems: the inertial sensor subsystem, and the optical metrology subsystem. Both subsystems are described in further detail in the following sections.

2.1. Inertial sensor subsystem

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

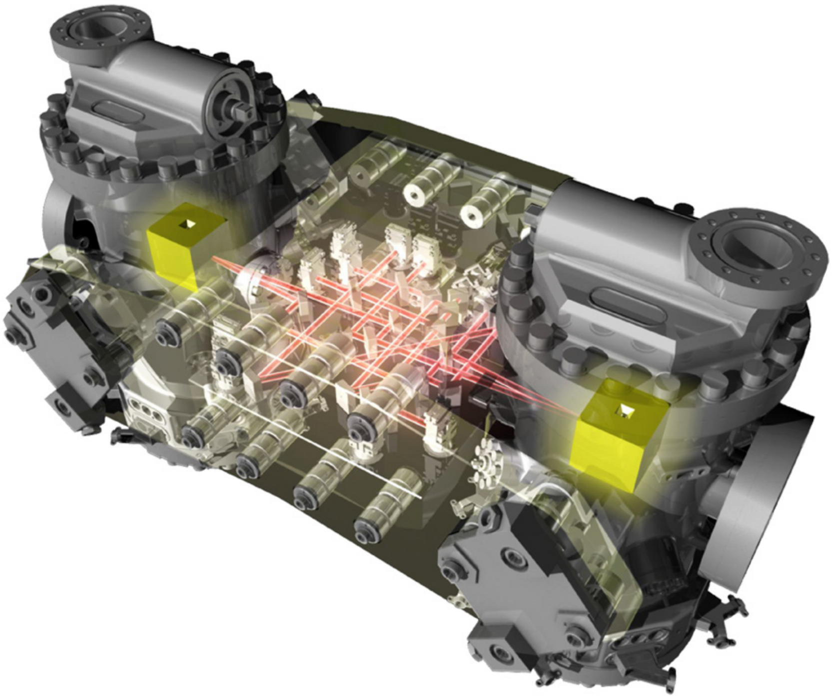

Figure 1. Artists impression of the LISA Technology Package.

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

The test masses consist of a 1.96 kg cube of gold:platinum mono-phasic alloy of dimension 46 mm on a side. The alloy is formed from 73% gold and 27% platinum, chosen as this alloy has an extremely low magnetic susceptibility ($\chi_m \approx 10^{-5}$) and high density $\approx 2 \times 10^4$ kg m^{-3}. The combination of both greatly reduces the effect of external forces on the test mass.

The test masses' position is readout by two means: high resolution laser interferometry, and electrostatic (capacitive) sensing. The former only senses the test mass position along the sensitive axis (the line joining the two test masses) and the angles of rotation around the axes perpendicular to the sensitive axis, whereas the capacitive sensor measures the position of the test mass in all six degrees of freedom. The capacitive sensor comprises a hollow cubic molybdenum housing with gold coated sapphire electrodes mounted in the faces (see figure 2). The housing is sized to allow for a $\approx$4 mm gap between the electrode faces and the test mass. The size of the gap is a trade off between reducing the effects of noise sources, e.g. from uncontrolled potentials on the electrodes, and being able to meet the capacitive sensing requirement of 1.8 nm Hz$^{-1/2}$ over the measurement bandwidth.

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

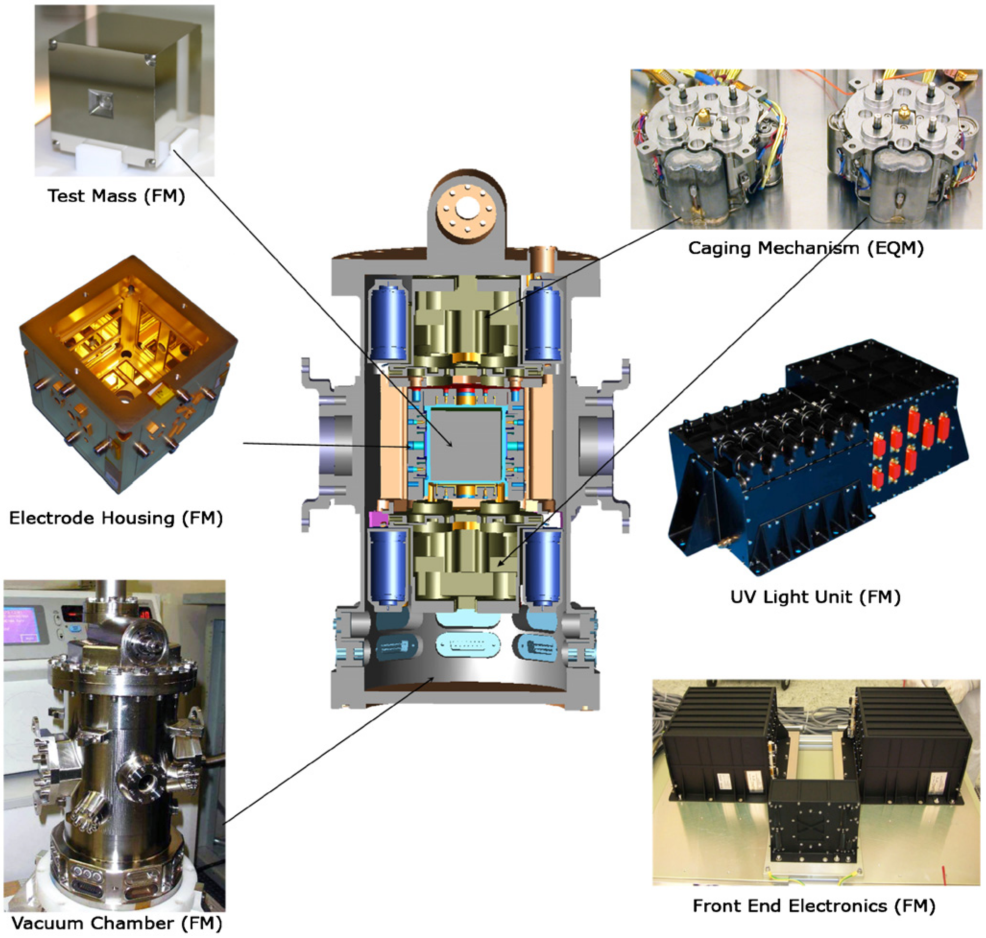

Figure 2. Photographs of the inertial sensor subsystem flight models (FM) and engineering qualification models (EQM). From bottom left: vacuum chamber (Carlo Gavazzi Space), electrode housing (Thales Alenia Space), (uncoated) test mass (Thales Alenia Space), caging mechanism (Thales Alenia Space), UV Lamp Unit (Imperial College London), front-end electronics (ETH, Zurich).

The test mass and electrode housing are mounted inside a dedicated vacuum enclosure. In order to meet the mission 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 (with the exception of a few components mounted on the outer wall of the spacecraft as far as possible from the test masses) only non-magnetic materials are permitted to be used in the system, forcing the vacuum chamber to be manufactured from titanium as opposed to the standard stainless steel construction techniques. Also, in order to limit the pressure increase due to outgassing or virtual leaks within the vacuum enclosure (see figure 2), 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, creates a force, resulting in additional noise in the test mass position. The charge is controlled using a non-contact discharge system based on the photo-electric effect. UV light from mercury vapour lamps is channelled to the electrode housing via fibre optic cables. Depending on the sign of the charge on the test mass, the light is either shone onto the test mass or the electrode housing, thereby extracting electrons from either surface, providing bi-polar charge management.

A further challenge which is unique to space flight hardware is the need for a launch-lock device to prevent hardware being damaged during the extreme vibration conditions experienced during launch. In LISA Pathfinder, this is especially true for the test masses—the most sensitive part of the experiment must survive a random load of $\approx 50\,g_{rms}$, 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 μm, 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 hydraulic actuator to provide the 1200 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 2.

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} K Hz$^{-1/2}$ over the measurement bandwidth; associated with the thermal stability requirement is the need to have thermometers with a resolution better than 10^{-5} K Hz$^{-1/2}$ 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).

2.2. *Status of the inertial sensor subsystem*

As shown in figure 2, most of the flight hardware of ISS has been delivered to the LTP Architect for integration into the LTP core assembly. The following paragraphs give the current status of each of the subsystems (as of August 2010).

- *Testmass*: the Au:Pt alloy of the flight test masses (and spares) has been forged, and both flight test masses have been cut, machined and polished.
- *Electrode housing*: the piece parts of the electrode housing have been delivered to the integrator, and the flight model is being integrated.
- *Caging mechanism*: the caging mechanism engineering qualification model (EQM) has undergone full environmental testing, and has now been delivered to the ISS integrator for further system testing. Integration of the flight caging mechanisms will proceed when the parts become available.
- *Vacuum enclosure*: both vacuum enclosure flight units have been delivered.
- *Inertial sensorfront-end electronics*: the ISS FEE flight units have been delivered to the LTP Architect.

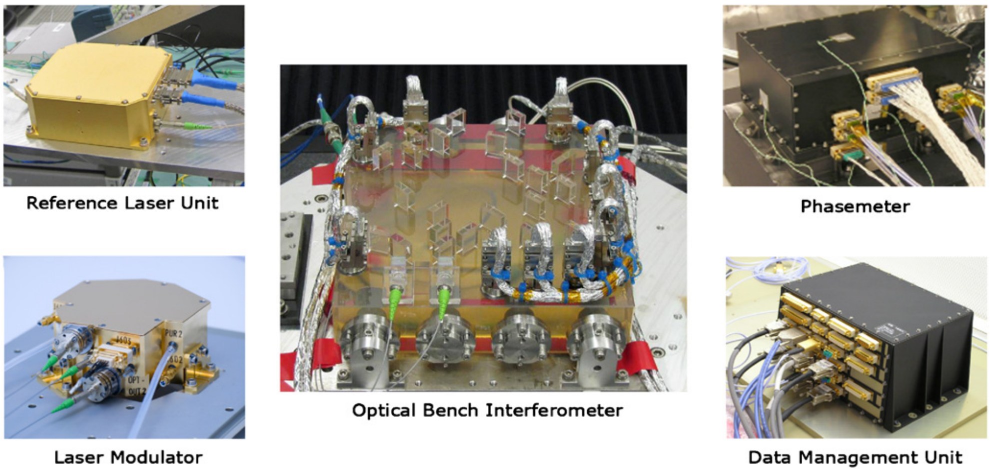

Figure 3. Photographs of the optical metrology system flight hardware. From top left: reference laser unit (Tesat), phasemeter (Uni. Birmingham), data management unit (ICE, Barcelona), laser modulator (APC/Contraves). Centre: optical bench interferometer (Uni. Glasgow).

– *Charge management system*: this subsystem consists of three main parts: the UV lamp unit, the fibre optic cable and the fibre optic vacuum feedthrough. The UV lamp flight unit is in final testing. Both the fibre optic cable and feedthrough flight units have been delivered.

2.3. Optical metrology subsystem

The optical metrology subsystem (OMS) is the high resolution laser interferometric readout of the test masses' positions. The OMS comprises several subsystems, namely the reference laser unit (RLU), the laser modulator (LM), optical bench interferometer (OBI) and the phasemeter.

The RLU comprises a 40 mW Nd:YAG non-planar ring oscillator [3] of the same design commonly used in metrology labs around the world (figure 3). 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 [4]. The RLU is baselined as the master oscillator in the LISA laser system.

The RLU output is fibre coupled using single-mode, polarization-maintaining (sm/pm) fibre. The fibre couples the light to the subsequent component in the optical chain, the LM (figure 3). The LM consists of a beam splitter, two acousto-optic modulators, and optical pathlength actuators. The light from the laser is split into two paths, each path is passed through an acousto-optic modulator. One modulator is driven at 80 MHz, while the other is driven at 80 MHz + 1.2 kHz, thereby creating two beams with a frequency difference of 1.2 kHz. The beams are then passed through the optical pathlength difference (OPD) actuator which consists of a fibre optic cable wrapped around a cylindrical piezo-electric transducer. The OPD is used to stabilize the optical pathlength of the fibre optic cables leading to the optical bench. After the OPD, the beams are transmitted, again via sm/pm fibre, to the *Optical Bench Interferometer* (OBI).

The main function of the OBI is to direct the beams to the relevant positions in three-dimensional space, without adding any significant noise to the measurement path (figure 3). The primary optical bench requirement is that the pathlength noise induced by the components on the optical bench should not exceed 1 pm $Hz^{-1/2}$ over the measurement bandwidth. The optical bench is constructed from a block of Zerodur ceramic glass with fused silica mirrors and beamsplitters bonded to the bench using hydroxy catalysis bonding [5] . The mirrors and beamsplitters are used to direct the two beams to form four interferometers: the $x_2 - x_1$ interferometer which measures the differential motion of the two test masses—this is the primary science measurement of the mission; the x_1 interferometer which measures the position and angles of test mass 1 with respect to the optical bench (and therefore, the spacecraft)—equivalent to the LISA local test mass interferometer; the *frequency* interferometer which is an unequal arm Mach–Zehnder interferometer, the output of which is sensitive to laser frequency fluctuations, and therefore can be used to stabilize the laser frequency and the *reference* interferometer which is a rigid equal arm interferometer which provides the system noise floor, and is used to stabilize the optical pathlengths via the OPD. The light from each fibre is also sent directly to a photodiode which is used to monitor the laser intensity noise. The signal from these photodiodes is used to stabilize the intensity of both beams by feeding back to the acousto-optic modulator drive signal.

The signals from the (quadrant) photodiodes of each interferometer (each interferometer has two quadrant photodiodes for redundancy) are sent to the *phasemeter assembly*. The phasemeter samples the data at 50 kHz and performs a single bin discrete fourier transform [6] to measure the phase of the signal at the heterodyne frequency. This technique is used due to the efficiency of the algorithm. The phasemeter not only outputs the longitudinal phase from the respective interferometers, but also outputs the angles between the wavefronts interfering on the photodetectors—commonly known as *differential wavefront sensing* (DWS)—at 100 Hz. The DWS signals from the x_1 and $x_2 - x_1$ interferometers are used to align the test mass to the interferometer. The longitudinal signals from the interferometers are used to stabilize the laser frequency, the optical pathlength and (with the DWS signals) as inputs for the drag-free and attitude control system (DFACS) [7].

As mentioned above, the phasemeter outputs the data at 100 Hz. However, the 100 Hz samples are not required for routine operation, and so the data are 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.

2.4. Status of optical metrology system

As can be seen in figure 3, all the OMS flight hardware, baring the photodiodes, are available. Performance testing of the complete OMS flight system has been completed, demonstrating a noise floor ≈6 dB lower than requirements[26]. The following paragraphs give the current status of each of the subsystems (as of August 2010).

- *RLU*: the RLU has been delivered and has been successfully tested as part of the laser assembly test campaign.
- *LM*: the LM has been delivered and has been successfully tested as part of the laser assembly test campaign.

[26] The reader is referred to the paper in this special issue of *Class. Quantum Grav.* [8].

– *Photodiodes*: during acceptance testing of the OBI with the flight photodiodes, several of the quadrant diodes were non-compliant to the requirements. This has been traced to an electrical over-stress during testing. New photodiodes are being procured.
– *OBI*: the optical bench flight model (and flight spare) have been fully integrated with all optical components. Delivery of the OBI FM has been postponed to the beginning of 2011 pending delivery and integration of the new photodiodes.
– *Phasemeter*: the phasemeter has been delivered and has been successfully tested as part of the OMS system testing.
– *DMU and associated software*: the DMU has been delivered and has been successfully tested on the real-time testbed, and as part of the OMS system tests.

2.5. Micropropulsion

The LISA Pathfinder micro-propulsion subsystem (MPS) is based on field emission electric propulsion (FEEP) technology. An extensive account can be found in [9] and [10]. In field emission electrical propulsion, positive ions are directly extracted from liquid metals (for LISA Pathfinder, caesium has been chosen as the liquid metal source) and accelerated by means of electrostatic force in high vacuum. This function is carried out by applying a 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^{-1}). An additional external source of electrons, the neutralizer, needs to be included to maintain the balance of the overall electrical charge of the system (ions$^+$ = e$^-$).

The LISA Pathfinder MPS is composed of three main parts: a FEEP cluster assembly; a power control unit (PCU); and a neutralizer assembly (NA). The FEEP cluster assembly consists of a self-contained unit of 4 FEEP thruster assemblies, which include propellant reservoir, mounted on a support structure. The four thrusters are devoted to provide thrust to the required vector directions and are commanded individually and work in hot redundancy.

The NA consists of a self-contained unit of two neutralizer units necessary to null the spacecraft charge imbalance due to ion thruster operations. The neutralization function is implemented by means of cold redundant hardware. The PCU consists of an electronic unit interfacing to the spacecraft for power supply and telecommand and telemetry tasks and provides power and control to both the FEEP cluster and NA.

2.6. Status of micro-propulsion system

As mentioned above, the MPS comprises three subsystems, the PCU, the NA and the thruster head. All three PCU flight units have been delivered, and have been integrated in the spacecraft, while the neutralizer flight units are scheduled for delivery in November 2010. The status of the thruster assembly will be discussed below.

The FEEP thruster assemblies have undergone many subsystem tests over the course of the LPF development. All thruster functions have been demonstrated at the component/subsystem level, including several thruster assembly priming tests (TAPT) which show repeatability in the end-to-end operation of single thrusters. In addition to the performance of the thruster, the structure has also successfully passed the mechanical tests.

Thruster performance requirements have been verified using a nano-balance facility developed specifically for LISA Pathfinder [11]. Results from the nano-balance are shown in figure 4. As can be seen the thrust noise measurement (red) is limited by the facility noise (grey); however, it demonstrates a worse-case thrust noise within a factor of 5 of the requirement at the frequencies of interest. DFACS simulations have been performed assuming this worst-case thruster noise curve and have shown that the full system is compliant with the

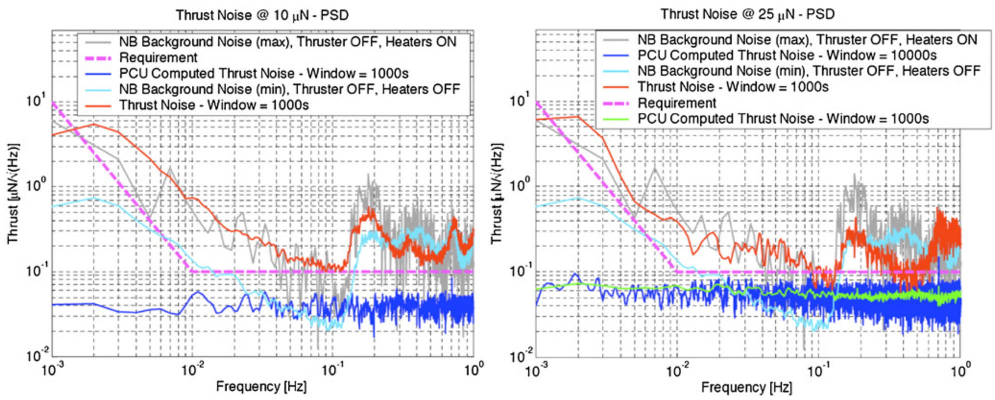

Figure 4. Thruster noise measured on the nano-balance facility for different thrust levels. The red line represents the measured thrust noise, while the grey line represents the facility noise during the test conditions. As can be seen the thrust noise measurement is limited by the facility background noise. The LPF requirement is shown in magenta. The blue data represents the calculated thrust noise as measured by the PCU from the current and voltage applied.

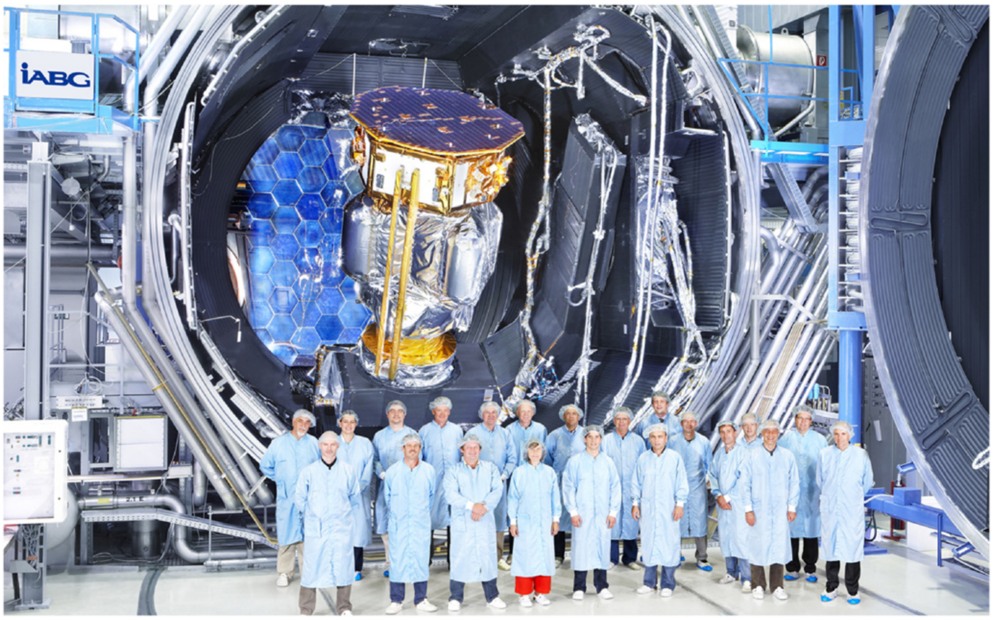

Figure 5. The LISA Pathfinder launch composite being in the vacuum chamber in preparation for the transfer orbit thermal balance test. The test was performed at the IABG, Germany.

science requirement listed in equation (1). It should be noted, however, that the computed thrust noise (blue), calculated from the current and voltage, is better than the performance requirements. The actual noise of the thruster lies somewhere between the red and blue traces, with all probability that it is closer to the lower (calculated noise) performance.

The main issue with the thruster continues to be lifetime. A new thruster is now being tested to confirm the LPF lifetime performance previously demonstrated. This test campaign has started and is due to continue into 2011, following which the FEEP thruster flight units will be manufactured.

3. Status of spacecraft

The spacecraft bus of LISA Pathfinder serves the purpose of protecting the test masses from all external forces, bar gravity. However, the proximity of the spacecraft hardware to the test masses places stringent requirements on the electric, magnetic, thermal and gravitational properties of these systems. As such, all electronic boxes and mechanical structures of the spacecraft undergo rigorous characterization and testing at unit level, prior to being integrated to the final spacecraft structure.

The spacecraft is now virtually complete, with all hardware, with the exception of the FEEP thruster clusters, integrated to the structure. Integrated system testing of the spacecraft and propulsion module is ongoing, with the magnetic stability and transfer orbit thermal balance tests (figure 5) already successfully completed. The next system level test is planned for early 2011 (sine test), followed by the first environmental test campaign.

4. 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 realized. Together, this prompted the European Space Agency to adopt the LISA Pathfinder mission—the science return of LISA easily justifies the technology development mission.

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

In conclusion, LISA Pathfinder is on track to demonstrate the first in-flight test of low-frequency gravitational wave detection metrology. Launch is scheduled for 2013, with first results available to the science community approximately 3 months thereafter.

Acknowledgments

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