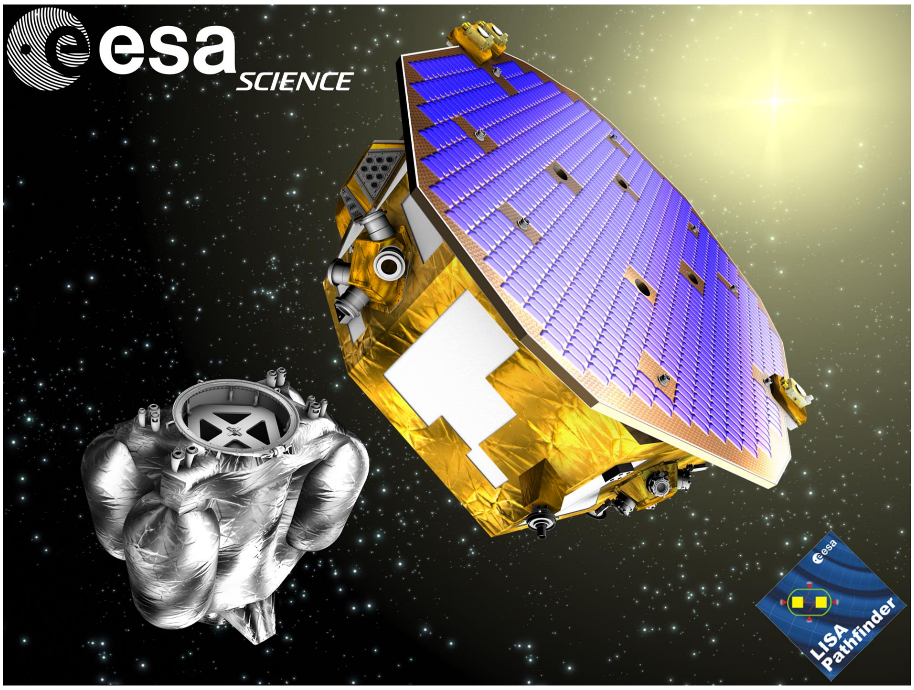
Overview of LISA Pathfinder



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Reference LISA-LPF-RP-0001
Issue 1
Revision 1
Date of Issue 29th April 2009

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 US 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 US 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 use the LTP inertial sensors.

LISA Pathfinder is due to be launched in 2011 on-board a dedicated small launch vehicle. The launcher selected is the new Arianespace 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°. Since the VEGA launcher is still under development a back-up launch possibility is maintained with the Russian vehicle, Rockot, which could launch LISA

[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.

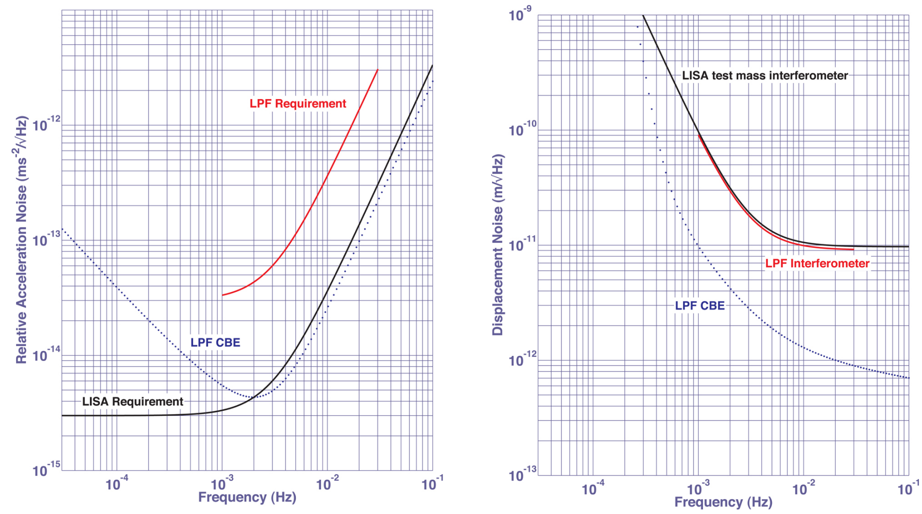

Figure 1: (*left*) Graph showing the Level One acceleration noise requirement of LISA Pathfinder and LISA. The line labelled *LISA Pathfinder Requirement* shows the value as listed in the Science Requirements Document [5]. The line labelled *LPF CBE* shows the Current Best Estimate of the expected performance of the mission. The gap between the LPF CBE line and the LISA Requirement represents the extrapolation required to transfer the LPF technology to LISA. (*right*) Graph showing the Level One Displacement Noise requirements. As can be seen, the LISA Pathfinder requirement on the performance of the readout interferometer is approximately equal to the performance of the LISA local (test mass readout) interferometer. The line labelled LPF CBE is the measured performance of the EM interferometer (optical bench, laser, phase meter).

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°. 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 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 LTP will control the DRS thrusters.

2 Relationship between LISA Pathfinder and LISA

From the outset, the LISA Pathfinder mission has been designed such that the technology can be directly transferred to LISA with little, or no, changes. However, as LPF is a pathfinder, and in order to keep costs down, the Level One mission performance requirement is relaxed with respect to the LISA hardware requirements. Specifically, the requirement on the relative acceleration noise of the test masses is relaxed by an order of magnitude in performance, and by a factor of thirty in frequency (see Figure 1). However, the secondary requirement of interferometer displacement noise, is not relaxed. This requirement is not affected to the same degree by the environmental noise of the spacecraft, and therefore, for no extra cost or complexity, the full LISA requirement can be demonstrated (see Figure 1).

The relaxation in the acceleration noise requirement significantly reduces the environmental requirements levied on the spacecraft. In particular, this relaxation is most evident on the thermal stability, gravitational balancing and magnetic cleanliness of the spacecraft. The environmental relaxation allows the LPF spacecraft to be in orbit around L1, as opposed to LISA's heliocentric Earth-trailing orbit. This has two advantages, namely in the time required to reach the desired orbit, and more importantly it greatly reduces the communication requirements onboard the spacecraft (distance to LPF is approximately 1.5 million km as opposed to 50 million km for LISA).

As stated above, LPF has been designed to test in flight those LISA technologies that cannot be tested on the ground. However, due the fact that LPF is a single spacecraft, several of the LISA technologies will not be flight tested, although it should be noted that these technologies can be fully ground tested, *e.g.* the telescope. Table 1 shows the link between LPF and LISA, and the current status of each of the LPF technologies. As can be seen, even in areas where LPF differs greatly from LISA (*i.e.* the laser source), the LPF technology has been developed to mitigate part of the risk associated with LISA.

3 LISA Technology Package

The LISA Technology Package (see Figure 2) is the European provided payload onboard the LISA Pathfinder spacecraft. The instrument is being built by a consortium of European National Agencies and ESA as defined in the LTP Multi-Lateral Agreement. The countries involved and their respective hardware responsibilities are shown in Table 2.

As well as the hardware responsibilities listed in the table, all National Agencies have responsibilities related to the testing of the hardware, and in supporting on-orbit operations.

The various subsystems will be integrated and tested under the control of Astrium GmbH (Germany), the LTP Architect. The fully integrated LTP will then be integrated into the LPF spacecraft under the control of Astrium UK Ltd., the LPF Industrial Prime Contractor.

4 Current Status

The LISA Pathfinder mission is currently in the Implementation Phase. Several significant milestones have been passed (see Table 3) in the previous few years, and the Project is now entering the Assembly, Integration and Verification (AIV) phase of the mission.

As commensurate with a mission in this stage of development, several flight hardware units have been delivered to the Industrial Prime contractor and are in use in the integration and test campaign, while other units are undergoing final

Subsystem	LISA Pathfinder	LISA	Comments	LPF Status
Laser	35mW @1064nm	2W @ 1064nm	LISA will use LPF-like laser as its master oscillator. Higher power achieved by amplifying 35mW output by optical fibre amplifier.	FM in final testing
Laser frequency stabilisation	Unequal-arm Mach-Zehnder	Unequal-arm Mach Zehnder or reference cavity	The laser onboard LISA requires several stages of frequency correction. The first stage, prestabilisation, could adopt an LPF type unequal arm-length Mach-Zehnder ineterferometer as the frequency discriminator.	Fully tested using EMs of optical bench, laser and phasemeter
Modulator	AOM	EOM	No demonstration of LISA electro-optic modulator on LPF.	FM in final testing
Optical Bench	Hydroxy catalysis bonded Zerodur bench	Hydroxy catalysis bonded Zerodur bench	Demonstration of the LISA optical bench manufacturability and pathlength stability was one of the main technology developments in LPF. Several technologies have been developed including hydroxy-catalysis bonded ultra-stable optical bench, and bespoke quasi-monolithic fibre injector assemblies	FM under construction
Phasemeter	SBDFT algorithm	Digital PLL	LISA requires high frequency phasemeter due to large Doppler shifts between s/c. As LPF uses a significantly lower hetrodyne frequency, it does not require such a sophisticated phasemeter.	FM under construction
Inertial Sensor			The inertial sensor is the main component of LISA which cannot be tested on the ground. The demonstration of the Inertial Sensor performance is the main reason for flying LPF. The LPF Inertial sensor has been designed as the LISA Inertial Sensor from the beginning	
Test Mass	46mm Au:Pt cube	46mm Au:Pt cube	The LPF test mass is identical to the LISA test mass.	FMs delivered
Electrode Housing	Molybdenum housing with gold coated sapphire electrodes	Molybdenum housing with gold coated sapphire electrodes	LISA electrode housing will be identical to the LPF electrode housing	FM replica delivered for testing. Flight units under construction
Caging Mechanism	3 actuator design	3 actuator design	LISA caging mechanism will be identical to the LPF caging mechanism. Consists of launch lock (CMSS) and grabbing, positioning and release mechanism (GPRM)	GPRM FMs delivered. CMSS FMs under construction
Vacuum enclosure	Titanium enclosure with getter pump	Titanium encosure with getter pump and gate valve	The basic vacuum enclosure of LISA will be identical to the LPF vacuum enclosure with the exception of a gate valve which can be used to vent the interior to space	FMs under construction
Front End Electronics	Differential Capacitive Bridge	Differential Capacitive Bridge	Due to frequency relaxation, LPF FEE performance has not been demonstrated at LISA's lowest frequency band. In some cases, LPF FEE is more difficult than LISA due to inband actuation along the sensitive axes.	FMs in final testing
Charge Management	Photoelectric discharge	Photoelectric Discharge	Only change could be utlisation of solid state UV light source as opposed to gas discharge lamp	FMs delivered
Micro Newton Thrusters	FEEPs/Colloids	FEEPS/Colloids	The demonstraton of micro-Newton thrusters is one of the primary goals of the LPF mission. Both FEEP and Colloid thrusters will be demostarted. The results of LPF will determine which thruster will be chosen for LISA. LPF FEEP thrusters have been designed to meet the LISA lifetime requirements, although full LISA lifetime will not be demonstrtaed in the framework of LPF	Cs FEEP FMs under construction.
DFACS	18-DoF	19-DoF	Additional DoF comes from constellation breathing (not applicable to LPF)	Open loop tests complete. Closed loop tests ongoing
Telescope	None	Off-axis Schiefspiegler	LPF does not carry a telescope	N/A

Table 1: Relationship between the LISA technology and LISA Pathfinder

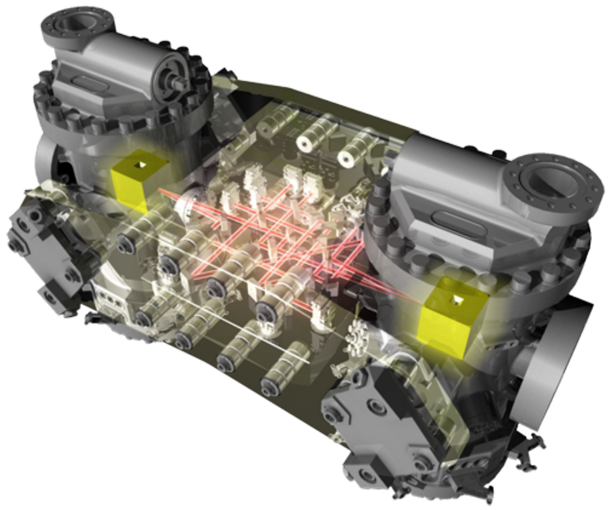

Figure 2: Artists impression of the LISA Technology Package, showing the inertial sensors housing the test masses (gold) and the laser interferometer (red).

Table 2: 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	University of Barcelona	Data Management Unit Data Diagnostic System
Switzerland	ETH Zürich/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 (IT) Astrium GmbH (DE)	Caging Mechanism LTP Architect

Table 3: 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
System Critical Design Review	November 2008
Future Milestones	**Date**
Mission Critical Design Review	September 2009
Ground Segment Implementation Review	December 2009

testing prior to delivery. In summary, most flight units will be delivered to the respective industrial prime (Astrium, UK for the spacecraft; and Astrium, Germany for the LTP) in 2009, with the exception of the FEEPs, which are scheduled to be delivered to Astrium UK in early 2010. However, the FEEPs are mounted on the external surface of the spacecraft, thereby allowing their integration to be performed respectively later than units mounted within the spacecraft structure. The current status of the LPF units can be found in rightmost column of Table 1.

Several test campaigns of the spacecraft have already started, including static load, acoustic, separation shock, and sine dwell testing of the structures (see Figure 3). These tests were performed using a combination of flight models (FMs), engineering qualification models (EQMs), and structural/thermal models (STM).

In parallel to the structure testing, subsystem hardware tests are being performed using the real-time test-beds. Currently the test-beds consist of mostly Engineering Models of the hardware, however, over the coming months the emphasis will shift to FM integrated tests.

As mentioned in Section 1, LISA Pathfinder also carries the NASA provided Disturbance Reduction System (DRS) comprising micro-Newton Thrusters and a payload computer. The DRS flight hardware was shipped to ESA at the end of 2008. The hardware will now be incorporated into the LPF test-bed, prior to mounting on the spacecraft. Figure 4 shows the DRS flight hardware.

Figure 3: Photograph showing the spacecraft and propulsion module being prepared for the acoustic test campaign. The hardware consisted of the FMs of the solar array, separation system, and propulsion module structure. EQMs of the spacecraft structure and FEEP thrusters, and STMs of the LTP Core Assembly, and FEEP thruster clusters.

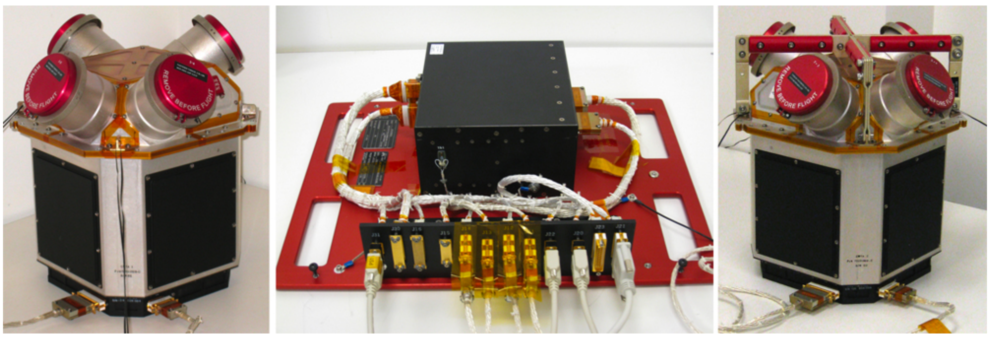

Figure 4: Photographs of the DRS flight hardware, showing the two clusters of micro-Newton Colloidal thrusters, and the Instrument Avionics Unit

5 LISA Pathfinder and LISA

The development undertaken for LISA Pathfinder directly retires the corresponding LISA development risks not only on technology and design but also on schedule and cost. The LISA risk posture continues to reduce as the LPF program progresses through its lifecycle, which consists of:

- Technology development and maturation on ground
- Subsystem and system level design
- Development of the flight hardware
- Design and development of Ground Support Equipment for Integration and Testing
- Integration and Testing on ground
- Launch, commissioning and calibration
- Completion of the on-orbit testing campaign

The risks and unknown performance issues associated with LISA continues to reduce at each of the above-mentioned steps of the LPF program. The continual reduction in the LISA risk posture can be documented as progress continues towards maturing the LPF mission. The following summary provides examples of the continual LISA risk reduction already achieved for Inertial Sensor Subsystem (ISS) and Micro-Newton thrusters.

5.1 Risk Reduction Achieved for Inertial Sensor Subsystem

The LPF program is designed to address the following risks associated with the ISS:

- Test Mass (TM) position readout does not have the required sensitivity
- ISS does not meet required total acceleration noise performance
- Magnetic control requirements cannot be met
- TM charging rate is larger than expected and cannot be balanced by suitable compensation voltage
- TM charge control system does not adequately discharge TM in suitable operating conditions
- Patch field fluctuations exceed budgeted level
- Thermal noise sources exceed budgeted levels
- Packaging complexity will complicate GRS integration
- Caging mechanism will not release TM
- Interface to local interferometer is not accurate enough

Tables 4 and 5 below show key milestones already achieved to demonstrate the progress made towards reducing the above-mentioned concerns. The table also lists the future milestones that will continue to reduce LISA risk posture before LPF launch.

5.2 Risk Reduction Achieved for Micro-Newton Thrusters

The LISA Pathfinder and ST7 programs are designed to address the following risks for the Microthrusters:

- Thrust command and control is not precise enough
- Thrust noise is too high

Table 4: Key milestones already achieved during the LPF development

Milestone	**Date**
Delivery of first prototype of large gap ISS	1999
Finalization of current concept design of LPF/LISA ISS	March 2003
First commissioning of single proof-mass pendulum, and demonstration of $10^{-13}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ equivalent acceleration noise on large gap ISS prototype	July 2003
Delivery of engineering model of ISS system with LPF/LISA ISS	June 2005
Flight ISS contract Kick-off for LPF	September 2005
LPF flight ISS Preliminary Design Review	January 2006
Completion of test-campaign on all surface disturbances and upper limit below $10^{-13}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ on LPF/LISA design ISS engineering model	October 2006
Completion of environmental and qualification test on ISS system engineering model	November 2006
LPF flight ISS Critical Design Review	May 2007
LPF flight ISS Test Readiness Review	November 2009
LPF 1st flight ISS Delivery	February 2010

Table 5: Significant results achieved during LPF development

Result	**Reference**
ISS readout model validated on prototype	Cavalleri: CQG (2001)
Initial performance measurements of first prototype housing using torsion pendulum	Hueller: CQG (2002)
Performance of first prototype ISS verified using torsion pendulum	Carbone: PRL (2003)
Proof mass magnetic properties demonstrated	Hueller: UTN (2003)
GEANT4 simulation of TM charging complete	Wass: CQG (2005)
Patch field fluctuations upper limit measured on torsion pendulum	Schlamminger:LISA6 (2006)
UV discharging demonstrated on torsion pendulum	S2-UTN-RP-3038 (2006)
Performance of 2nd prototype ISS verified using torsion pendulum	Carbone: PRD (2007)
Thermal noise sources validated	Carbone: PRD (2007a)
Momentum transfer demonstrated for TM un-caging	Benedetti: AMJ (2008)

- Thrust range (min and max thrust) is not large enough to meet all the mission requirements and operational modes
- Thruster performance cannot be verified on the ground
- Thruster exhaust may impinge or backscatter onto spacecraft surfaces
- Precise thrusters components cannot met environmental requirements
- Thruster lifetime is too limited or cannot be demonstrated adequately

Tables 6 and 7 show that a majority of the risks have been addressed in both the FEEP and Colloid Microthruster programs. Both types of thrusters will be demonstrated on LPF and continue to be developed in parallel for LISA to minimize overall risk. Already the ST7 colloid thruster flight units have been delivered and the LPF FEEP thrusters have begun flight unit fabrication and qualification. Both thruster programs have significantly reduced or eliminated risks related to performance and contamination issues pertaining to LISA, many of which will be further reduced or eliminated by on-orbit testing. For example, direct measurements of thrust noise have been made between 0.007-0.1 Hz, verifying the requirements to the limit of the available ground-based thrust stands. The thrust stand measurements also verified thrust models that predict the microthruster will meet the thrust noise requirements over the full bandwidth based on current and voltage measurements. The verified frequency range will be extended to the LISA measurement bandwidth by on-orbit measurements including the GRS. Thruster lifetime remains the most significant outstanding risk for LISA, and the remaining work in the Microthruster technology development programs focuses on this issue.

Tables 6 and 7 show the key milestones already achieved to demonstrate the progress made towards reducing the above-mentioned concerns. The table also lists the future milestones that will continue to reduce LISA risk posture before LPF launch.

6 Conclusions

This document gives a very brief overview of the LISA Pathfinder mission. A more in depth discussion of the mission can be found in the literature (*e.g.* [6],[7]). However, it demonstrates that, by the end of 2008, all technology development has been concluded, and we are now in the process of building the flight articles and testing the integrated system.

LISA Pathfinder is the first mission of its kind; the path from the original concept to the production of flight hardware has not been easy – however, all technologies have been demonstrated to EQM-level or higher, with all likely show-stoppers behind us. Also, in the process of developing the mission, we have also gained the industrial experience required to build LPF, and similar missions in the future, most notably LISA.

In conclusion, LISA Pathfinder is on track to demonstrate the first in-flight test of low frequency gravitational wave detection metrology.

Table 6: Key milestones already achieved during the LPF development

Colloid Thruster Milestones	**Date**
Prototype Colloid Thruster performance measured on a thrust stand showing that precision, noise, and range all meet requirements (thrust noise measured directly from 0.01-0.1 Hz)	January 2004
3000 hr endurance test of a single prototype colloid thruster (one emitter) completed successfully	March 2004
Colloid Microthruster CDR for ST7	October 2004
Fabrication of a complete EM-level colloid thruster system	February 2006
EM-level thruster exhaust plume properties measured, verifying that the maximum extent of the plume is $< 35^{\circ}$ and demonstrating the thrusters will not contaminate the spacecraft surfaces $> 0.1\,\mu g/cm^2$	October 2006
3400 hr endurance test of EM-level thruster system (multi-emitter) completed successfully	November 2006
Thrust stand performance measurements using the EM-level colloid thruster system verify precision, noise, and range requirements (thrust noise measured directly from 0.007-0.1 Hz)	November 2007
Flight units: fabrication complete	December 2007
Flight units: protoflight-level dynamic environmental testing complete	March 2008
Flight units: protoflight-level thermal environmental testing complete	April 2008
ST7 Flight units delivered to JPL	May 2008
JPL Integration and Test activities with ST7 flight avionics and thrusters complete	November 2008
Delivery of ST7 flight system to ESA for integration with LPF	Summer 2009
Complete accelerated testing of ST7 thruster components to LISA lifetime requirements	September 2009
Begin long-duration wear test of both CMNT and FEEP LISA prototype microthrusters	October 2010
Milestone for 8000 hours of wear test	December 2011
Milestone for 20000 hours of wear test	LISA PDR
Milestone for 40000 hours (plus margin) of wear test	LISA CDR

Table 7: Significant results achieved for colloid thrusters during ST7 development

Result	Reference
Colloid thrusters meet thrust precision, noise, and range requirements (thrust stand measurements)	Gamero: JPP (2004), Roy: JANNAF (2008)
Colloid thruster exhaust plume property measurements showing contamination requirements have been met	Hruby: CDR (2006), Marrese: JPC (2006), Demmons: JPC (2008)
EM-thruster 3400 hr long duration test completed successfully	Ziemer: D25712 (2008), Ziemer: IEPC (2007)
ST7 flight hardware qualification, delivery to JPL, and Integration and Test activities	Ziemer: JPC (2008)

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Acronym List

AEI	Albert Einstein Institute
AIV	Assembly, Integration and Verification
AOM	Acousto-Optic Modulator
APC	AstroParticule et Cosmologie
Au	Gold
CBE	Current Best Estimate
CDR	Critical Design Review
CMSS	Caging Mechanism Support Structure
Cs	Caesium
DFACS	Drag-Free and Attitude Control System
DoF	Degree of Freedom
DRS	Disturbance Reduction System
ELITE	European LISA Technology Experiment
EM	Engineering Model
EOM	Electro-Optic Modulator
EQM	Engineering Qualification Model
ESA	European Space Agency
ETH	Eidgenössische Technische Hochshule
FEE	Front-End Electronics
FEEPS	Field Emission Electric Propulsion
FM	Flight Model
GPRM	Grabbing, Position and Release Mechanism
ISS	Inertial Sensor Subsystem
LISA	Laser Interferometer Space Antenna
LPF	LISA Pathfinder
LTP	LISA Technology Package
NASA	National Aeronautics and Space Administration
nm	nano-metre
PDR	Preliminary Design Review
PI	Principle Investigator
PLL	Phase-Locked Loop
pm	pico-metre
Pt	Platinum
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
STM	Structural Thermal Model
UV	Ultra Violet