Journal of Physics: Conference Series

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To cite this article: LISA Pathfinder collaboration 2017 *J. Phys.: Conf. Ser.* **840** 012001

11th International LISA Symposium IOP Publishing
IOP Conf. Series: Journal of Physics: Conf. Series **840** (2017) 012001 doi:10.1088/1742-6596/840/1/012001

LISA Pathfinder: First steps to observing gravitational waves from space

LISA Pathfinder collaboration

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Abstract. LISA Pathfinder, the European Space Agency's technology demonstrator mission for future spaceborne gravitational wave observatories, was launched on 3 December 2015, from the European space port of Kourou, French Guiana. After a short duration transfer to the final science orbit, the mission has been gathering science data since. This data has allowed the science community to validate the critical technologies and measurement principle for low frequency gravitational wave detection and thereby confirming the readiness to start the next generation gravitational wave observatories, such as LISA.

This paper will briefly describe the mission, followed by a description of the science operations highlighting the performance achieved.

Details of the various experiments performed during the nominal science operations phase can be found in accompanying papers in this volume.

1. Introduction

LISA Pathfinder (LPF), the European Space Agency's second SMART [1] mission, was instigated to demonstrate technologies for future spaceborne gravitational wave observatories, for example, the Laser Interferometer Space Antenna (LISA) mission, recently proposed to ESA [1].

LISA has continually been ranked as one of the most scientifically important missions under study [2]. However the very concept of low frequency gravitational wave detection, *i.e.* that a particle falling under the influence of gravity alone follows a geodesic in spacetime, has never been demonstrated to the required precision. LISA Pathfinder has been designed to demonstrate that low frequency gravitational wave detection from space is indeed possible.

LPF mimics one arm of the LISA constellation by shrinking the 2.5 million-kilometre armlength down to a few tens of centimetres, and hosting the hardware inside a single spacecraft. This results in giving up the sensitivity to gravitational waves, however, it maintains (and in some cases worsens) the instrumental noise which could disturb the eventual LISA measurement. The concept is to measure, using laser interferometry, the relative separation of two free-falling test masses nominally following their own geodesics (Figure 1), and thereby determining the relative residual acceleration between them over a measurement bandwidth from 1-30 mHz, about a decade above the lowest frequency required by LISA.

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[1] SMART = Small Missions for Advanced Research in Technology

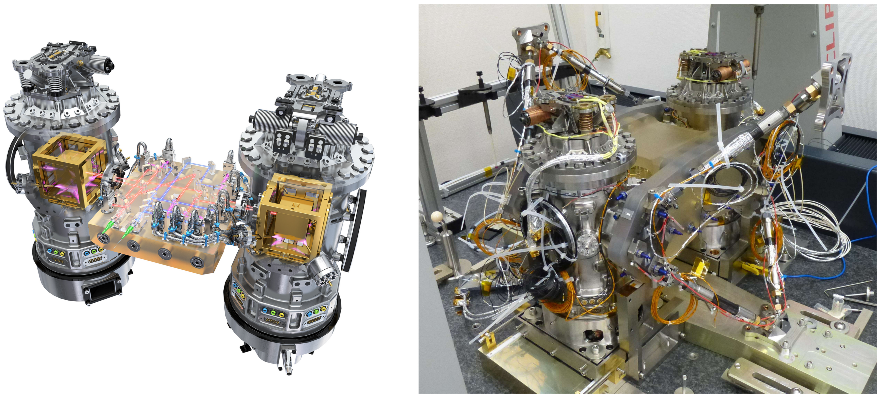

Figure 1: *Left*:Artist's impression of the LISA Technology Package Core Assembly showing the gold:platinum test masses housed in their respective electrode housings. Credit: ESA/MediaLabs, *Right*: LTP flight hardware during integration. Credit: Airbus Defence and Space

LISA Pathfinder was launched on 3 December 2015 on-board a dedicated VEGA launch vehicle, with the spacecraft and expendable propulsion module being injected into a low earth orbit (200 km x 1540 km). After a series of 6 apogee raising manoeuvres, LPF entered a short duration transfer trajectory towards the final science orbit, an 800,000 km x 500,000 km Lissajous orbit around the first Sun-Earth Lagrange point (L1) (see Figure 2). Following the initial on-orbit check-out and instrument calibration, the in-flight validation of the LISA technology began on 1 March 2016.

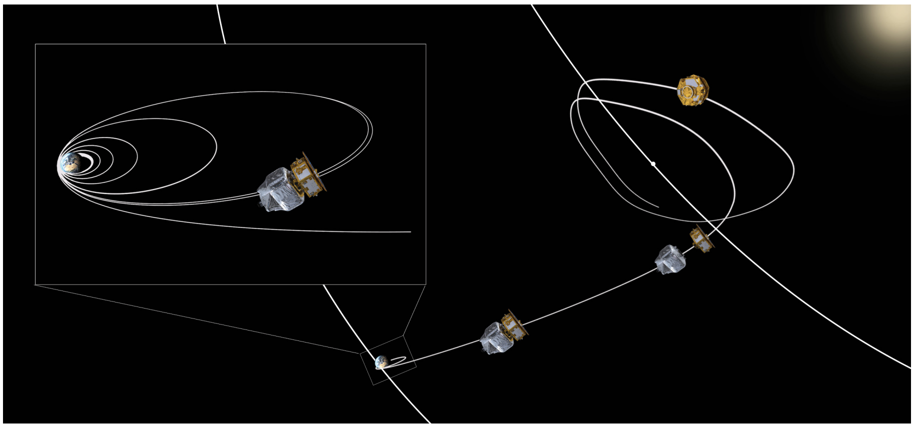

Figure 2: Artist's impression of the Launch and Early Orbit Phase (LEOP) of the mission, resulting in the final science orbit around the first Sun-Earth Lagrange point (L1). Credit: ESA/MediaLabs

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 carries two payloads: the LISA Technology Package (LTP), provided by a consortium of European national space agencies

(France, Germany, Italy, Spain, Switzerland, the Netherlands, and the United Kingdom) and ESA; and the NASA provided Disturbance Reduction System (DRS), part of NASAs New Millennium Program. Only the LTP will be described in this paper.

The LTP consists of two major subsystems; the Inertial Sensor Subsystem, and the Optical Metrology Subsystem. Both 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 compared to LISA.

The inertial sensor subsystem comprises the test masses and all systems interacting directly with the test masses, *i.e.* the electrode housing, front-end electronics, vacuum system, charge management, and caging mechanism (see Figure 3). This section will describe each of these subsystems in turn.

The test masses consist of a 1.93 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 $\approx 2 \times 10^4\,\mathrm{kgm^{-3}}$. The combination of both greatly reduces the effect of external forces on the test mass.

The test masses' position is readout by two means: high resolution laser interferometry, and electrostatic (capacitive) sensing. The former only senses the test mass position along the sensitive axis (the line joining the two test masses) and the angles of rotation around the axes perpendicular to the sensitive axis, whereas the capacitive sensor measures the position of the test mass in all six degrees of freedom. The capacitive sensor comprises a hollow cubic molybdenum housing with gold coated sapphire electrodes mounted in the faces (see Figure 3). The housing is sized to allow for a ≈4 mm gap between the electrode faces and the test mass. The size of the gap is a trade off between reducing the effects of noise sources, *e.g.* from uncontrolled potentials on the electrodes, and being able to meet the capacitive sensing requirement of $1.8\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$ 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 at the output of the bridge, which is used as an input to the drag-free control system. As well as sensing the position of the test masses, the ISS FEE can also be used to actuate (force) the test mass.

The test mass and electrode housing are mounted inside a dedicated vacuum enclosure. To meet the mission requirements, the vacuum around the test mass must be maintained, throughout the mission lifetime, to less than 10^{-5} Pa. In order to limit the pressure increase due to outgassing or virtual leaks, the enclosure was vented to space once the spacecraft reached its operational science orbit.

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

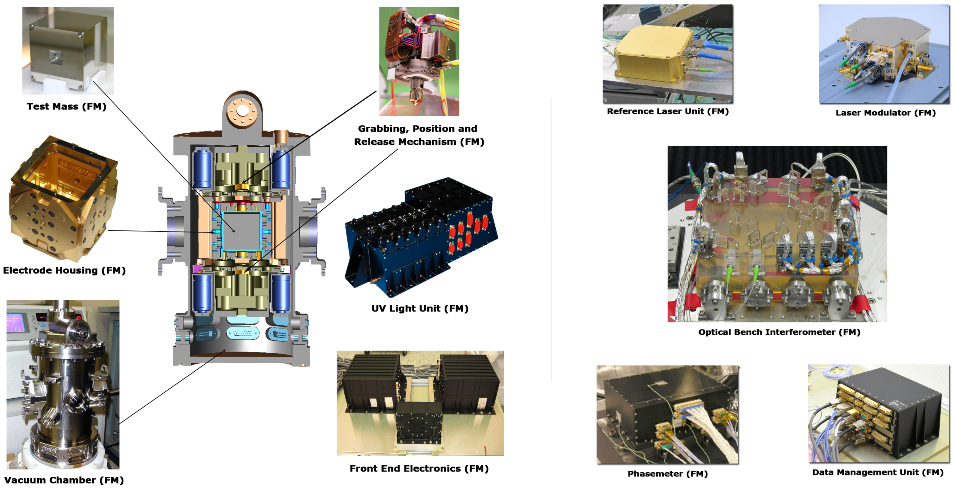

Figure 3: *Left*: Photographs of the Inertial Sensor Subsystem. From bottom left: Vacuum Chamber (CGS), Electrode Housing (CGS), (uncoated) Test Mass (Thales Alenia Space), Caging Mechanism (RUAG), UV Lamp Unit (Imperial College London), Front-End Electronics (ETH, Zurich). *Right*: Photographs of the Optical Metrology System hardware. From top left: Reference Laser Unit (Tesat), Laser Modulator (APC/Contraves), Data Management Unit (ICE), Phasemeter (Uni Birmingham). Centre: Optical Bench Interferometer (Uni Glasgow)

electrode housing, thereby extracting electrons from either surface, providing bi-polar charge management.

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 - and associated with the thermal stability requirement is the need to have thermometers with a resolution better than $10^{-5}\,\mathrm{K}/\sqrt{\mathrm{Hz}}$.

2.2. 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, the optical bench interferometer, the phasemeter, and the data management unit (Figure 3).

The *Reference Laser Unit* (RLU) comprises a 40 mW Nd:YAG non-planar ring oscillator [3] 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 is baselined as the master oscillator in the LISA laser system.

The RLU output is fibre coupled using single-mode, polarisation-maintaining (sm/pm) fibre. The fibre couples the light to the subsequent component in the optical chain, the *Laser Modulator* (LM). The LM consists of a beam splitter, two acousto-optic modulators, and optical pathlength actuators. The light from the laser is split into two paths, each path is passed through an acousto-optic modulator. One modulator is driven at 80 MHz, while the other is driven at 80 MHz + 1 kHz, thereby creating two beams with a frequency difference of 1 kHz. The beams are then passed through the optical pathlength difference (OPD) actuator. The OPD is used to stabilise the optical pathlength of the fibre optic cables leading to the optical bench. After the

OPD, the beams are transmitted, again via sm/pm fibre, to the *Optical Bench Interferometer* (OBI).

The main function of the OBI is to direct the beams to the relevant positions in 3-dimensional space, without adding any significant noise to the measurement path. The 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 [4] . The mirrors and beamsplitters are used to direct the two beams to form four interferometers: the x_{12} interferometer which measures the differential motion of the two test masses - this is the primary science measurement of the mission; x_1 interferometer which measures the position and angles of test mass 1 with respect to the optical bench (and therefore, the spacecraft) - equivalent to the LISA local test mass interferometer; the *Frequency* interferometer which is an unequal arm Mach-Zehnder interferometer, the output of which is sensitive to laser frequency fluctuations, and therefore can be used to stabilise the laser frequency; and the *Reference* interferometer which is a rigid equal arm interferometer which provides the system noise floor, and is used to stabilise the optical pathlengths via the OPD. The light from each fibre is also sent directly to a photodiode which is used to monitor the laser intensity noise. The signal from these photodiodes is used to stabilise the intensity of both beams by feeding back to the acousto-optic modulator drive signal.

The signals from the (quadrant) photodiodes of each interferometer are sent to the *Phasemeter Assembly*. The phasemeter samples the data at 50 kHz and performs a Single Bin Discrete Fourier Transform [5] 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_{12} 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) [6].

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

3. Operations Timeline

Following the launch and early operations, the spacecraft was put on a transfer towards the first Sun-Earth Lagrange point (L1). After ≈50 days cruise, the propulsion module was jettisoned, and LPF entered its final science orbit. This triggered the formal start of the spacecraft commissioning phase.

After initial check-out of the hardware subsystems, the launch locks holding the test masses during launch were released, however the test masses were still mechanically held in place via piezo actuated fingers. In addition to performing the launch lock function the actuators were also used to open a valve, allowing the interior of the vacuum enclosure to be vented to space. This activity took place on 2 Feb 2016. The test masses were released from their mechanical actuators on 15 & 16 February, after which they were free floating with no mechanical contact to the satellite.

LISA Pathfinder science operations began on 1 March 2016, with the nominal mission ending on 26 June 2016.

The goal of LISA Pathfinder is to not only demonstrate the required free-fall performance

Table 1: List of the high level experiments to be performed during the LISA Pathfinder nominal operations. The colour corresponds to the colours in the timeline in Figure 4.

Label	Experiment type
🟦	Differential acceleration noise run
🟩	Measurement of dynamical coefficients by system identification
🟪	Measurement of cross-talk
🟦	Measurement of stray DC potentials
🟥	Dedicated optical metrology experiments
🟧	Measurement of the thermal environment of the system
🟨	Measurement of the magnetic environment of the system

for future gravitational wave observatories, but also to understand the physical model of the forces which perturb the test masses from pure free-fall. For this reason, the operations of LISA Pathfinder were designed to probe different aspects of the system, and thereby validate the system noise model. Table 1 lists the high level experiments run during the mission. Each of the experiments are then sub-divided in to a number of individual investigations which are run on the spacecraft.

Figure 4 graphically displays the dates on which each experiment was run. As can be seen, long periods of the operations are dedicated to noise runs. This is essential in order to understand the system at the lowest frequencies of the measurement bandwidth. As will be seen in Section 5, this becomes even more apparent when the system is used to investigate the lowest measurement frequencies of interest to LISA ($\approx 20\,\mu$Hz) where each noise run lasts a minimum of two weeks of operational time.

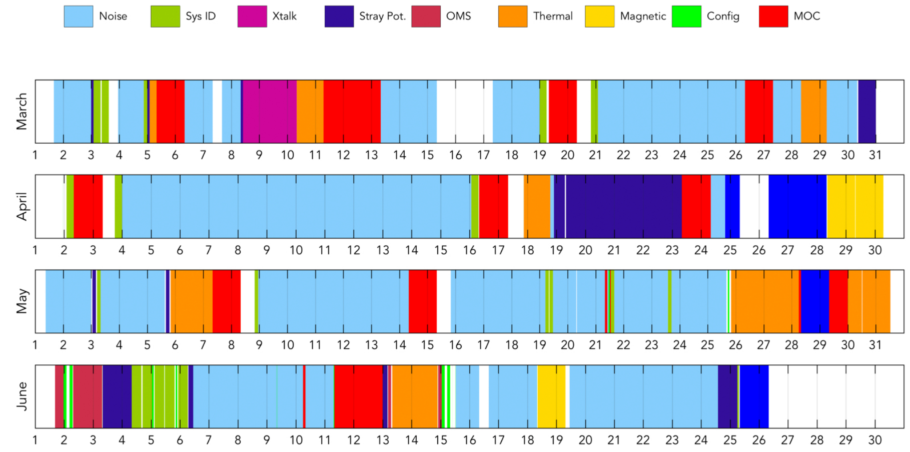

Figure 4: Timeline of the nominal science operational phase of LISA Pathfinder showing the experiments being run on a given day. The colours relate to the experiments listed in Table 1. Note: the blocks labelled *Config* relate to changes in the instrument configuration to prepare the system for the upcoming experiment, while the blocks labelled *MOC* are windows reserved for the Mission Operations Centre (MOC) team to perform routine activities such as station keeping.

Details of each of the experiments and associated investigations can be found in the accompanying papers in this volume.

4. First Results

As mentioned previously, the primary science measurement of LISA Pathfinder is the measure of differential acceleration between the test masses. Being a precursor mission, the corresponding differential acceleration requirement was relaxed with respect to LISA, however, the relaxation comes from the spacecraft environment and the nature of the LISA Pathfinder mission (two test masses sharing the same sensitive axis).

Figure 5 shows the performance of the system on the first day of operations, before any tuning of the system parameters had taken place. It is clearly seen that the primary performance requirement was already met. The performance was limited by three main noise sources: 1) at frequencies >20 mHz, the limiting noise source is the interferometer sensing noise, 2) mid-band frequencies are limited by residual gas damping (Brownian noise), 3) the low frequencies (<1 mHz) are limited by actuation noise of the second test suspension control system.

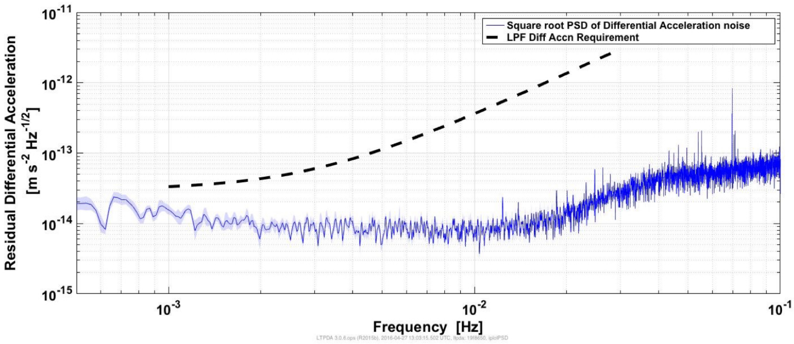

Figure 5: Differential acceleration, Δg, performance between the two free floating test masses, as measures on the first day of science operations.

The evolution of each noise source will be described in more details in the following paragraphs

The interferometer sensing noise has been stable since the beginning of science operations, with a noise floor of $\approx 35\,\mathrm{fm}/\sqrt{\mathrm{Hz}}$ - this is approximately 250 times lower than the sensing noise requirements, demonstrating the ability to monitor the position of free-falling test bodies to sub-picometre precision.

Concerning the mid-band frequencies; as the interior of the electrode housing was vented to space, the pressure, and hence Brownian noise, reduced over time, with the noise following a exponential decrease with the t_0 being centred around the opening of the venting valve on 2 February. This has resulted in the mid-band noise continuously reducing as science operations have progressed.

As mentioned above, the low frequency noise was dominated by the voltage noise of the electrostatic actuation system of the second test mass suspension control system. The required force (and hence voltage) to be applied is driven by the differential gravity experienced by test mass two with respect to test mass one. The LPF requirement was such that the differential gravity, coming from the self-gravity of the spacecraft, shall be less than 2000 pN. On the first day of operations, the differential gravity was measured, by looking at the force required to keep TM2 following TM1, to be ≈40 pN, a factor of 50 lower than requirements. This allowed the science operations team to lower the required maximum applied force, and thereby reduce the effect of the voltage noise in the actuation system [7]. In so doing, the low frequency noise was significantly reduced.

Figure 6 shows the differential acceleration performance published in the LPF first results paper [7]. As can be seen, the performance has significantly improved, approaching the levels required for a full gravitational wave observatory such as LISA. The data shown in the first results paper is from April 2016. Details of the performance can be found in [7]. The instrument performance continued to improve over the lifetime of the mission, and more so during the extended mission [1].

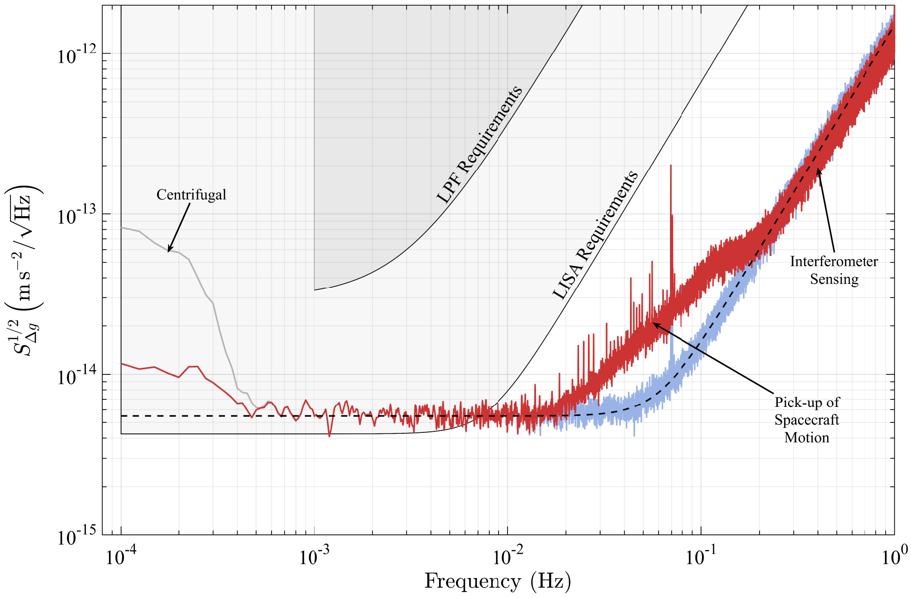

Figure 6: LISA Pathfinder differential acceleration performance result as published in the first results paper ([7])

5. Extended Mission

Following the LPF nominal science mission, the control of the satellite was handed over to the NASA Disturbance Reduction System (DRS) payload.

The DRS nominal operations concluded on 7 December 2016, signalling the start of the mission extension. This phase of the mission will run until 30 June 2017. The mission extension operations are focused on the investigation of the low frequency noise, especially at lowest frequencies of interest to LISA (20 μHz to 1 mHz) - this necessitates long noise runs (typically 2-3 weeks) in order to build statistics of the noise content. The performance of the LTP now exceeds the LISA performance requirement, however, quantitative analysis of the data is ongoing.

6. Conclusions

The LISA Pathfinder satellite has proven the concept of low frequency gravitational wave detection from space is possible. The performance of the LISA Technology Package has demonstrated residual differential acceleration noise between free floating test masses to over an order of magnitude lower than the mission level requirements, fulfilling the LISA performance goals over the entire LISA measurement bandwidth.

The success of LISA Pathfinder has paved the way for LISA. The European Space Agency have selected the LISA concept for further study, with a launch date slated for 2034.

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