Brief Article

The Author

1 Section

1.1 Subsection

Abstract

As the launch of LISA Pathfinder draws near, more and more effort is being put in to the preparation of the data analysis activities that will be carried out during the mission operations. The operations phase of the mission will be composed of a series of experiments that will be carried out on the satellite. These experiments will be directed and analysed by the data analysis team, which is part of the operations team. The operations phase will last about 90 days, during which time the data analysis team aims to fully characterise the LISA Pathfinder satellite, and in particular, its core instrument the LISA Technology Package. By analysing the various couplings present in the system, the different noise sources that will disturb the system, and through the identification of the key physical parameters of the system, a detailed noise budget of the instrument will be constructed that will allow the performance of the different subsystems to be assessed and projected towards LISA. This paper describes the various aspects of the full data analysis chain that are needed to successfully characterise LPF and build up the noise budget during mission operations.

2 Introduction

The LISA space-borne Gravitational Wave Observatory [**?**], when operational, will provide a unique view of the universe at spectral frequencies unobservable with ground based detectors. As well as directly observing the gravitational radiation from a number of known sources, LISA will also provide the opportunity to observe unexpected signals and sources.

In order to detect the known sources with a high signal-to-noise ratio, the strain sensitivity of LISA has to be of the order of $10^{-21}/\sqrt{\mathrm{Hz}}$ at milliHertz frequencies. Many of the technologies required to build an instrument that can achieve such a strain sensitivity are currently being constructed and will be tested on the LISA Pathfinder satellite (LPF). In order to reduce the cost and complexity of LPF, the performance of the various subsystems required to achieve the desired sensitivity for LISA has been relaxed such that the main goal for LPF is to demonstrate the ability to put a test particle in free-fall to such a level that the residual external force per unit mass acting on the particle is below $3 \times 10^{-14}\,\mathrm{ms}^{-2}/\sqrt{\mathrm{Hz}}$ at 1 mHz. Additionally, in order to show that the performance of the various subsystems under test is good enough, or can be extrapolated to a level suitable for LISA, the final measured performance of LPF will need to be completely explained in the measurement bandwidth (1 mHz through 30 mHz). That means that, as well as assessing the residual forces acting on the test particle, one of the key data analysis activities will be to build up as complete a noise model as possible.

In more concrete terms, LPF will place a macroscopic test particle, a 2 kg test-mass (TM) made from a gold-platinum alloy, in free-fall. In order to assess the residual acceleration of the test-mass, a second, nominally identical, test-mass is flown and a differential measurement is made. This allows the relatively noisy jitter of the spacecraft (SC) to be isolated from the measurement process. From the differential measurement, we then estimate the residual differential acceleration of the two bodies [**?**]. A spacecraft is required to shield the two TMs from external influences (such as solar radiation pressure) and to provide a platform for the measurement equipment. To achieve the best possible free-fall, the forces acting on the first TM along the x-axis (the axis joining the centres of mass of the two test-masses) will be kept to a minimum. As such, no control forces will be directly applied to that TM. This leads to a control scheme where the jitter of the SC relative to the first TM is measured and minimised via a *drag-free* [**?**] control-loop utilising micro-Newton thrusters attached to the spacecraft. The differential position of the two TMs is also controlled via the electrostatic actuators surrounding the second TM. The other degrees of freedom of the three bodies are also controlled via a mixture of the electrostatic actuators surrounding the two TMs and the spacecraft thrusters. The full control scheme is referred to as the Drag-Free Attitude and Control System (DFACS) [**?**].

All together, LPF is a complicated system of nested and coupled control-loops operating across 15 degrees-of-freedom. In order to achieve the best possible level of free-fall and to establish a complete noise budget for the x-axis (as described above), these various loops and couplings have to be characterised and optimised through a series of dedicated experiments.

The TMs, sensors and actuators, together with supporting diagnostic and computer systems make up the LISA Technology Package (LTP), the core instrument on-board LISA Pathfinder. The LTP contains two main sensor systems which can be used to readout the different degrees-of-freedom of the two TMs relative to each other and to the spacecraft. The Gravitational Reference System (GRS) [?], is based on a pattern of electrodes surrounding both TMs, and capacitively reads the SC-TM relative motion along all 6 degrees-of-freedom to within $1\,\mathrm{nm}/\sqrt{\mathrm{Hz}}$. The TMs are polarised via an oscillating electric field to allow their position to be capacitively readout. By simultaneously applying voltages at different frequencies to the same electrodes it is also possible to electrostatically apply forces and torques to reposition and rotate the TMs themselves according to the commanded forces and torques coming from the DFACS controllers.

The second, and more sensitive, sensor system is interferometric and provides readouts of the x-axis position of the first TM relative to the spacecraft (the X_1 interferometer) and the differential position of the two TMs (the X_{12} interferometer) to an accuracy of around $9\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ at $1\,\mathrm{mHz}$. In addition, two interferometric angular readouts of each TM via differential wavefront sensing are implemented; these are accurate to about $20\,\mathrm{nrad}\,/\sqrt{\mathrm{Hz}}$. The laser, modulators, optical components, phase-meter, and processing computer together form the Optical Metrology Subsystem (OMS) [?].

These two sensors (the GRS and the OMS) allow for two main science control modes. The difference between the two is in how the x-position of the SC relative to the first TM is measured: the first (Science Mode 1) uses the capacitive sensor; the second (Science Mode 1 all-optical) uses the output of the X_1 interferometer. In both modes, the position of the second TM relative to the first is controlled using the output of the X_{12} interferometer. Further details of the main science objectives of LPF can be found in this volume in [?] and a schematic of LPF in Science Mode 1 all-optical is shown in Figure 1.

LPF is a short duration mission, where the LTP phase lasts about 90 days. During that time, the full optimisation and characterisation of all the subsystems must take place. In order to do that, the various experiments that will be performed need to be analysed in real-time so that following experiments can be adjusted and/or rescheduled to allow optimal use of the available mission time. For example, the available actuators (micro-Newton thrusters and electrostatic actuators) will need to be balanced and diagonalised in some of the early experiments, thus suppressing various noise sources. In addition, an experiment may reveal that some part of the system is not operating correctly, and should be switched off or optimised to reduce its noise contribution. Similarly, the identification of particular parameters, images/lpf_schematic.pdf

Figure 1: This figure gives a schematic representation of the x-axis control of LPF in control mode Science Mode 1 all-optical. Here, the first test-mass, TM1, is drag-free, and the second test-mass, TM2, follows TM1. The two interferometer readouts, o_1 and o_{12} are indicated. In practice, all 12 micro-Newton thrusters are used when moving the SC along x according to the output of the drag-free controller, H_{df}, and both pairs of electrodes are used to actuate the second test-mass along x according to the output of the low-frequency suspension controller, H_{sus}.

like actuator gains or coupling coefficients, may require the stimulus signals in subsequent experiments to be reduced or increased in order to maintain sufficient signal-to-noise, or to not exceed limits of the system. For more discussion, see Section **??**, and references [**?**, **?**].

To ensure that it is possible to gain the maximum science return from the mission, the various experiments needed to characterise the instrument will be planned in advance and packed together in a preliminary mission time-line. Being able to analyse the experiments in real-time implies that the data analysis for each experiment needs to be planned, prepared and tested in advance of the mission. Additionally, to ensure that we design the optimal set of experiments given the information to date, we need to simulate and validate each experiment prior to launch. The design, simulation, and analysis of the experiments and data analysis pipelines, together with the supporting computing infrastructure [**?**], are the main tasks of the LTP data analysis team. The rest of this paper aims to provide an overview of the activities and status of each of those tasks. We also aim to provide references, when appropriate, to the more detailed analyses that are being developed to allow for a more in-depth off-line treatment of the experiment data.

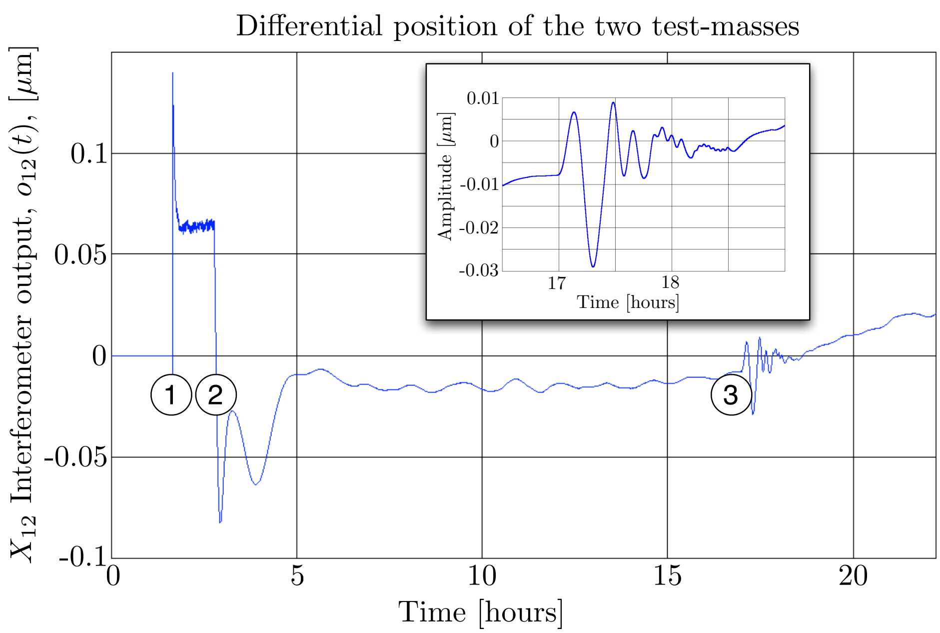

Figure 2: My Nice Figure.

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