LTP – LISA technology package: Development challenges of a spaceborne fundamental physics experiment

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LTP – LISA Technology Package:
Development Challenges of a Spaceborne Fundamental
Physics Experiment

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Abstract. The LISA Technology Package (LTP) is the main payload onboard the LISA Pathfinder Spacecraft. The LTP Instrument together with the Drag-Free Attitude Control System (DFACS) and the respective LTP and DFACS operational software forms the LTP Experiment. It is completed by the FEEPs of the LPF spacecraft that are controlled by DFACS in order to control the spacecraft’s attitude along with the experiment’s needs. This article concentrates on aspects of the Industrial development of the LTP Instrument items and on essential performance issues of LTP. Examples of investigations on specific issue will highlight the kind of special problems to be solved for LTP in close cooperation with the Scientific Community.

1. Introduction
The LISA Technology Package (LTP) is the main payload onboard the European Space Agency's LISA Pathfinder Spacecraft (LPF). The development currently is on the turn from existing engineering models to building the final flight items. LPF is scheduled for launch in 2010.

LTP is a pre-cursor experiment that shall prove in space feasibility of the edge-of-technology techniques necessary to build the Laser Interferometer Space Antenna (LISA), a Gravitational Wave Observatory currently being under study by the European Space Agency (ESA) and by NASA together with space industry.

An overview on the LTP Mission and its science objectives has been provided by S Anza et al. [1]. The essentials of the Drag-Free Attitude Control System (DFACS) of the LTP Experiment have been summarized by, e.g., Fichter et al. [2]. DFACS will not be addressed specifically herein. Overviews on the LTP Instrument have been presented by R Gerndt et al. ([3] and [4]).

This paper is providing examples of specific challenges being encountered during development of the LTP Instrument. However, this snap shot is not meant to qualify techniques not mentioned here to be easily achievable. For all elements of LTP the development teams of the European LTP Consortium have had to exploit technical solutions of unusual precision for space borne instrumentation in order to comply with the demanding requirements put on LTP equipment and the LTP Mission.

¹ To whom any correspondence should be addressed and who herein is summarizing work done by a lot of LTP colleagues (see Acknowledgement Section).
2. LTP Instrument and its Mission

2.1. Instrument Overview

The LTP Instrument consists of two main functional subsystems, namely the Inertial Sensor Subsystem (ISS) and the Optical Metrology Subsystem (OMS) as shown in Figure 1, which are controlled by the Data & Diagnostics Subsystem (DDS).

The ISS is providing all technical means necessary to bring the two LTP Test Masses (TM) into orbit and then - steered by DFACS algorithms - to control the TM attitude and position through electrostatic actuation and suspension so that one TM is freely falling in direction towards the other.

The OMS serves as a high precision optical sensor of the differential movement of the two TM and of the movement of one of the TM with respect to the LPF Science Module (SCM). It is based on heterodyne Mach-Zender interferometry allowing for high precision measurements of TM position and attitude, e.g. intrinsically reaching the range of $6 \times 10^{-12} \text{ m/Hz}^{1/2} [1+(f/3 \text{ mHz})^2]$ for 3 - 30 mHz in case of position sensing. For OMS details the reader is pointed to other publications like, e.g., those by G Heinzel et al. [5] and A F Garcia Marin [6].

2.2. The Main Challenge of LTP: Launch Test Masses Safely and Keeping them Free-Floating

The essential task of LTP is to demonstrate that it is possible to launch a spacecraft without endangering the integrity of the Test Masses on-board and then to assure that on-station - despite of the artificial environment the TM are located in - they may be kept in a geodetic motion along their common coordinate axis x.

The acceleration noise level of less than $3 \times 10^{-14} \text{ m s}^{-2} \text{ Hz}^{-1/2}$ at 1 mHz to which the residual differential accelerations of the two TM along x need to be controlled is the main LTP mission requirement. Any time-varying process impacting directly on the TM movements or on the precision of the LTP electrostatic actuation and electrostatic and optical sensors need to be handled carefully in order to avoid disturbances of the geodetic motion beyond the level set by that prime mission requirement.

Figure 1. Functional Breakdown of LTP Instrument: The LTP Subsystems and Units
Any physical process may compromise the acceleration noise and thus quite a variety of field and direct forces need to be controlled by proper engineering of LTP and LPF items and their accommodation around the Test Masses. Figure 2 provides an overview on both, DC forces and AC forces, and the order of precision to which they need to be defined and controlled during the LTP mission in order to achieve the prime mission requirement.

\[
S_{a}^{1/2}(f) \leq 3 \times 10^{-14} \left[ 1 + \left( \frac{f}{3 \text{mHz}} \right)^{2} \right] m \frac{1}{s^{2} \sqrt{Hz}}
\]

3. Technology Challenges Resulting from LTP Mission Task (Examples)

3.1. SCM Accommodation of LTP and Control of Self-Gravitation

Figure 3 shows the accommodation of the LTP elements on the LPF SCM. Besides the usual work to place the elements inside an spacecraft, locations of LTP and SCM items (and their internal mass distribution) need to be neatly defined during the design phase and the hands-on integration needs to be controlled with specific effort aiming at gaining the knowledge of the real mass distribution around the TMs. Based on the achieved as symmetrical as possible mass distribution, balance masses will be designed that internal to the ISHs will guarantee that the TMs finally will be located in the centre of the combined gravity field of all the spacecraft's mass surrounding them. This gravity balancing shall allow for keeping the residual gravitationally induced acceleration below about 1 to 3 nm/s² and to control down to \(3 \times 10^{-15} \times [1+(f/3 \text{mHz})^2] \text{ m s}^{-2} \text{ Hz}^{-1/2}\) the noise contribution due to gravitational field variations that in turn are caused, e.g., by thermal expansion of the SCM.

Still self-gravity will be one of the largest contributions to the differential acceleration noise and thus considerable effort needs to be spent in order to acquire precise knowledge on the mass distribution and the uncertainties about the as-built properties. As example, Figure 4 illustrates the complexity of items like the LTP Instrument harness. For defining the routing the gravitational balance needs had to be obeyed so that finally harness elements at SCM of cm-range length will be known in position to within several mm. This requires an accordingly precise pre-definition of the routing path and an integration process precise to an order not applied yet in space business.
3.2. Structural Integrity and Stability of the LTP Core Assembly (LCA)

The Optical Bench Assembly needs to support an Optical Bench made of Zerodur (OBI) centered between two heavy Inertial Sensor Heads (ISH). The Optical Bench Assembly then is integrated into the SCM by help of a set of struts providing a quasi-hyperstatic mounting of this set-up, called the LTP Core Assembly. For LCA design high launch load cases for LPF are to be encountered along with extremely tight structural stability and alignment requirements.

Alignment stabilities to be reached are in the order of 100 pm/Sqrt(Hz) for the IS heads distance and of 500 pm/Sqrt(Hz) and 0.1*10^{-6} rad/Sqrt(Hz) for position and attitude stability of OBI with respect to the Electrode Housings around the TM. The E2E performance simulation carried out to ensure a proper design of the LCA with respect to opto-dynamical stability and the self-gravity disturbance stability has been described in more detail by Brandt et al. [7].

Zerodur is the material of choice for the intermediate support structure due to the material’s superior thermo-elastic stability. Application of Zerodur in space technology requires a good knowledge of the mechanical behavior of the challenging glass ceramic. The demanding Ultimate Physical Stress limit of 15 MPa including uncertainty factors needs to be guaranteed through specific design measures despite of the launch loads. The resulting design of an ultra-stable LCA structure is shown in Figure 5. Figure 6 shows the Structural Model of the LCA that was used to demonstrate that the LCA can survive the launch loads while keeping the internal alignment within the tolerances of several tens of microns respectively several mrad.

3.3. Launching Test Masses Safely and Releasing it into Free Fall

During launch quasi-static loads of about 50 g will result in forces of 1000 N acting on the TM. To safe-guard the TMs during launch the Caging Mechanism (CM) holds the TM with 8 fingers (Figure 7). A form-fit interface between fingers and TM ensures equal load per finger and avoids slippage of the 8 fingers on the TM that could damage its surface. 1-2 µm machining accuracy of fingers and TM corners are needed and technology tests have proven that such accuracies can be achieved despite of the fact that delicate materials are to be handled. To lay-out and to prove the design solution of the TM-to-finger interface extensive structural analyses had to be performed like such illustrated in Figure 8.
The LCA integrates the ISHs with the OBI and provides a very stable alignment between TMs and OBI.

Each of the fingers still has to carry a load of 125 N causing, together with other effects, quite high adhesion forces between TM and CM fingers. To overcome these adhesion forces without damaging the TM surfaces and to release the TM into free fall another part of the CM, the Grabbing, Positioning and Release Mechanism, is used. The challenges of this mechanism are as well demanding but cannot be discussed here.
3.4. Finite-Element Electrostatic Analysis of the Inertial Sensor (IS)

Comprehensive finite-element electrostatic analysis of the Inertial Sensor's electrostatic fields within the Electrode Housing with Maxwell 3D (and 2D) field simulation software have been performed to verify the approximations of the IS electrostatic modeling (used in performance analysis, simulation and on-board algorithms). This tool was used as well to confirm compatibility of operational scenarios with electrostatic need for issues like test mass release with resulting electrostatic impact of grabbing plunger inside the EH volume close to the TM. Another example is the investigation of the acceptability of TM corners - the specific form design of which is dedicated to the CM finger interface needs - for the electrostatic TM control process. As well TM surface patch effects for un-coated surfaces have been analyzed. Figure 9 illustrates the effort put into this performance issue of LTP.

4. Conclusion

The LTP Instrument consists of elements most of which are based on edge-of-technology designs that shall assure achieving the extreme level of performance of their functionality necessary to reach the LTP mission requirement on the Test Masses differential acceleration noise.

Extensive performance analyses and performance budget control show that the expected performance of the LTP Instrument is compliant with the mission requirement. The performance analysis is now more and more confirmed by incoming results from performance measurements performed with Engineering Models of the LTP configuration items, so that technical evidence is building up that the real hardware and software of the flight model can achieve the required performance.

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