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LISA Pathfinder: Optical Metrology System monitoring during operations

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Abstract. The LISA Pathfinder (LPF) mission has demonstrated excellent performance. In addition to having surpassed the main mission goals, data has been collected from the various subsystems throughout the duration of the mission. This data is a valuable resource, both for a more complete understanding of the LPF satellite and the differential acceleration measurements, as well as for the design of the future Laser Interferometer Space Antenna (LISA) mission. Initial analysis of the Optical Metrology System (OMS) data was performed as part of daily system monitoring, and more in-depth analyses are ongoing. This contribution presents an overview of these activities along with an introduction to the OMS.

1. Introduction

The LISA Pathfinder satellite is a technology demonstrator that has proven the feasbility of some key technologies required for the future Laser Interferometer Space Antenna (LISA) mission [1]. These technologies include the use of picometre precision interferometry and microNewton thrusters to achieve control of a free-falling test mass (TM), such that it is influenced only by the local geodesics of space-time. The differential acceleration of the two LPF test masses is the scientific product that defines how well free-fall has been achieved.

The differential acceleration is calculated from the differential longitudinal displacement of the TMs. This, along with the angular fluctuations of the TMs around the sensitive axis, is derived from interferometric measurements made by the Optical Metrology System (OMS) [2].

2. The Optical Metrology System

The subsystems that make up the OMS are shown in Figure 1. A brief overview of the measurement chain is given in this section. The monitoring of the system health, and other relevant activities are presented in subsequent sections.

Light from the Reference Laser Unit (RLU) is coupled via a fibre into the Laser Modulation Unit (LMU), where it is split into two beams. Each beam passes through an Acousto-Optic Modulator (AOM) and the beams are shifted in frequency such that the difference between them is 1 kHz, the heterodyne frequency. The beams are transmitted onto the optical bench where they form four interferometers, as shown in Figure 2:

- The X1 interferometer determines the position of TM1 relative to the optical bench.
- The X12 interferometer determines the position of TM1 relative to TM2.

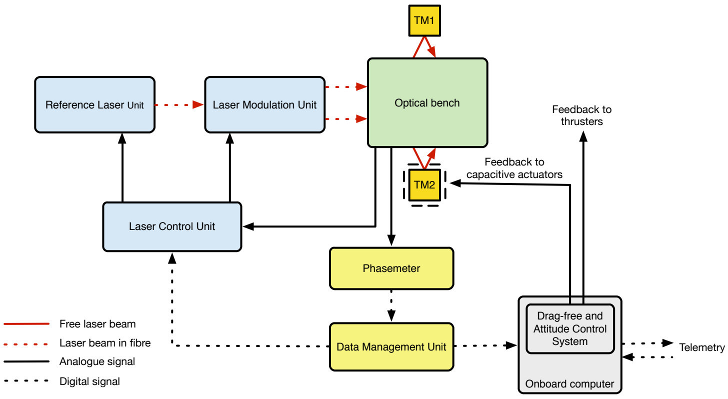

Figure 1. A basic block diagram showing subsystems of the optical metrology system in the blue, green, and yellow boxes. The gray boxes show how the signals from the optical metrology system are used as inputs for the Drag-Free and Attitude Control System (DFACS) to maintain the suspended condition of test mass two, and the drag-free condition of test mass one. Image taken from [2].

- The frequency (Freq.) interferometer has a deliberate pathlength mismatch between the two interfering beams, allowing measurement of laser frequency noise. The processed output from the frequency interometer is the input to the nested frequency control loop. This loop suppresses laser frequency noise by acting on the laser crystal piezo actuator and the crystal temperature, and is described in more detail in the corresponding proceeding [3].
- The two beams of the reference interferometer (Ref.) traverse paths of equal length, and are confined to the optical bench. The processed signal from this interferometer is subtracted from the other interferometer outputs to remove common-mode noise. The processed phase output from the reference interferometer also acts as the input for the Optical Pathlength Difference (OPD) control loop. The signal is fed back to piezo actuators in the Laser Modulation Unit (LMU) to adjust the relative length of the measurement and reference beams to counteract fluctuations in the pathlengths due to environmental disturbances that occur before they reach the stable optical bench. This control loop is described in more detail in [4].

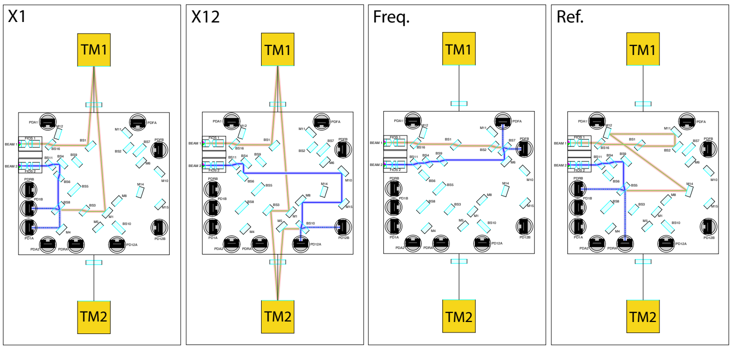

Figure 2. Optical diagrams showing the beampaths of the four interferometers on the LISA Pathfinder optical bench. The measurement beam is shown in red, and the reference beam in blue. Picture courtesy of Airbus Space and Defense and the Institute for Gravitational Research, Glasgow.

Each interferometer signal is detected by two quadrant photodiodes, one nominal and one redundant. The output signals from the individual quadrants are the inputs to the phasemeter. In the phasemeter, each input is converted to a voltage via a trans-impedance amplifier, then low-pass filtered, digitised, and scaled. A single-bin discrete Fourier transform is performed at the heterodyne frequency, giving the real and imaginary components of the complex amplitude. The total power per quadrant is also calculated. These three products are passed from the OMS to the Data Management Unit (DMU), where they are processed, nominally using the mean of the nominal and redundant photodiode channels, to give the main OMS outputs in the form of telemetry. These outputs include the longitudinal fluctuations of TM1, and of TM1 relative to TM2, the angular fluctuations of TM1 and TM2, and the contrast of each photodiode.

In order to measure the power on the optical bench, a beamsplitter splits off a fraction of each beam directly after the fibre injectors. This is then read out by a single element photodiode, one each for the measurement and reference beams. This signal also provides the input for the laser power control loop. This loop was designed as a nested loop, with two 'fast' analogue loops that take the signal from each of the photodiodes to the corresponding AOM to change the amount of light that passes through, and a 'slow' loop, which uses an average of the two signals, calculated in the DMU, to feedback to the RLU and directly control the DC output of the laser. During ground-based test campaigns, and in-flight, the decision was made to use only the 'fast' loops, as the 'slow' control loop did not function as required [2].

3. Laser Monitoring during operations

In flight, housekeeping telemetry from the OMS subsystems is downloaded from the satellite. This telemetry is monitored regularly in order to:

- check system health and functionality
- monitor system performance, and any changes throughout the mission
- identify noise sources, particularly those that might impact the differential acceleration measurement
- provide information that may be useful when considering the LISA design

Responsibility for the monitoring activities is allocated according to the country that provided each unit, along with support from industry. As such, the monitoring for the laser subsystem falls to the Max Planck Institute for Gravitational Physics (AEI), Hannover.

Housekeeping telemetry for the laser subsystems includes the laser power and temperature inside the RLU, currents and voltages of the RLU and the laser electronics, the laser power measured on the optical bench, as well as error flags. The telemetry is downloaded monthly, and a report produced which is available to the full collaboration. This report includes:

- the mean, maximum, and minimum values
- a time series plot
- the trend of the data over the month
- a power spectral density along with a reference, if appropriate
- alerts if the parameter crosses into predefined warning or critical regions

Alerts and anomalies are investigated and reported to Mission Operations Control. A technical note is produced each month to summarise the performance and show the longer term behaviour.

4. Conclusions

A huge amount of data relating to the laser subsystems are available, and analyses are ongoing to extract the maximum amount of useful information. These include and are not limited to:

- laser stability during each of the acceleration measurement investigations
- the laser power stability with temperature
- differences in noise levels between different operational periods
- investigations into the spikes seen in the power control loop signals

Acknowledgments

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