

Laser Frequency Noise Stabilisation and Interferometer Path Length Differences on LISA Pathfinder

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Abstract. The LISA Pathfinder mission is a technology demonstrator for a LISA-like gravitational wave observatory in space. Its first results already exceed the expectations. This is also true for the optical metrology system which measures the distance in between the two free-floating test masses with unprecedented precision. One noise source that can possibly affect the measurement is the laser frequency noise. It is measured with a dedicated interferometer and suppressed with a control loop. We measured the laser frequency noise and characterised the control loop in flight. The coupling of laser frequency noise into the measured phase is directly proportional to the path length difference in the respective interferometer. Dedicated experiments have been performed to estimate the path length difference in flight. In addition, this frequency stabilisation scheme is also a possible solution for the LISA mission.

1. Introduction

On LISA Pathfinder, key technologies for the LISA mission are being tested. One of them is the optical metrology system (OMS).

From this point of view, LISA Pathfinder is a unique optics laboratory in space. It experiences only extremely low temperature gradients and mechanical vibrations. In addition, the free-floating test masses produce an outstanding alignment. For more information on the OMS, we refer to the corresponding proceedings article [1].

Our aim is to understand as good as possible the factors that result in the current measured OMS noise level. This means we account for all known effects to find the fundamental limits. This knowledge is essential for the future development of interferometers for LISA and other space missions.

One possible noise contribution which has been known for a long time is the laser frequency noise. In general, laser frequency noise, δf , produces a phase noise, $\delta\phi$, in an interferometer if the light in the measurement beam does not travel exactly the same distance as in the reference beam. The difference of these two lengths is called a path length difference or an arm length mismatch, denoted Δs . This relation is summarised in Equation 1[2]:

$$\delta\phi = 2\pi \frac{\Delta s}{c} \delta f. \quad (1)$$



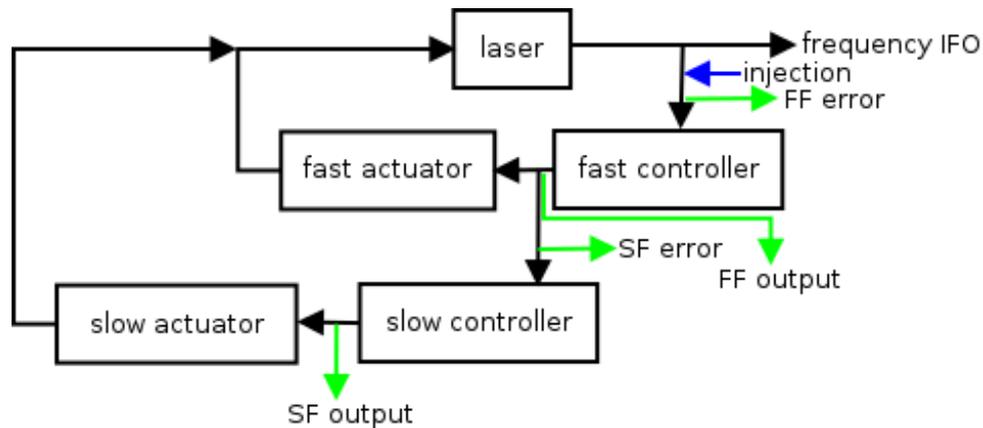


Figure 1. A simplified diagram of the laser frequency control loop. The quantities with the green arrows are housekeeping data channels and the frequency interferometer is a science data channel. The injected signal (blue arrow) cannot be downloaded.

In a real interferometer, the path length difference is never exactly zero. This is also the case on LISA Pathfinder. Equation 1 is valid for all four interferometers and this phase noise contribution cannot be distinguished from any other phase signal and directly affects the measurement. To minimise this undesired noise, there are two approaches, which are both used on LISA Pathfinder. We try to stabilise the laser frequency with a dedicated control loop to minimise the laser frequency noise, δf , and the utmost care was taken during the construction and integration of the satellite to have minimal path length differences, Δs .

Accordingly, the measured value for Δs provides a way to check the integration quality. In addition this number is required to estimate the contribution of laser frequency noise to the total noise in the differential measurement. Details will be given in Section 3.

The frequency noise measurements on LISA Pathfinder, and the performance of the stabilisation scheme, are especially interesting because a similar approach is being discussed for LISA. Other possibilities are the arm-locking technique [3] and the use of a cavity.

2. Laser Frequency Noise Stabilisation

In LISA Pathfinder, the laser frequency noise is measured by a dedicated interferometer on the highly stable optical bench. Its most important characteristic is the intentional path length difference of 0.382 m [4]. It occurs in the fibres between the laser modulator unit and the optical bench. On the optical bench itself, the path of the two beams in the frequency interferometer is equally long. Following Equation 1, the intentional path length mismatch amplifies the frequency noise.

The measurement of the frequency interferometer is the input to the frequency stabilisation control loop, as shown in Figure 1. This measurement has already the measurement from the reference interferometer subtracted, which we will assume implicitly in the remainder of the article. The frequency control loop is implemented digitally in the data management unit (DMU) and operates at 100 Hz. As shown in Figure 1, it is a nested loop containing both a fast frequency controller and actuator and a slow frequency controller and actuator. Both controllers are infinite impulse response filters. The nominal filter equations for the fast frequency controller are $y_i = -1.58 \cdot (\Delta x + \delta x_i - x_i) + 1 \cdot y_{i-1}$ and for the slow frequency controller $y_i = -5 \cdot 10^{-5} \cdot (\Delta x + \delta x_i - x_i) + 1 \cdot y_{i-1}$. In the filter equations, y_i is a selected sample of the controller output. This value depends on any commanded constant offsets Δx as well as on the value of a possible time-varying probing function, denoted as δx , and on the current input

value, x_i , and previous output value, y_{i-1} . The fast frequency actuator is a piezo which acts on the laser crystal and the slow frequency actuator is a heater [5]. In Figure 1, all loop channel quantities that can be downloaded are marked with the channel names. We also marked the point of the injection with a blue arrow even though this channel cannot be downloaded. All internal measurements are only available at 1 Hz for most of the time, but the measurement of the frequency noise is provided at 10 Hz during most of our dedicated OMS experiments. These data rates are a function of the design of the DMU. In the DMU, data is treated differently depending on whether it is part of the so-called ‘science data’, as is, for example, the frequency noise measurement, or whether it is part of the so-called ‘housekeeping data’, as are all the loop parameters [6]. The DMU offers a special feature to deviate from this procedure which is called the interferometer data log (IDL). This allows us to collect data at 100 Hz from nominal science or housekeeping channels. This is only possible for very limited durations, of the order of minutes.

The aforementioned control loop has been characterised in flight during dedicated experiments. The aim was to ensure that the loop performs as expected. In these experiments, a sinusoidal probing function was injected at the point marked by the blue arrow in Figure 1 into the fast frequency controller error signal. The selected amplitude was 0.05 rad and eight frequencies from 0.011 Hz to 1.123 Hz were chosen. Each sinusoid lasted for 20 cycles at the respective frequency. For frequencies above 0.5 Hz, the IDL was used to record the data. Moreover, open-loop and closed-loop measurements of the laser frequency noise have been undertaken. During the nominal LPF mission, the frequency noise is downloaded at 1 Hz for most of the time to minimise the telemetry load. Thus, the long term monitoring can only be done with this data.

3. Measurements of Interferometer Pathlength Differences

As mentioned in the introduction, interferometer path length differences or arm length mismatches occur in all realistic interferometers. On LISA Pathfinder, this means they are present in all of the four interferometers. In the frequency interferometer, the path length difference is known to some accuracy. In the differential interferometer, X12, and in the spacecraft interferometer, X1, the path length difference depends on the absolute position of one or both test masses.

We can measure the arm length mismatch in the interferometers X1, X12 and Ψ_R from the coupling of laser frequency noise into the respective interferometer. Indeed, as we measure, δf , we can solve Equation 1 for Δs and calculate it. The path length difference is measured best when we amplify the frequency noise at known frequencies. To this end, we use sinusoidal injections similar to the loop characterisation experiment but at frequencies of 1.123 Hz and 2.879 Hz. The signals are injected for approximately half an hour each to improve the signal-to-noise-ratio. In the first version of the arm length mismatch experiment, the aforementioned signals have been injected two times. During the first set of injections, the reference test mass was at its nominal position and during the second set of injections, the same test mass was offset by approximately 9.5 μm . This allows us to check the two measurements for consistency and to get the sign of the mismatch. In the arm length mismatch experiment, these two sets of two injections each are followed by an open-loop measurement of the laser frequency noise at the original position of the reference test mass. From the increased noise, we can estimate again the arm length mismatch but with larger errors. The strategy of this experiment is summarised in Figure 2. The experiment was successfully executed on June 14th 2016. The arm length mismatch can be estimated best with this dedicated experiment.

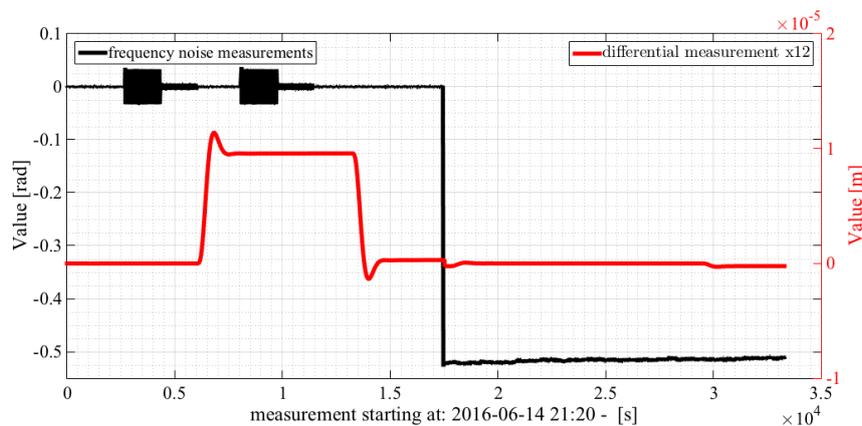


Figure 2. The concept of the arm length mismatch experiment. The black trace (corresponding to the left y -axis) shows the laser frequency noise measurement. The two sets of two injections are clearly discernible. The DC value of the signal is at a lower level during the open-loop measurement. The distance between the two test masses is shown in red (refer to right y -axis). The second set of modulations is taking place at the offset position. Some transients are discernible.

4. Conclusion

On LISA Pathfinder, there is a dedicated interferometer to measure the laser frequency noise. This signal is used by a digital nested control loop which stabilises the laser frequency. A similar scheme is also being discussed for LISA. The interferometer path length differences on LISA Pathfinder are measured with a dedicated experiment which was successfully executed on June 14th 2016. Analysis of this experiment and the control loop characterisation is ongoing and the results will be reported in a future publication.

5. Acknowledgements

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