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Coupling of relative intensity noise and pathlength noise to the length measurement in the optical metrology system of LISA Pathfinder

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Abstract. LISA Pathfinder is a technology demonstration mission for the space-based gravitational wave observatory, LISA. It demonstrated that the performance requirements for the interferometric measurement of two test masses in free fall can be met. An important part of the data analysis is to identify the limiting noise sources.[1] This measurement is performed with heterodyne interferometry. The performance of this optical metrology system (OMS) at high frequencies is limited by sensing noise. One such noise source is Relative Intensity Noise (RIN). RIN is a property of the laser, and the photodiode current generated by the interferometer signal contains frequency dependant RIN. From this electric signal the phasemeter calculates the phase change and laser power, and the coupling of RIN into the measurement signal depends on the noise frequency. RIN at DC, at the heterodyne frequency and at two times the heterodyne frequency couples into the phase. Another important noise at high frequencies is path length noise. To reduce the impact this noise is suppressed with a control loop. Path length noise not suppressed will couple directly into the length measurement. The subtraction techniques of both noise sources depend on the phase difference between the reference signal and the measurement signal, and thus on the test mass position. During normal operations we position the test mass at the interferometric zero, which is optimal for noise subtraction purposes. This paper will show results from an in-flight experiment where the test mass position was changed to make the position dependant noise visible.

1. Introduction

In the first mission studies and noise projections Relative Intensity Noise did not play a major role, and many steps were taken to suppress the other noise sources researched. This was very successful, which is why Relative Intensity Noise was found to be one of the limiting noise sources at higher frequencies. RIN is a property of the laser, and these intensity fluctuations are frequency dependant. The impact of this noise source is reduced with different methods, RIN couples to the measurement signal in three ways.

RIN at low frequencies couples directly into the phase measurement, but this contribution is so low that it can be disregarded.

RIN at the heterodyne frequency, ω_{het} , is suppressed with the fast amplitude control loop, and subtracted with balanced detection.

RIN at two times the heterodyne frequency also couples, and the impact of this noise is also suppressed with the fast amplitude control loop.



But balanced detection does not suppress this noise. When the Drag Free Attitude Control system (DFACS) transitions from Inertial Sensor control to OMS control we have two choices for the setpoint of the test mass: Stay at the position the test mass currently has, and use this as setpoint. For each transition the offset is different, but this reduces the transition time between DFACS settings. Alternatively we can move the test mass so that the phase difference between the measurement signal and reference signal is always the same. This increases the transition time depending on the TM position at the beginning, but it has the advantage that the measurement is more reproducible. Zero phase difference between the two signals was chosen since this subtracts RIN from the measurement signal.

In the following we will give a short overview of the coupling mechanism, and of the experiment that was performed to explore the noise at higher frequencies for different test mass positions in preparation for the LISA mission. [2]

2. Relative Intensity Noise

The phase measurement is performed with heterodyne interferometry, the interferometer is bonded on a Zerodur baseplate and sits at the heart of the system in between the test masses. The photodiode current generated by the interferometer signal also contains RIN. From the electric signal the phasemeter calculates the phase change, and thus the motion of the test masses, as well as the DC laser power.

We add a noise term to the laser signal on the photodiode, and calculate the normalised photodiode signal $y_{A/B}(t)$:

$$y_{A/B}(t) = (1 + r(t)) (1 \pm c \cos(\omega_{\text{het}} t - \varphi)),$$

where $r(t)$ is a frequency dependant noise term, and the noise is small compared to the total power, $r(t) \ll 1$. The coupling of RIN into the phase measurement signal depends on frequency. The contribution can be derived analytically, the relevant noise frequencies are the following:

RIN at DC is pure amplitude noise, and to first order this noise does not couple into the phase.

RIN at the heterodyne frequency is near the same frequency as our signal, and ends up in the same phasemeter bin. Since this bin covers only a small frequency band around the heterodyne frequency, RIN couples as a white noise into the phase measurement. Per interferometer we use two photodiodes. These two signals are subtracted from each other to create the interferometer signal. This subtraction is called balanced detection since we use the symmetric and antisymmetric port of the beam splitter to remove noise sources common to both signals.

For RIN at two times the heterodyne frequency the situation is different. It also couples into the phase measurement, but the coupling to the phase has a sign difference between the two ports. When the two photodiode signals are now subtracted this noise is not removed from the interferometer signal, and therefore is still present in the phase measurement. The same noise is also present in the reference interferometer signal. This interferometer has the same path length difference as the measurement interferometers, and also uses balanced detection. The signal is not only used as an error point for the optical path length difference control loop (OPD loop), but also to subtract remaining noise from the other signals. RIN at $2\omega_{\text{het}}$ is one of the noise sources that is subtracted with the reference signal. For normal operations this subtraction works very well. If the test mass is removed from its nominal position this subtraction does not work properly, and some amount of RIN remains and leads to an increase in noise at higher frequencies. One example where the test mass is moved many nanometers is the free fall experiments, a description of these experiments can be found in "The free-fall mode experiment on LISA Pathfinder: first results" in this issue.

3. In-flight experiment

To understand the coupling, and the level at which the noise is increased for different test mass positions, we moved Test Mass 2 to various offsets and measured the noise. This measurement showed the position dependency of this high frequency noise, and confirms the model derived mathematically from a calculation of the phase with RIN present at different frequencies.

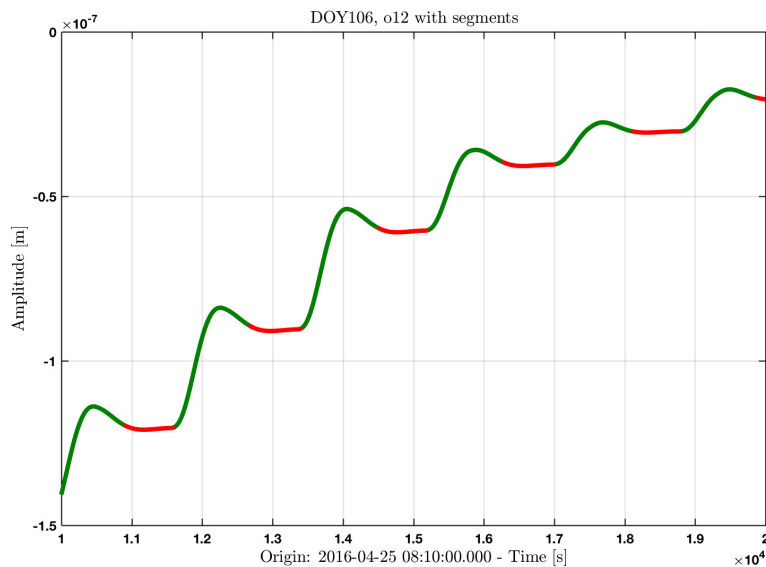


Figure 1. The test mass is moved in steps, at every position a noise measurement is performed. This plot shows a short segment of a longer experiment, marked are the timespans where the test mass is stable enough to calculate a noise level.

For the analysis of these steps the timespans of each step where the test mass was stable was cut into smaller parts, for each part the spectrum was calculated. From these many parts the spectra with glitches are removed, and then the average of all of these are used as a mean noise level from this step. The distribution of the noise levels are used for the error calculation.

From this noise over position measurement a fit is made with different models to combine the RIN to other measurement noise sources, and to calculate the amount of RIN present in the system for specific test mass positions. Other noise sources of interest in this frequency range are cross coupling from the angular degrees of freedom, and the noise floor consisting of ADC quantisation noise, electronic noise and shot noise.

For the mission extension an additional experiment is planned to explore not only the contribution of RIN from $2\omega_{\text{het}}$, but also the noise behaviour with RIN at $1\omega_{\text{het}}$ and $2\omega_{\text{het}}$ present at the same time. This is accomplished by turning one phasemeter side off and therefore removing balanced detection.

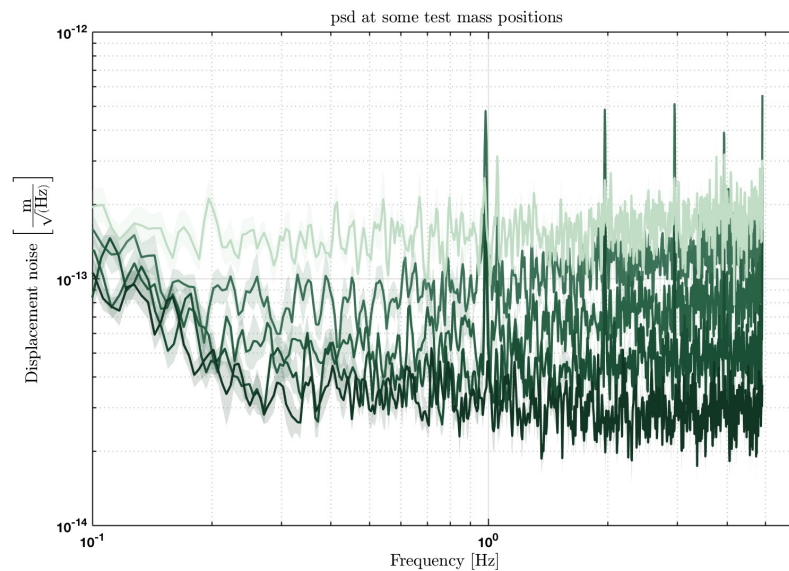


Figure 2. This is the high frequency spectrum for a few steps, the difference in the noise level is visible. For each step an average noise level is calculated, and plotted over the mean test mass position. We use a BH window with 50% overlap,

4. Acknowledgments

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5. References

- [1] Armano M *et al.* 2016 *Physical Review L* **116** 231101
- [2] Danzmann K *et al.* 2017 *A proposal in response to the ESA call for L3 mission concepts* URL <https://www.lisamission.org/proposal/LISA.pdf>