Development and Preliminary Testing for the LISA on Table Experiment

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Abstract

The LISA on Table, or LOT, is a Mach-Zehnder interferometer that will serve as a terrestrial prototype of the upcoming gravitational wave observatory known as LISA. The purpose of the LOT is not to make preliminary attempts at detecting gravitational waves, but rather to serve as a study in noise reduction and signal acquisition. Using acousto-optic modulators and electro-optic modulators, signals are injected into the LOT's lasers which allow us to test the signal acquisition potential of LISA. In order to improve signal acquisition and understand the kind of signal clarity to be expected for LISA, we attempt to put the LOT experiment in a vacuum. Before we do so however, we examine using a basic interferometer what kind of effect a vacuum can be expected to have on an optical interferometer and whether the LOT will actually benefit from being put into a vacuum chamber. Based upon our experiments, we can conclude that the LOT in a vacuum will see a concrete and signifigant reduction in noise over atmospheric test.

Introduction

One of the greatest success of the LISA Pathfinder mission lies in the demonstration of signal clarity. In order to detect length expansion and contraction on the requisite scale (the LIGO detection was on the order of 10e-21 meters), LISA scientists must achieve a superb isolation of the interferometer from all noise sources. While LISA pathfinder demonstrated that this could potentially be done (and indeed vastly exceeded expectations), it was only the beginning. A great number of other experiments in noise reduction and signal acquisition are currently in progress by the LISA collaboration, one of which is known as the LISA on table, or LOT. The LOT is an terrestrial model of the LISA system, designed with the dual mission of signal acquisition and noise analysis and reduction. Once development of the LOT is completed, it will be used to test whether simulated signals can be identified through the noise present in LISA-like conditions.

Unlike LISA and LIGO, the LOT is a Mach-Zehnder type interferometer, meaning that the interfering lasers form a square, with the interference happening at a seperate location from the laser sources. Along the way, the lasers are sent through acousto-optic modulators and electro-optic modulators (one of each for each beam), that allow signals to be encoded into the phase of the lasers. This is the method by which we can simulate noise sources and test our ability to isolate (simulated) gravitational wave signals from the background. Also unlike LISA, the LOT contains three piezoelectric actuators attached to mirrors on various arms. These actuators have a dual purpose of both signal encoding (simulating a strain in the arm length) and noise reduction. The output from the LOT interferometer is collected by two photo-diodes and transported to a phasemeter developed by the

Albert Einstein Institute at Hannover. This special phasemeter allows us to accurately detect minute variations in phase, as well as apply relative phase corrections using phase comparison between the two beams. With these tools, we can achieve both supreme precision in the phase detection as well as drastic reduction in phase noise to workable levels.

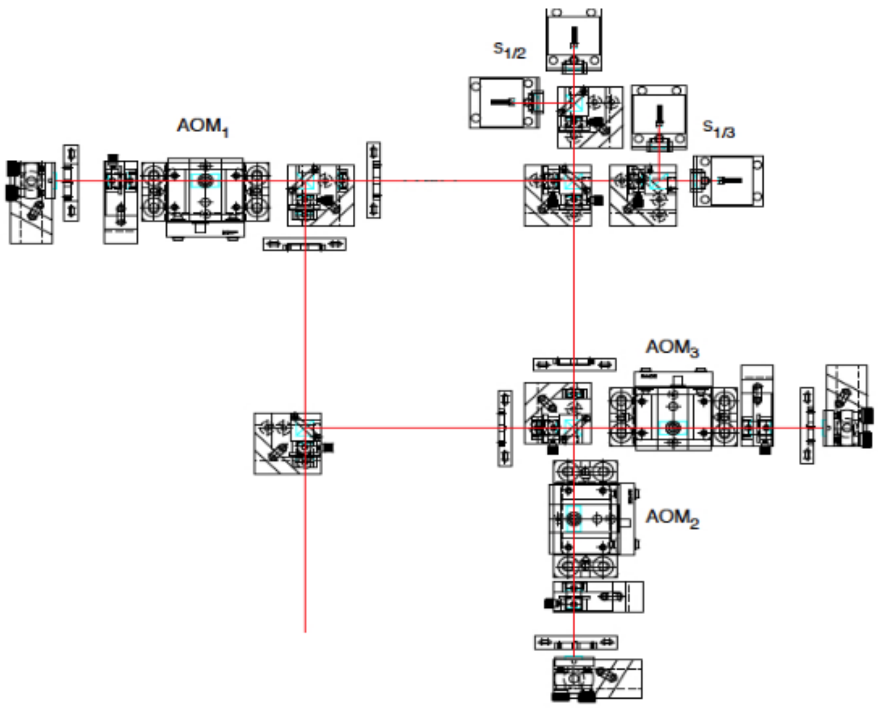

Figure 1: Pictured is a schematic of the LOT’s optical interferometer

The LOT contains an electronic interferometer counterpart to the optical interferometer. While electronic interferometers are more precise and easier to work with than their optical counterparts, they are more or less useless for the purposes of gravitational wave interferometry since they aren't sensitive to perturbations in space. However, since we aren't concerned with actual gravitational wave signals with the LOT, an electronic interferometer provides a good source of comparison for the results of the

LISA on Table's optical interferometer. Like the optical interferometer, the LOT's electronic component signals are sent through the AOMs so that we can simulate noise sources and potential signals. By comparing the electronic output against the optical, we can see directly how effective our noise reduction techniques have been, how far we have to go, and accumulate good information as to which noise structures in the data are environmental (air flow, seismic activity, etc.) and which are instrumental (most notably, the phasemeter).

With construction of the LOT completed, the next phase in the LISA proto-type experiment is to search for ways to reduce noise as well as development a better simulation of the conditions that LISA will experience in space. To that end, we turn to putting the LOT in a vacuum chamber.

Methods

The first step in the process of putting the LOT into vacuum was to ensure the integrity of the phasemeter. If we are to be confident in the data produced by the LOT, we must have confidence in the measuring devices that produce that data, so it was necessary to test the phasemeter to confirm functionality. To this effect, we set up a function generator to produce two sinusoidal signals, one at approximately 7.5 MHz and one at 8.5 MHz. Each signal was split four ways and paired with one of the other types using a signal combiner. Additionally, we set up a clock reference at 55,555 kHz that we fed directly into the phasemeter. This configuration allowed us to have four identical signals input into the four channels of the phasemeter that we would use for the LOT. In this way, we could compare the channel outputs to one another and note any discrepancies that could be attributed to a flaw in the phasemeter. Additionally, we took the opportunity to test a phase noise correction algorithm that utilized the relative phase of the two interfering beams.

This test did not go as planned, however, as there was a recurring glitch (a frequency spike) that was ruining the data. We attempted to find the source of the glitch by removing certain components from the process (splitter, combiner, etc.) and checking to see if the glitch was removed as well. After a number of tests, we determined the source of the glitch was likely a screwdriver inserted through a hole in the combiners to hold them together. With the screwdriver removed, data became much cleaner and we were able to get a good picture of the functionality of the phasemeter. The results of this test are shown in figure 2.

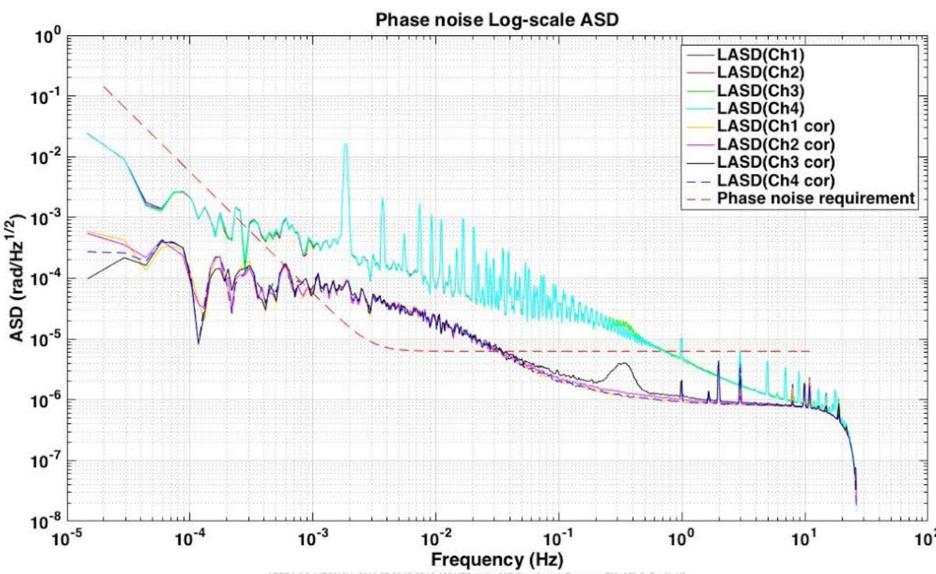

Figure 2: Plotted here are the results of the tests we ran on the phase meter channels, with the dotted line reperesenting the maximum phase noise at which LISA can operate. Of special note here is the stark reduction in phase noise using the correction algorithm. Also of note are the high frequency peaks and the bump present solely in Ch4. Fortunately they remain below the phase noise requirement, so they are not of much concern.

With the glitch resolved, we succeeded in testing the four channels and determined they all behaved exactly as expected (except for a small bump in one channel at high frequency that remained under the noise requirement). Next, we moved on to testing the vacuum chamber. We were eager to see if the phase noise level of the LOT could be reduced by introducing a sealed vacuum environment. Before we did that however, we needed to have some idea of what effect the vacuum chamber has on a basic interferometer. So, in order to find out, we built a small interferometer in the chamber. This test interferometer was an extremely basic Mach-Zehnder interferometer, with a long arm and a small arm. The test interferometer also included two AOMs, one for each arm, however no signal was encoded into them. The AOMs were put in place to test their functionality in the vacuum chamber (ensuring they didn't over heat or in some way break), and to reduce the possibility of unexpected issues when switching to the LOT.

We first did a basic experiment on the test interferometer by hooking up the output to the phasemeter. Unfortunately, the phasemeter had an immense amount of trouble locking onto the signal in one of the arms. At first we theorized that this was due to over saturation of photo-diode, but adding optical densities didn't seem to help. Next we considered the possibility that the issue could be due to a diameter mismatch in the two interfering signals. To solve this, we added in a lens to condense the larger laser. While this improved signal readout as seen on an oscilloscope, the phasemeter would still lose the signal quite quickly (or not find it at all) once a measurement was begun. Finally, we determined that the cause of the poor acquisition must be due to a constant component in the interferometer output that was confusing the phasemeter. We fixed this by creating a simple high-pass filter using a capacitor, which we attached to the interferometer outputs. This resolved the issue and the phasemeter no longer had trouble with signal acquisition.

Finally, we had a good idea of the interferometer's noise spectrum in open atmosphere, and were ready to test out the vacuum chamber. Our first test in this regard was simply to put the top on the vacuum and hopefully thereby filter out any noise caused by air currents or, to a lesser degree, ambient light. Upon analysis of the noise spectrum from this test, we did notice a slight improvement over the open-top spectrum. Next we activated the vacuum chamber and preformed another test. Again, there was a slight improvement over the top-on and open-top results, but much less than we had hoped. In an attempt to find a reason for this reduced effectiveness, we plotted the amplitude of the signal coming from both arms of the interferometer throughout the duration of the test. These plots revealed significant variation in amplitude over the course of each of our tests, which we believed could be affecting the noise spectrum. Simply put, the laser output was unstable. We theorized that this could be due to vibrations in the fiber-optic cable that transferred the laser beam from its source on a nearby optical bench to the chamber. The cable was necessarily quite long due to the layout of the clean room, and the laser was not built to be functional in the vacuum, so our best way of solving this problem was to use the laser from the LOT instead, which would require a much shorter length of cable. With this fix in place, we noticed a stark decrease in the amplitude oscillations for all of our tests, and the noise spectrum likewise improved.

We decided to redo all of our tests (open-top, top-on, in vacuum) with the new fiber-optic set up in place. The noise level was improved across the board, however the top-on test had an unexpectedly large improvment in the noise level in the .1 Hz to 1 Hz range. At this point in the spectrum, there was a distinctive trough that brought us very close to an ideal noise level. However, this improvement was not present in the subsequent vacuum test, as one might expect. After a few more tests, we reached the conclusion that the laser needed time to stabilize after it had been turned on. The stabilization period turned out to be actually one to three days, a non-trivial period of time, but in no way an issue as the laser was perfectly fitted to be left on for days at a time. Still, even once the laser had time to stabalize, we were not able to reach quite the same noise level in that region with the vacuum test. The results of all of the experiments with the test interferometer are shown in figure 3.

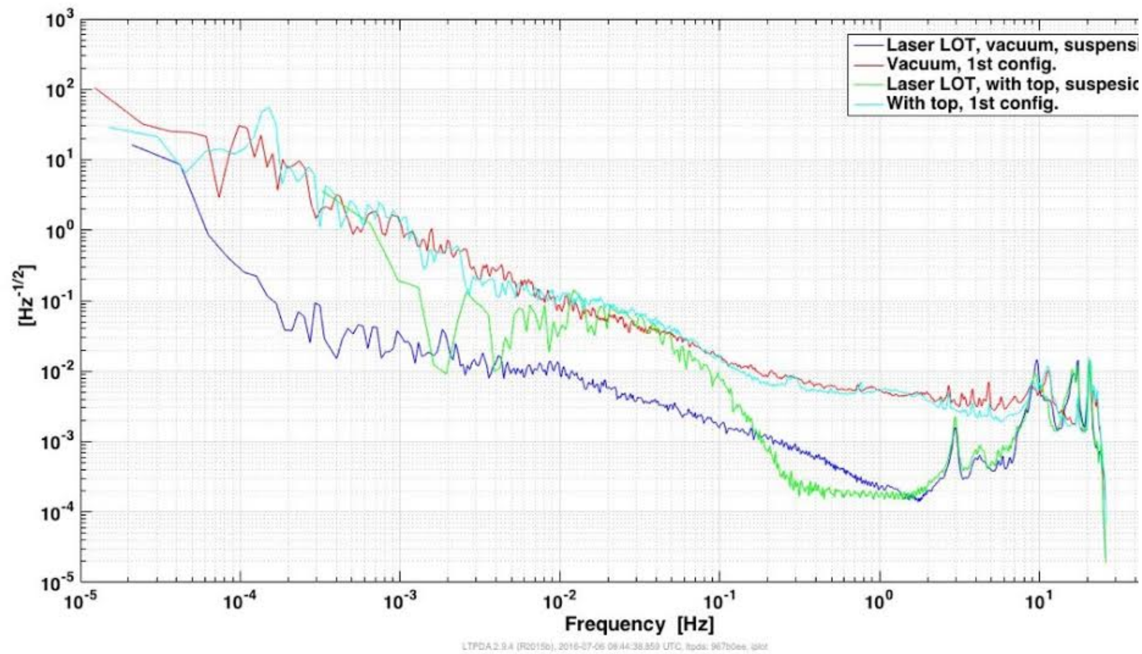

Figure 3: Plotted are the results of the test interferometer with the vacuum top on and with the vacuum in effect. Note the stark difference in the vacuum's effectiveness when we utalized the LOT's laser, rather than the initial configuration. The trough where the top-on experiment reached a lower noise level than the vacuum experiment remains an interesting mystery. We were never able to identify the cause or to reduce the vacuum noise to that level.

Now that we had fully tested the vacuum chamber, we had a reference for our future work with the LOT. We spent a bit of time calibrating the LOT as it had been inactive for some time, and then proceeded to do a basic open-air test. The results came back as expected, with a large amount of noise present in the interferometer output. We put a basic wooden cover over the lot and tried again, but saw little improvement with the new readings, as expected. While uneventful, these tests were a vital prerequisite for transferring the LOT into the vacuum chamber. One of the main purposes of moving the

LOT to vacuum is to see the effect that the vacuum would have on the interferometer itself as well as the noise level. We could not do this without an accurate reference to compare future results against.

Our first major noise reduction technique for the LOT was the introduction of piezoelectric actuators. piezoelectrics are extremely useful instruments that allow variations on atomic scales. They are simply chunks of material with an appropriately arranged atomic latices such that a potential difference is created in the a material when exposed to mechanical stress. Inversely, one can apply a voltage across a piezoelectric device in order to create a mechanical strain, resulting in expansion of the material. Piezoelectric actuators vary in fluctuation scale, typically 10e-8 meters, and expand and contract based on the potential difference across their terminals. To this effect, you can input a varying signal into such an actuator and be able to accurately predict the displacement. For the LOT, we implemented three piezoelectric actuators; one was given a 22 kHz sinusoidal input which created a modulated signal in the interferometer, and the other two were then tasked with correcting the modulation. The modulating signal was designed to keep the interferometer output on a dark fringe. With the modulation piezoelectric actuator in place, the output from both photo-diodes was split. Half of the signal was sent to the phasemeter for plotting, while the other half was input into a demodulator. The offset from the dark fringe was then deconstructed, amplified, and then funneled back into the corresponding correction piezo. In this way, not only was the phase noise from the modulation piezo corrected, but additional low-frequency noise that contributed to the dark-fringe offset as well.

With our piezoelectric actuators set up, we had a choice as to what to set for the demodulator's time constant. The time constant governs the elasticity of the demodulator's output signal (sent to the correction piezos) in relation to the input signal (from the photo-diodes). A short time constant means that the correcting piezos will be very reactive to rapid changes in the photo-diode signal, which corresponds to high frequency noise sources, such as seismic activity. On the other hand, a long time constant would orient the piezos more towards correcting low frequency noises sources, such as those caused by day/night temperature variations. For our time constant values, we tried 300 μs, 1s, 10s and 30s. We noticed the greatest reduction in noise with a 1s time constant, which makes sense as the piezos on the LOT are intended mostly as correctors for low frequency thermal noise. Additionally, it is important to note that while the 300 μs does in theory correct for very high frequency noise sources, such frequencies are well beyond our focus in the LOT experiment. The results of the tests with the piezoelectrics are shown in figure 4.

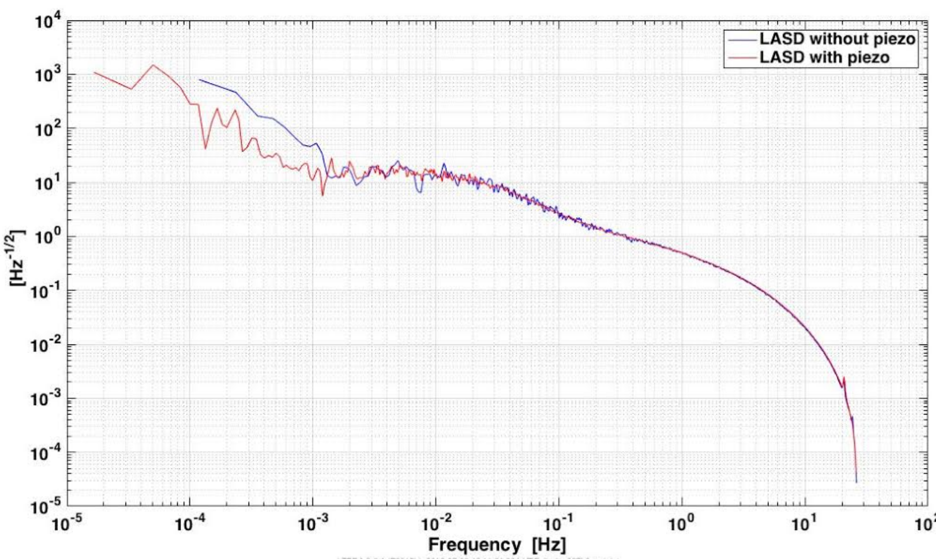

Figure 4: Shown are the results of the phase noise analysis of the LISA with piezoelectric actuators and without. Note the improvement in phase noise at low frequency. We suspect that we will see a more derastic improvement once the piezoelectrics are applied within the vacuum.

At this point it is important to note that LISA itself will not contain piezoelectric actuators. They are used in the LOT for the purposes of noise reduction as well as signal encoding, the former of which is unsafe for use in LISA and the latter is irrelevant to LISA's mission. Since the piezoelectric actuators correct for small variations in space, if they were used in LISA they could very possibly compensate for a gravitational wave signal perturbing the interferometer arms. Needless to say, this would defeat the purpose of creating LISA at all, so they are not included.

With all of the groundwork finally laid, our last task was to actually move the LOT into the vacuum chamber. While at first this may seem a relatively straightforward task, the sensitivity of the optical instruments in the LOT required some extra considerations. The LOT requires extremely precise tuning in order to function properly, and it can be quite difficult to get it back to a workable state after it has fallen out of tune. Additionally, many of the components that make up the LOT are very fragile and could easily break if the right precautions are not taken. For both of these reasons, we needed move the LOT as smoothly as possible to avoid too much jostling that might harm the integrity of the experiment. Additionally, we feared that lifting the LOT with a crane tethered to hard points at each corner of the optical bench on which the LOT is built, as we had originally planned, would cause the bench to bend minutely, which would throw the instruments out of tune. Simply carrying it with our hands was also out of the questions, as the bench was way to heavy to move safely. Eventually, we decided to slide the LOT over a makeshift bridge of tables to a location where it could be reached by an overhead crane. Then, we lifted the LOT up by hand high enough to slide under it a metal frame to which we could tether the crane. We believed that the frame would provide enough support to the optical bench to prevent bending. Then, we would lift the LOT with the crane and lower it gently into the vacuum chamber. Unfortunately, our fears proved to be well founded as in the process of setting the LOT onto the frame, we had to drop the optical bench about two centimeters to prevent injury to our fingers. Small though it was, this drop was enough to separate a mirror from one of the piezoelectric actuators as well as send the rest of the instruments out of tune. We found that when we turned the LOT on in the vacuum chamber, there was no way to take a usable measurement without repairs and extensive retuning. At this point however, we were out of time and our work was concluded.

Results and Further Study

One of the main objectives in our two month period of work on the LOT and test interferometer in the vacuum chamber was to determine whether the noise levels of the LOT may be benefited by use of a vacuum. Based on our results from the test interferometer, we can see a clear decrease in noise when both the vacuum lid and the vacuum itself were applied. From this, we can conclude with good certainty that when we study the LOT in the vacuum, we will see noise reduction as well. Although we expect, due to the advanced nature of the optical set up of the LOT as opposed to the relatively simple test interferometer, that LOT will see a greater reduction in noise than was observed with the test interferometer, there will be no way to know for sure without actually doing the tests.

Additionally, we now have good confidence in the accuracy of the phase meter, as well as a base noise level for the LOT in atmosphere. The next steps in the development and implementation of the LOT will be to go through the same tests on the LOT as those that we did with the test interferometer, specifically a noise analysis with the vacuum lid on and another with the vacuum in effect. We can then directly observe the degree of effect that a vacuum will have on a LISA-like interferometer, and thereby extrapolate to how the vacuum of space will affect the LISA itself. From there, further tests can be done utilizing piezoelectric actuators and seismic dampeners for further noise study and reduction. The reduced noise will be a great help when the LOT is finally ready for its intended purpose of testing simulated gravitational wave signal isolation and acquisition. From there, we will finally start to get a good picture of how successful LISA may be.

References

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