Chapter 7

Summary and Future Directions

Although LISA will not be launched for several years it is imperative to conduct laboratory demonstrations of key mission technologies. This is both to confirm the ability to conduct the LISA mission as well as to develop the technology for ground verification of LISA flight hardware. This verification will mitigate the risk of the hardware not performing according to the requirements to perform the required tasks, such as the measurement of gravitational waves, when LISA is launched.

In this chapter we summarize the key elements of each of the proceeding chapters (Chapters 3–6) and the results presented within. At the conclusion of this chapter we make suggestions on directions for future research.

7.1 Phase Measurement

A large portion of our research has focused on the phase measurement of the LISA fringe signal. The LISA fringe signal contains the gravitational wave information and therefore measurement of the fringe is one of the most important LISA technologies to be demonstrated. In Chapter 3 we demonstrated a method for measuring the phase of a signal. This method is the zero-crossing technique, sometimes referred to as counting-and-timing or the stopwatch method. In this technique we measure the phase of the input signal by comparing the times of its zero-crossings with a fiducial clock. Between clock ticks we count the number of zero-crossings to estimate the frequency of the signal. This is a widely used technique, not only to measure the phase, but also the frequency of a signal to high precision.

We have demonstrated that the zero-crossing phasemeter has a noise floor which depends both on the timing accuracy of the stopwatch as well as the frequency of the signal. This is indicative of the accuracy with which the zero-crossing phasemeter measures a fractional cycle of the input signal. Using electronic signals from our frequency synthesizers we have investigated signals of various amplitudes (see Figure 3.8), ranging in frequency from 20 Hz to 20 MHz (see Figure 3.9), with a linear frequency sweep rate of 1 Hz/s (see Figure 3.10), with various linear frequency sweep rates (see Figure 3.11), and with a sinusoidally modulated frequency (see Figure 3.13). We also have investigated the effects of stepping the local oscillator during the data taking process (see §3.3.2), the effects due to the bandwidth of this stepping (see Figure 3.12), and the effect of sweeping the local oscillator in order to track the sweeping signal and keep the intermediate frequency constant (see §3.4.6).

Most of our electronic signals easily satisfied the LISA requirement of 5 μcycles/$\sqrt{\text{Hz}}$ between 1 mHz and 1 Hz, rising no faster than $f^{-1/2}$ below 1 mHz. We found that the signal amplitude should be above -10 dBm, the frequency should be below about 1 MHz, and that the sweep rate should not be too high (1 kHz/s is manageable). The bandwidth of the phasemeter is limited by the fractional-cycle timing accuracy and is 1 MHz.

7.2 LISA Testbed Interferometer

Since the success of the LISA phase measurement depends critically on the character of the LISA fringe signal, we have conducted research into the realistic simulation of that signal. This has involved designing and constructing a table-top interferometer which produces an optical signal with the three key aspects of the LISA fringe signal: (1) a baseband fringe frequency ranging from 50 kHz to 20 MHz, (2) a fringe frequency sweep rate of 1 Hz/s, and (3) a small signal level resulting from the heterodyning of a 100 pW laser beam and a 0.5 mW laser beam. In Chapter 4 we reported on the design, implementation, and results from this interferometer.

Using the zero-crossing phasemeter described in Chapter 3 we have demonstrated that our testbed interferometer can produce LISA-like fringes below the LISA phase noise requirement. These signals range in frequency from 50 kHz to 20 MHz, sweep at a rate of 1 Hz/s, and are created by heterodyning a 100 pW laser beam with a 0.5 mW laser beam. The results of these measurements are shown in Figures 4.14 and 4.15. Also we have demonstrated the ability to track the sweeping frequency with the local oscillator to produce a constant frequency signal input for the phasemeter (see §4.3.5).

7.3 Sciencecraft Intercommunication

Our table-top interferometer is an excellent testbed for different phase measurement methodologies as well as for the investigation of other LISA interferometric techniques, such as sciencecraft intercommunication. We have modified out testbed interferometer with the goal of demonstrating laser communication on the LISA laser beam. This has involved inserting an electro-optic crystal to use as a phase modulator of the laser beam in the dim arm of our interferometer. This represents the data modulation on the incoming laser beam to one of the LISA sciencecraft. In Chapter 5 we presented the design, implementation, and results from our intercommunication-modified interferometer.

We phase modulated a 30 MHz signal onto the laser beam with a modulation depth of a few percent. When operating at low fringe frequencies, such as 50 kHz, we could use a bandpass filter on the output of our science photoreceiver to extract the data modulation. For higher fringe frequencies we required the use of a separate photoreceiver for the demodulation process as described in §5.1.2. The data presented in Chapter 5 come from the latter setup since it was the most versatile.

Aside from improvements made to our interferometer (namely the addition of acoustically damping foam on the interior of our optical cover) the phase noise level of the fringe signal remains unchanged by the laser communication modifications (see Figures 5.6 and 5.7).

For the modulation of audio data onto the laser beam, the demodulated signal was sent to a speaker where the audio was heard quite readily. The phase noise level of the 30 MHz modulation was measured to be about 10 μcycles/$\sqrt{\text{Hz}}$, a factor of 10 below the LISA requirement for the ultra-stable clock oscillator (USO) phase measurement noise (see Figure 5.8).

Modulating the 30 MHz subcarrier with a 10 kHz sidetone simulates the situation in LISA where possibly 100 kHz sidetones will be modulated onto the USO subcarrier to be used for ranging measurements. The phase noise level of this 10 kHz sidetone was found to be over a factor of 10 below the LISA requirement of 20 m for the ranging sidetones (see Figure 5.9).

Although there are several differences between our laser communication setup and the current plan for LISA (see §5.3), we have demonstrated the ability to use the LISA laser beam for communication between sciencecraft, i.e., the modulation and demodulation of data. More importantly, we have demonstrated that this modulation does not affect the LISA science fringe signal in any significant manner, even when the fringe signal frequency is a factor of two away from the modulation frequency.

7.4 LISA Data Disturbances

In Chapter 6 we presented a simple algorithm which identifies and removes monochromatic signals in the presence of data disturbances in a LISA-like data stream. We examined the response of our algorithm's ability to extract a lower frequency (3 μHz) and then a higher frequency (100 μHz) signal in the presence of data disturbances in a roughly 38 day-long data set. We found that data disturbances, if properly removed, have little if any effect on the extraction of higher frequency signals from the LISA data stream (see Table 6.4). We found that our algorithm performed worse with lower frequency signals in the presence of data disturbances, as evident by the higher Δ^2 values in Table 6.2. However, our algorithm still was able to remove the disturbances and identify the signal parameters to within a few percent (see §6.4.1).

In §6.5 we examined the ability of our algorithm to identify and remove a 3 μHz signal in the presence of multiple data disturbances. We used the results of this analysis (presented in Table 6.6) to determine a limitation on the frequency of data disturbances. This information is of particular use for LISA sciencecraft operations, such as the frequency of telecommunication antenna rotations. As mentioned in §2.4.4, the high gain antenna used to transmit data to Earth will need to be rotated periodically. The analysis presented in §6.5 shows that rotating the antenna less frequently than once every 3.5 days would be acceptable based on the ability of our algorithm to identify and remove a 3 μHz signal from our LISA-like data stream.

7.5 Directions for Further Study

LISA technology development has only just begun. Although all of the LISA-related technologies seem feasible theoretically, laboratory demonstrations, using ever more realistic hardware, of these technologies are needed for assuredness and verification prior to launch approval.

The work we have completed relates to the interferometry measurement system of LISA. One of the next logical upgrades to our table-top interferometer used to simulated LISA interferometry would be to add an EO modulator to the bright arm of the interferometer. In this way we could better simulate the actual laser communication system plan of LISA. Use of a higher frequency source and gigahertz EO crystals would further improve our simulation of the sciencecraft intercommunication. Modulating the subcarrier with a hundred kilohertz ranging tone rather than a ten kilohertz ranging tone also would be beneficial in this regard.

We currently have the ability to change the armlengths by dithering the spherical mirror on the end of the dim arm of the interferometer. We can produce a change of about 10 microns with our piezo-electric device on which the mirror is mounted. If we placed the optical mount on a motorized translation stage, which had a range of several centimeters we could attempt to measure distance changes with the ranging sidetone as planned in LISA. This development of technology will be key for ground verification purposes as discussed below.

Other developmental technologies include table-top demonstrations of offset-locking and arm-locking configurations. Setups involving two or more lasers currently are underway at NASA Goddard Space Flight Center [53] and at the University of Florida [59]. All of the advancements accomplished and demonstrated by our research, such as the use of large baseband fringe frequencies, sweeping fringe frequencies at 1 Hz/s, and having power differentials in the millions between laser beams, will be applicable to and necessary to implement in these laboratory demonstrations.

Further advancements will be to fully simulate the LISA laser communication system. An important aspect of this demonstration will be to use the beats between USO subcarriers to cancel-out laser frequency noise using time delay interferometry. The technologies we have developed will be good starting points for such laboratory experiments.

7.5.1 System Verification

The technologies we have developed will be useful for the ground verification of LISA flight hardware. Verification that flight hardware meets or exceeds all requirements is necessary prior to launch approval of the LISA mission by NASA. Although verification by analysis may be acceptable, there is no substitute for physically testing the equipment. Similarly, testing of individual components, such as the research we have conducted, yields valuable information on the performance of LISA, but testing of more realistic and complete systems is always more convincing.

LISA has substantial technological challenges. In particular, the interferometry measurement system must test for picometer distance changes in a distance of 5×10^9 m. The technologies involved in LISA are fairly uncommon. Technology development, such as our work, has shown that current technologies are easily adapted to meet the LISA requirements. In addition, new testing technologies will be needed to fulfill the testing requirements of the technology development milestones. The advancements we have made with the use of acousto-optic and electro-optic modulators are developments towards these testing technologies which will be used in future ground verification of the LISA flight hardware.

The formulation of the LISA mission is now well underway. Laboratory demonstration of key technologies relevant to LISA is an on-going process and will continue until project hardware selection has been made. At this point ground testing of flight hardware suitable for LISA will commence. During this time and afterwards, future space-based gravitational wave missions may begin preformulation studies and new laboratory demonstrations of more advanced technologies may begin.