A demonstration of LISA laser communication

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Abstract
Over the past few years, questions have been raised concerning the use of laser communications links between sciencecraft to transmit phase information crucial to the reduction of laser frequency noise in the LISA science measurement. The concern is that applying medium frequency phase modulations to the laser carrier could compromise the phase stability of the LISA fringe signal. We have modified the table-top interferometer presented in Pollack and Stebbins (2006 Demonstration of the zero-crossing phasemeter with a LISA test-bed interferometer Class. Quantum Grav.) by applying phase modulations to the laser beams in order to evaluate the effects of such modulations on the LISA science fringe signal. We have demonstrated that the phase resolution of the science signal is not degraded by the presence of medium frequency phase modulations.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

There are numerous interferometric fringe signals in the LISA interferometer. Most of these fringes are created by heterodyning a local laser on one spacecraft with a remote laser located on another spacecraft. The characteristics of the received beam cause the LISA fringe to have several unique aspects. In [1], we presented a test-bed interferometer designed to produce LISA-like fringes. We captured three aspects of the LISA-like fringe: (1) a baseband fringe frequency which ranges from zero to tens of MHz, (2) the fringe sweeps at a rate up to 1 Hz s$^{-1}$, and (3) the fringe has a small signal level resulting from the heterodyning of 100 pW and 0.5 mW laser beams. We mentioned in [1] the utility of our setup to demonstrate and investigate

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other aspects of the LISA interferometry measurement system. In this paper, we discuss a plan for laser communication and demonstrate this plan with our table-top interferometer.

The three LISA sciencecraft operating in concert constitute the gravitational wave detector. The photoreceivers on each optical bench in the LISA constellation record phase information. The measurement of gravitational waves requires at least two working arms of the LISA constellation. In addition, the lasers onboard each sciencecraft must be related to each other somehow in order to make the proper phase comparisons which lead to a strain measurement. Each laser is independently stabilized to a frequency reference or to the LISA arms [2–4]. An alternative stabilization scheme is to stabilize all lasers to one master laser, and yet another is to allow the six lasers to run independently (see e.g. [5]). Regardless of the choice to stabilize or which stabilization method will be implemented, the frequency difference and noise between the lasers must be measured and cancelled out to reach the required strain sensitivity for LISA. The frequency noise correction system is based on an algorithm known as time-delay interferometry (TDI) which is well discussed in the literature (see e.g. [6] and references therein).

2. LISA telemetry and ranging

Time-delay interferometry is the process of combining phase information with time delays inserted to cancel out phase noise. In particular, the phase noise due to frequency jitter in the lasers can be reduced dramatically. TDI requires not only the phase information produced by the interferometric fringe of LISA, but also some knowledge of the relative jitter between the ultra-stable oscillators (USOs) onboard each sciencecraft.

2.1. Ultra-stable clock oscillator

Onboard each LISA sciencecraft is an ultra-stable oscillator which provides the reference frequency for the LISA frequency distribution system (FDS). The FDS provides frequencies to several key LISA systems, including the phase measurement system, the laser stabilization system, the frequency noise correction system and the telemetry system.

Jitter in the USOs on each sciencecraft will appear as jitter in the phase of the LISA fringe signal. Therefore, it is imperative to actively measure the phase noise of the USOs onboard LISA.

In each optical assembly, a high frequency sideband derived from the USO will be modulated onto the laser beam. This will be referred to throughout this paper interchangeably as the USO sideband, the USO subcarrier or just simply the subcarrier. The subcarrier will be present on each laser beam so that it will be sent both ways on each of the arms and between the optical benches contained in each sciencecraft. Beating of this sideband with the sideband produced by the local USO produces the error signal used for frequency noise correction.

The current baseline plan for modulating the USO onto the laser beam is as follows. Each laser will consist of a neodymium yttrium-aluminium-garnet (Nd:YAG) master oscillator fibre-coupled to a ytterbium (Yb:YAG) fibre amplifier. The current plan is to insert a fibre modulator before the fibre amplifier. The fibre modulator will be an electro-optic (EO) device used for phase modulation. The modulation depth of the EO will be about 10% to facilitate transfer of this signal.

Naturally, there is some requirement on the measurement of the USO sideband. This is determined by the requirement on sampling synchronization from TDI. The phase measurement requirement on the USO sideband is $10^{-4}$ cycles Hz$^{-1/2}$ at 1 mHz [7].
The frequency selection of the USO sideband has two constraints: (1) it must be of high enough frequency to minimize the effect of shot noise, and (2) it must be of low enough frequency to be realized with an EO modulator. The current baseline design for LISA is to utilize sideband–sideband beatnotes to allow the USO sideband frequency to be much higher than in a sideband–carrier scheme. This further reduces the effect of shot noise in the phase measurement of the USO. The USO sideband frequency currently is set at 2 GHz [8]. The USO sidebands on each sciencecraft will be slightly different. For instance, they might be 2 MHz apart. In this way, the sideband–sideband beatnote will be ±2 MHz around the carrier–carrier beatnote between the incoming and local laser beams. The carrier–carrier beatnote contains the science information (i.e., gravitational wave signals). The frequency of all the beatnotes will be shifted by the Doppler frequency due to orbital motions of the sciencecraft over the course of a year, roughly ±20 MHz.

2.2. Ranging tones

In addition to the USO signal on the LISA laser beam, ranging tones may be modulated onto the beam. The TDI algorithm for laser frequency noise correction requires absolute knowledge of the armlength differences of the LISA constellation to tens of metres accuracy [6]. This requirement is not easily met using ground tracking alone. Combining the ground tracking with a laser-based ranging measurement will yield an estimate of the armlengths to the required accuracy. One alternative to using ranging tones would be to determine the distance using the new technique of time-delay interferometric ranging whereby the ranging distances are solved for by a minimization of the noise in the TDI variables rather than actually being measured [9]. However, for now we will assume that ranging tones will still be required for LISA.

To prevent contamination of the LISA science data, the ranging tones will be phase modulated onto the USO signal before phase modulation onto the laser beam. This is the source of the terminology of the USO sideband being referred to as the subcarrier. This second-order phase modulation, or phase-modulated phase modulation, will suppress ranging tone sidebands around the LISA science fringe signal.

The current baseline plan for ranging tone modulation is to phase modulate the USO signal before injection into the fibre modulator. The modulation depth of the ranging tones will be half that of the USO. The frequency selection of the ranging tones will be on the order of 100 kHz. This selection yields a distance ambiguity of roughly 3 km. Varying this tone during acquisition or using multiple tones can reduce this ambiguity [8].

2.3. Digital data transmission

Complicating the situation further, one operating mode for the LISA mission is expected to be that digitally recorded phase data from each sciencecraft are sent to one selected sciencecraft for data preprocessing. These preprocessed data are then downloaded to Earth from the master sciencecraft. Again, to prevent contamination of the LISA science data, the digital data transmission between LISA sciencecraft will be phase modulated onto the USO sideband. Currently, it is thought that digital data modulation will happen in a similar way to the ranging tones described above. The frequency of modulation most likely will be in the MHz range to facilitate high data rates and good frequency separation from other signals. One difference between the digital data modulation and ranging tones or the clock tone is that the data modulation sideband cannot beat against another data sideband if any usable information is to be extracted. Instead, the digital data sideband on the incoming beam will beat against the USO subcarrier on the local beam. We describe this process in more detail in section 3.1.
Alternatively, both the digital phase data and the ranging tones might be modulated onto the subcarrier using pseudo-random codes and 180° phase-shift keying [8].

2.4. Modulation summary

The LISA laser beam will be phase modulated with a phase-modulated subcarrier at gigahertz frequencies derived from the USO. The subcarrier is modulated with ranging tones in the hundreds of kilohertz and possibly data in the megahertz. After traversing the five million kilometres between sciencecraft, the laser will have been Doppler shifted. The Doppler shift ranges in frequency up to 20 MHz and changes at a rate up to about 1 Hz s⁻¹. Beatnotes between the incoming laser beam and the local laser beam will contain the following signals to be measured: the science signal from which the gravitational waves will be extracted is the result of beating the two laser carrier frequencies, the USO signal is the result of beating the two USO subcarrier frequencies, the ranging signals are the result of beating different ranging sidetones, and the digital data signal is the result of beating the digital data sideband on one laser with the USO subcarrier on another laser.

In this paper, we present results from our table-top interferometer with data modulations present on the laser beam. In particular, we demonstrate the ability of transmitting a clock tone with a ranging sidetone and audio data on the laser beam from the distant sciencecraft and receive that transmission.

3. Laser communication design and implementation

In [1], we presented a test-bed interferometer which produces LISA-like fringes. To investigate the effects of modulating information on the LISA laser beam, we need to make only slight modifications to our test-bed interferometer. In particular, we add optical elements to modulate data onto the laser beam and electronic components to read out the data.

As described in section 2.1, the baseline plan for LISA is to modulate the laser beams using electro-optic modulators (EOMs). Our table-top interferometer simulates one end of one arm of the LISA interferometer. As described in [10], we make use of a modified Mach–Zehnder design which utilizes polarized light. One arm of our interferometer is attenuated to 100 pW by using neutral density filters (NDFs). This ‘dim beam’ represents the incoming light from one of the far sciencecraft. The ‘bright beam’ represents light from the laser beam on the local sciencecraft. The power of the bright beam is very close to 0.5 mW.

Our experimental setup is shown in figure 1. In order not to double pass our EOMs, we place them before the polarizing beamsplitters (PBSs) in each arm. For the dim arm, this placement simulates the LISA situation in which the laser beam is modulated before attenuation by the pathlength distance between sciencecraft.

3.1. Implementation of data modulation

Our 5 × 5 × 20 mm birefringent crystals are made of lithium niobate (LiNbO₃). We drive each EO crystal with synthesized function generators. The maximum frequency of these devices is 30 MHz. The maximum signal level of these devices is 10 V-peak. For our setup, the resulting modulation depth with maximum signal level is about 3%. The modulation depth planned for LISA is 10% [11].

Each frequency synthesizer provides us with the subcarrier frequency for data transmission. These signals are modulated with ranging tones and digital data and then sent to the EOM, as shown in figure 1. The frequencies \( f_1 \) and \( f_2 \) represent the USO derived signals.
used in LISA. In LISA, the sideband–sideband beatnote will contain the relative phase jitters between the USOs onboard the two sciencecraft. In our setup, this beatnote contains phase jitters resulting from the relative electronic phase noise in the two frequency synthesizers.

Ideally, we would simultaneously simulate both the ranging tone modulation and the digital data stream modulation. Due to hardware limitations, and for simplicity, we have made measurements with only one of the modulations present at any time.

Our frequency synthesizers have a built-in phase modulation option. The ranging tone sidebands, $f_{m1}$ and $f_{m2}$, are chosen to be in the hundreds of kHz. Their separation, $|f_{m1} - f_{m2}|$, is in the several tens of kHz. The ranging sideband–sideband beatnote will be used as a vernier to determine metre-scale distance changes between the sciencecraft. The larger scale distance determination between sciencecraft will be performed by ground-based measurements.

For simplicity, when simulating digital data modulation we have opted to use the built-in analogue amplitude modulation port of our frequency synthesizers rather than using a third-party data modulator, such as a phase-shift keyer. We utilize this port to stream data from our computer to the EOM. When transmitting data, we do not have ranging tones present on the EO frequencies, $f_1$ or $f_2$. For the case of digital data modulation, we do not utilize a sideband–sideband beatnote. Instead, we beat the digital data sideband on one laser beam with the subcarrier sideband on the other laser beam. This produces a signal with frequency given by, e.g., $\delta f + |f_1 - f_2| + f_d$, where $\delta f$ is the difference frequency between the carriers and $f_d$ is the digital data modulation frequency. Ideally, we would choose $f_d$ to be in the MHz. Since we are not using an external data modulator, our digital data modulation frequency is limited to 10 kHz. For timely feedback on fidelity while aligning the interferometer we stream audio data from the computer onto the laser for our ‘digital’ data transfer. The speaker shown in figure 1 is used for ‘readout’ of this signal.

Figure 1 contains a summary of the frequencies used in our demonstration of sciencecraft intercommunication. The frequency $\nu$ is the laser frequency of our 1064 nm Nd:YAG. The

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**Figure 1.** A schematic of our table-top fringe generator with laser communication components. The electro-optic modulators (labelled ‘EOM’) are placed before the polarizing beamsplitters (PBSs) in each arm of the interferometer. Data from the computer are modulated onto $f_1$ which in turn is phase modulated onto the laser beam as described in section 3.1. The ‘readout’ electronics consist of a mixer, a low-pass filter, an amplifier and an audio speaker. The demodulation scheme is described in detail in section 3.2.
USO subcarrier and ranging tone frequencies, \( f \) and \( f_m \), are slightly different in the two arms. The difference \(|f_1 - f_2|\) is chosen to be 2 MHz and the difference \(|f_{m1} - f_{m2}|\) is 50 kHz. Ideally, our digital data sideband has a frequency of 1 MHz, as shown in the schematic. In our setup, the digital data signal, \( f_d \), is audio in nature and bound above in frequency by 10 kHz from the carrier.

To prevent beatnotes from having negative frequencies after the heterodyne process in the interferometer we limit our carrier–carrier beatnote to be between 5 and 25 MHz (assuming a maximum Doppler shift due to orbital motions of 20 MHz). The 5 MHz offset can be accomplished in the control loop of frequency locking the laser to a cavity or the LISA arms.

### 3.2. Demodulation of data

The electrical signals at the output of the photoreceiver are shown at the bottom chart of figure 2. The demodulation scheme is depicted in figure 3. The electrical signal from the photoreceiver is sent to a distribution amplifier with four outputs. Each output from the distribution amplifier is the radio frequency (RF) input to a mixer. The local oscillator (LO) input to each mixer is controlled by the computer so that the intermediate frequencies (IFs) are suitable for our zero-crossing phasemeters (see [1, 10, 12] for discussions of our zero-crossing phasemeter).

The first output from the distribution amplifier is used for Doppler tracking as well as science extraction. The carrier–carrier beatnote frequency is \( \delta f = |v_1 - v_2| \), which would range from 5 MHz to 25 MHz due to the Doppler. As explained above, the 5 MHz offset is inserted to prevent beatnotes from crossing DC. The frequency \( f_{1,0} \approx \delta f \) will approximate this difference frequency. Slow feedback from the computer will keep the intermediate frequency from the first mixer close to \( \Delta f \), a frequency suitably chosen for our phasemeter. The
Figure 3. Our proposed demodulation plan for use with the zero-crossing phasemeter. The intermediate frequency $\Delta f$ is chosen appropriately for our phasemeter to be on the order of 10 kHz. Feedback from the computer adjusts the oscillators for the slow Doppler frequency sweep due to orbital motions of the sciencecraft.

requirements on the tightness of this feedback were discussed in section 3 of [1]. Since all of the signals will sweep in frequency at essentially the same rate, the sweep rate derived from the feedback of $f_{LO}$ will be used for the other demodulation frequencies.

The second output from the distribution amplifier is used in the extraction of the USO signal. The USO data are located in frequency space at $\delta f \pm |f_1 - f_2|$. The frequency $f_{\text{Clock}}$ approximates this frequency: $f_{\text{Clock}} = f_{LO} + 2$ MHz. Slow feedback from the computer will fix the IF of the second mixer at $\Delta f$, suitable for our phasemeter.

The third output from the distribution amplifier is used for extraction of ranging information. In our frequency plan, figure 2, the ranging tone sideband–sideband beatnote is at 50 kHz. This allows us to set the demodulation frequency $f_{\text{Range}} - \Delta f = f_{\text{Clock}}$. In this way, the IF from the third mixer will be 50 kHz. Although higher than our usual IF of 10 kHz, 50 kHz is an acceptable frequency for our phasemeter. As discussed in [1], our phasemeter can accommodate IFs as high as 100 kHz without being dominated by timing noise errors.

Our proposal for the digital data signal is to use phase-shift keying. The demodulation process would proceed as follows. The data demodulation frequency approximates the expected frequency of the digital data sideband beatnote: $f_{\text{Data}} = f_{\text{Clock}} + 1$ MHz. Instead of mixing the signal from PDs with $f_{\text{Data}} - \Delta f$, which would result in a phase-shift keyed $\Delta f$ signal, we propose to mix the PDs signal with $f_{\text{Data}}$. This results in a TTL-like signal jumping from high to low based on the phase shifts between the LO and the signal from PDs. This TTL-like signal can then be sampled with a 1-bit ADC.

As mentioned in section 3.1, for simplicity we are modulating audio data onto our subcarrier rather than a sub-subcarrier containing phase-shift keyed digital data. When audio data are present, there are no ranging tones on the subcarriers. In this setup, the subcarrier for the dim arm of the interferometer is amplitude modulated with audio data. The demodulation scheme used for this setup is that shown in the schematic of figure 1. The demodulation frequency used for the audio data demodulation is set to the USO frequency, $f_{\text{demod}} = f_{\text{Clock}}$, just as in the case for the ranging data demodulation. The demodulated output is amplified
and sent to a speaker rather than the phasemeter. When the speaker is turned on, the streaming audio data sent by the computer are heard quite readily.

An alternative demodulation scheme would be to mix out the signal in successive steps. This scheme is similar to that which most likely would be used with a digital phasemeter. At each step, the signal is split into two paths. One path demodulates the signal to an IF suitable for the phasemeter and the other path demodulates the signal to ‘DC’. The first demodulation step is to take out the carrier–carrier difference frequency of $\delta f$. The Doppler is included in this demodulation step. The next largest frequency component is the subcarrier–subcarrier difference frequency. After this demodulation, the ranging tone sideband–sideband beatnote and the digital data sideband remain. The disadvantages with this demodulation scheme for an analogue phasemeter are the increased number of mixers and frequency sources. For a digital phasemeter, these disadvantages are not present since the demodulation process occurs in software.

4. Data comm results

We present data taken from our modified table-top interferometer with the zero-crossing phasemeter, presented in [1], of the science fringe signal, the USO signal and the ranging signal. In our setup, the digital data signal was an analogue audio stream which was heard on a speaker as described above. In all cases, the dim arm of the interferometer is 100 pW and the bright arm of the interferometer is 0.5 mW, as explained in [1].

To demonstrate that the EOM phase modulation does not adversely affect the LISA science results, we take science fringe data at a collection of Doppler offset frequencies, $\delta f$, ranging from 50 kHz to 20 MHz, similar to the data presented in [1]. In all cases, the Doppler frequency sweeps at a rate of 1 Hz s$^{-1}$. In [1], we demonstrated that our phasemeter is capable of handling sweep rates as fast as 1 kHz s$^{-1}$. The phase noise that we present is computed by subtracting the known phase of our signal generator from the reconstruction of the phase from our phasemeter (see [12]). From this set of residuals, we compute an amplitude spectral density, the phase noise, as a function of frequency from the signal frequency.

4.1. Timing a LISA-like fringe with data modulation present

The data presented in figure 4 were taken while streaming audio was sent from the computer to the EO crystal in the dim arm of the interferometer. The signal to the EO crystal in the bright arm of the interferometer was unmodulated. This creates a data-modulated signal on the fringe 2 MHz from the fringe frequency, which is the carrier–carrier beatnote. The low-pass filter in our data demodulation scheme (see figure 3) removes the unwanted signals, such as the audio data and the subcarrier–subcarrier beatnotes, and isolates the much larger amplitude science fringe frequency.

Each of the spectra in figure 4 is the average of four 4.5 h long data sets. For these data, we instructed the LO to keep the IF between 1 and 2 kHz. Since the subcarriers are small in amplitude, and separated in frequency by 2 MHz, the subcarrier frequency has little effect on the science results.

There is some residual noise at approximately 3 mHz. Instructing the frequency synthesizer to output a constant frequency removes this noise bump. Figure 5 shows data with swept and constant frequency signals. This increase in phase noise most likely is caused by small changes in the phase delay through the crystal filter used in the frequency generation technique explained in [1]. The phase delay through the crystal filter is frequency dependent. This small change in phase appears to be the source of the increased phase noise around 3 mHz,
Figure 4. Phase noise of LISA-like fringes with a data modulation present. The phase noise appears independent of baseband frequency over the range examined. See figure 5 for comparison of phase noise levels with and without data modulations.

Figure 5. Comparison of phase noise of LISA-like fringes with and without data modulations present. The noise bump at 3 mHz is present only for the data where the interferometric fringe is sweeping in frequency and is due to the frequency generation technique as explained in the text. The addition of data modulations does not hinder the science performance of our interferometer.

although why it peaks up near 3 mHz is not clear. This noise source was not apparent in the data of [1] because acoustic noise was the dominating noise source below 100 mHz. The reduction of acoustic noise has been mediated in these data by enclosing the interferometer in a sound-insulating box.

4.2. Timing the USO subcarrier–subcarrier beatnote

It is important not only to preserve the phase integrity of the science fringe when data modulation is present, but also to preserve the data modulation integrity itself. In particular, as discussed at the beginning of this paper, the subcarrier will be a signal derived from the USO. In the data presented in the previous section, we amplitude modulated the subcarrier in the dim arm with audio data. These audio data were modulated onto the laser beam in our interferometer, and we listened to a speaker to verify fidelity.
To determine the phase integrity of the subcarrier frequency which represents the information transfer of an ultra-stable clock, we do not modulate on streaming audio. Audio frequencies range from 20 Hz to 20 kHz. If we wish to time the subcarrier–subcarrier beatnote by mixing it, e.g., from $\delta f + 2$ MHz to a suitable IF for our phasemeter, e.g., $\Delta f = 10$ kHz, then our signal would be contaminated with irremovable audio data.

Modulating a sub-subcarrier onto the subcarrier at a much higher frequency, e.g., 1 MHz as shown in the frequency plan of figure 2, would make filtering the audio data far more feasible. Our frequency synthesizer has a maximum analogue modulation frequency of 10 kHz. Using an external modulator, such as a phase-shift keyer with an additional frequency source, would allow us to have a higher frequency modulation rate.

Instead of modulating audio data onto the subcarrier in the dim arm while leaving the subcarrier in the bright arm unmodulated, we phase modulate a 100 kHz ranging tone onto one subcarrier and a 150 kHz ranging tone onto the other. The sidebands present on the subcarrier-subcarrier beatnote are the two ranging tones individually as well as the ranging tone sideband–sideband beatnote. Since the ranging tones are in the hundreds of kilohertz and the ranging tone beatnote is 50 kHz, we use an IF of $\Delta f = 1$ kHz with strong filtering to remove the unwanted signals.

Recall from section 2.1 that the phase noise requirement on the USO signal is less stringent than that on the fringe signal, the requirement is $10^{-4}$ cycles Hz$^{-1/2}$ at 1 mHz. Figure 6 contains the phase noise spectrum of the subcarrier–subcarrier beatnote signal passing through the interferometer as well as the phase noise spectrum of the subcarrier–subcarrier signal sent directly to the demixer, without passing through the interferometer. The latter case signal was generated by mixing the two subcarriers together, sending them through a low-pass filter, producing a $|f_1 - f_2|$ signal, and then a demixer to a suitable IF, $\Delta f = 1$ kHz. The noise level of the subcarrier beatnote is higher than that of the fringes presented in figure 4 but still below the LISA USO requirement. The increase in phase noise is due to the smaller signal amplitude of the subcarrier beatnote on the output of the photoreceiver as well as the fact that our acoustical stabilization loop attempts to fix the phase of the fringe signal but does not stabilize other signals [1].
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Figure 7. 100 kHz and 150 kHz tones are phase modulated onto the subcarriers. The phase modulation depth was set to 90°. The phase noise level is being dominated by voltage noise in our photoreceiver circuit. The assumed LISA ranging requirement of 20 m is about $6.7 \times 10^{-3}$ cycles Hz$^{-1/2}$, well above the noise levels presented here.

4.3. Timing the ranging tone sideband–sideband beatnote

Ranging tones may be modulated onto the subcarrier and used to assist in the determination of the armlengths of the LISA interferometer. The ranging tones on LISA will be in the hundreds of kilohertz, and the modulation depths will be about 5% of the total laser beam. This is a 50% modulation on the subcarrier. We can demonstrate this process by modulating tones onto our subcarriers in much the same way that is planned to be done on LISA.

As for the case of timing the USO subcarrier–subcarrier beatnote, we do not modulate on streaming audio as this will confuse the phase of our subcarrier and tone. We modulate one subcarrier with 100 kHz and the other with 150 kHz. We demodulate the signal from the photoreceiver PDs with $f_{\text{range}} - \Delta f = f_{\text{clock}}$ as described in section 3.2. The resulting signal frequency after filtering is 50 kHz. Changes in the phase of this signal are a result from changes in the pathlength difference of our interferometer, akin to LISA. Figure 7 contains phase noise data of this 50 kHz signal as well as the corresponding electronic signal created by mixing the two subcarrier signals electronically.

There is no firm LISA requirement on the ranging tones. However, it is assumed that a measurement sensitivity of $\Delta L = 20$ m would be a reasonable goal. At $f = 100$ kHz, this is a phase measurement of $f \Delta L/c = 6.7 \times 10^{-3}$ cycles Hz$^{-1/2}$. Our data exceed this measurement requirement.

5. Summary

We have modified our table-top interferometer presented in [1] with a laser communication system. We have successfully modulated 100 kHz phase-modulated 28 and 30 MHz signals onto our laser beam. We have timed the phase of the ranging tone sideband–sideband beatnote and the subcarrier–subcarrier beatnotes separately and have demonstrated that the phase noise levels are below the LISA requirements. For verification of data transfer on the subcarrier, we amplitude modulated the subcarrier in the dim arm with analogue audio data. During this exercise, the subcarrier in the bright arm of the interferometer was unmodulated. These data were received, demodulated and the audio data were played back on a speaker.
There are a number of differences between our setup and that which will be implemented in LISA. We have phase modulated each arm of our interferometer with signals derived from phase-locked frequency synthesizers. In the case of LISA, the phase modulations will be derived from independently running USOs. The phase of the heterodyned beatnote is measured. In the case of LISA, this phase information contains the relative phase fluctuations between the USOs onboard the two spacecraft and is used in the TDI algorithm to correct for laser frequency noise. In our case, this phase information contains the relative jitter between our two phase-locked frequency synthesizers. The phase noise level of the USO signal we have measured is much smaller than that expected for LISA. Regardless of the level of the noise, the measurement precision required by TDI is $10^{-4}$ cycles $Hz^{-1/2}$. We have measured the noise to a precision of $10^{-6}$ cycles $Hz^{-1/2}$.

Another difference between our experiment and LISA is the choice of frequencies. The USO subcarrier frequency will be in the gigahertz range on LISA, whereas we used 28 and 30 MHz. Using a much higher frequency further reduces the effects on the science fringe. In addition, having a high frequency phase modulation, such as 2 GHz, reduces the effect of laser frequency noise contamination of the subcarriers. In our experimental setup, since we use one laser for the heterodyne measurement, the laser frequency noise contribution to our measurement is effectively absent.

An improvement to our experimental setup would be to better demonstrate the full LISA laser communication plan described in section 3.1. In particular, we would use an external phase-shift keyer to modulate sub-subcarrier signals at $f_{d1}$ and $f_{d2}$. These frequencies might be 1 MHz and 3 MHz (see figure 2). These sub-subcarriers would then be phase modulated onto the subcarriers $f_1$ and $f_2$ before modulation onto the laser beams with the EOMs. Demodulation of the science photoreceiver signal by $f_{Data} = f_{Clock} + 1$ MHz or by $f_{Data} = f_{Clock} + 3$ MHz would produce a TTL-like signal containing the phase-shift keyed data.

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