Overview of the LISA Phasemeter

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Abstract.
The LISA phasemeter is required to measure the phase of an electrical signal with an error less than 3 µcycles/√Hz over time scales from 1 to 1000 seconds. This phase sensitivity must be achieved in the presence of laser phase fluctuations 10^8 times larger than the target sensitivity. Other challenging aspects of the measurement are that the heterodyne frequency varies from 2 to 20 MHz and the signal contains multiple frequency tones that must be measured. The phasemeter architecture uses high-speed analog to digital conversion followed by a digital phase locked loop. An overview of the phasemeter architecture is presented along with results for the breadboard LISA Phasemeter demonstrating that critical requirements are met.

Keywords: LISA, phasemeter, gravitational wave
PACS: 04.80.Nn,04.30.Nk,95.55.Ym,95.85.Sz

1. INTRODUCTION

LISA measures changes in the separation of the proof masses using heterodyne interferometry. The interference produces a beat note at the lasers’ difference frequency. Length information (and gravitational wave information) is contained in the phase of this beat note which can be extracted using a phasemeter.

Several types of phase measurement have been considered for use in LISA. The most common phase measurement technique is to accurately time the zero-crossing points of the signal waveform. This approach suffers from poor performance in the presence of broadband noise due to aliasing of noise at harmonics of the heterodyne signal. This technique is not suitable for LISA because the variation of the heterodyne frequency prevents the use of analog anti-aliasing filters. The phasemeter developed here employs high-speed digitization followed by a digital phase-locked loop (DPLL).

2. PHASEMETER REQUIREMENTS

The LISA phasemeter’s primary function is to provide a high accuracy measurement of the phase of the input signal for the science measurement.

The dynamic range of the phase measurement is affected both by the orbital dynamics of the spacecraft and by the short-term fluctuations in frequency of the lasers. The relative motion between two spacecraft (up to ±15 m/s) leads to a Doppler shift (1 MHz per m/s), over the 1 year orbital period of the constellation’s Earth-trailing orbit.

The reference laser is to be stabilized to a thermally isolated reference cavity and to the 5 million kilometer arm length. The laser frequency noise is expected to be less
than 30 Hz/$\sqrt{\text{Hz}}$ at frequencies from 1 mHz to 1 Hz. This laser frequency noise is equivalent to a phase noise of 1000 cycles/$\sqrt{\text{Hz}}$ at 5 mHz. To obtain the desired accuracy of 3 $\mu$cycles/$\sqrt{\text{Hz}}$ at 5 mHz (corresponding to a displacement noise of 3 pm/$\sqrt{\text{Hz}}$), the phasemeter must have a dynamic range on the order of 10$^8$.

The spectrum of the heterodyne signal will contain additional tones 1 MHz from the carrier with $-20$ dBc amplitude for transferring the clock noise between spacecraft, so the phasemeter must be able to measure multiple tones. The phase of each photodiode quadrant is individually measured to provide alignment information for the spacecraft and/or proof mass orientation control.

The science measurement, clock noise measurements and quadrant phase measurements are performed using identical duplicates of the basic digital phase locked loop structure. Additionally, the phasemeter must provide a low latency, high-speed output for phase-locking one laser to another. This measurement employs significantly different filtering algorithms, trading off the need for low latency with relaxed requirements on accuracy and dynamic range.

The phasemeter is also be responsible for extracting inter-spacecraft communication, ranging and clock synchronization measurements using a spread spectrum signal. Although the architecture chosen is well suited for this measurement, this spread spectrum capability has not yet been implemented.

2.1. Phasemeter architecture

The architecture of the phasemeter is shown in Figure 1. The output of the photoreceiver is passed through an analog anti-aliasing filter, digitized at 40 MHz, then fed into a field programmable gate array (FPGA). The signal is then multiplied by a local oscillator (LO) at the same frequency as the signal. In stable operation, the output of this multiplier is proportional to the phase difference between the LO and the signal. This phase difference is then used to update the LO frequency (and thereby phase) to keep the DPLL frequency locked to the incoming signal. The tracking loop operates at the 10 kHz output frequency, so the LO frequency is updated every 0.1 ms.

The phase of the local oscillator is approximately equal to the phase of the signal. Imperfections in locking, due to finite gain or controller quantization error, will limit the accuracy of the phase estimate based on such a system. These errors can be corrected by retaining the residual tracking error information in the in-phase ($I$) and quadrature ($Q$) signal components and combining this with the LO phase. This technique significantly improves phase accuracy in the presence of excess noise.

The phase-locking output is also shown in Figure 1. The digitized signal from the 40 MHz analog to digital converter (ADC) is split off to a separate local oscillator, which instead of having a tracking DPLL feedback loop, is compared to a programmable local oscillator. The internal digital-to-analog converter (DAC) runs at 1 MHz, giving a low latency phase measurement for laser phase-locking and arm-locking. The laser phase-locking output consists of all digital controllers except for a simple RC filter on the output of the DAC to filter out-of-band DAC glitches. The phase-locking output has an auto-acquisition mode which automatically brings the lasers into lock if their beat note
FIGURE 1. Phasemeter block diagram, showing the integer field programmable gate array (FPGA) and floating point processor which make up the science phasemeter, and the phase-locking output. The 40 MHz digitized signal is filtered and decimated to 10 kHz in the FPGA, then filtered and decimated again to 100 Hz for recording. The signal bandwidth for the science phasemeter is from 1 mHz to 1 Hz.


is within the bandwidth of the ADC (20 MHz), and senses lock and switches the digital controller from the low-gain acquisition mode to the high gain science mode. The LO which determines the laser offset frequency is dynamically adjustable from 1 MHz to 20 MHz.

2.2. Analog to digital conversion

Quantization error of the analog to digital converter will produce phase noise. The root power spectral density (RPSD) phase noise as a function of sampling rate, $f_s$ and number of bits $N$ is

$$\phi = \frac{1}{\pi 2^N \sqrt{6f_s}}.$$  (1)

With a 15 bit ADC sampling at 40 MHz, this quantization noise is negligible (less than $10^{-9}$ cycles).
FIGURE 2. Top hat window versus Bartlett. While any unfiltered noise above the Nyquist frequency $f_n$ will alias, only noise at multiples of $nf_s$ will alias back into the signal band from 1 mHz to 1 Hz. All noise at frequencies above the signal band will be rejected in the final filter/decimation stage.

Another source of error introduced by the ADC is jitter in the sampling time. The RPSD phase noise as a function of timing jitter RPSD $\tilde{t}_s$ and heterodyne frequency $f_h$ is

$$\tilde{\phi} = \frac{\tilde{t}_s}{f_h}.$$  \hspace{1cm} (2)

For the phasemeter demonstrated here, the sampling time jitter is less than $10 \mu$cycles/$\sqrt{\text{Hz}}$ with a 5 MHz heterodyne frequency (Figure ??). If needed, the ADC jitter can be calibrated by digitizing a reference tone.

2.3. Precision filtering and decimation

The signal sent to ground must be at a much lower rate than 40 MHz due to limitations of data transfer imposed by the Deep Space Network and mission costs. Phase measurements are decimated in two stages, from 40 MHz to 10 kHz in the FPGA, and from 10 kHz to 100 Hz in the floating-point processor (ultimately to 3 Hz for LISA). Decimation introduces the potential for aliasing of higher frequency noise, so careful design of digital anti-aliasing filters is needed. The requirements of the anti-aliasing filters depend upon the characteristics of the signal phase noise.

Filter characteristics can be relaxed by realizing that aliasing can be tolerated everywhere except the signal band from 1 mHz to 1 Hz. For example, when decimating from 40 MHz to 10 kHz, only noise within 1 Hz of 10 kHz (and its harmonics) will alias into the signal band. By carefully placing the nulls of the filter at $nf_s$, very good rejection of aliasing in the signal band can be achieved, as shown in Figure 2.

A Bartlett filter is used prior to decimation in the FPGA. Computation is reduced by calculating only the points that will not be thrown out by the decimation, decreasing the number of calculations needed by the ratio of the output rate to the input rate.

After the phase reconstruction at 10 kHz, a finite impulse response (FIR) filter is used prior to decimation to the final rate of 100 Hz. To minimize computation the same principle of only calculating the decimated points that are going to be kept is used. A
FIGURE 3. Frequency response of decimation filter

FIGURE 4. Block diagram of phasemeter linearity test

600 point FIR filter kernel was designed to be flat in the passband to one part in $10^7$ and have a rejection of one part in $10^8$ in the relevant parts of the stop band (Figure ??).

2.4. Implementation

The phasemeter is implemented on a single field programmable gate array. The FPGA is programmed using LabVIEW, which is also used as the interface to the user. The ADC is based on a Maxim development board, which digitizes 15 bits at 40 MHz. The phasemeter output for phase-locking one laser to another uses a 1 MHz digital-to-analog converter to drive the temperature and piezo-electric frequency actuator of the Nd:YAG laser to maintain a microcycle stable phase lock from 1 mHz to 1 Hz.

3. RESULTS

Figure 4 is a block diagram of a linearity test, simulating three individual lasers which are phase-locked to each other. The difference between each pair of lasers looks like
Uncorrelated phase noise, as shown in Figure 5.

When the three phase difference outputs are linearly combined appropriately, the noise should add to zero; any residual noise is due to nonlinearity in the phasemeter. Figure 5 shows this to be at the microcycle level. These are the results for a test where the noise signals were generated digitally, bypassing the ADCs. The root power spectral density of the noise for the sum of the signals is less than $5 \mu\text{cycles}/\sqrt{\text{Hz}}$, showing that the numerical part of the phasemeter easily meets the requirements.

The phasemeter must be able to track the heterodyne frequency as it varies with the orbit at a rate of up to 4 Hz/s. We have measured the tracking rate of the phasemeter to be 1 MHz/s.

The phasemeter has also been used to measure the performance of the LISA Interferometry Testbed at JPL. Figure 6 shows a measurement of the time-delay interferometry $\alpha$ variable in the Sagnac interferometer. Similar to the digital test described above, all three photodetector signals must be measured and combined correctly for the noise to cancel. The laser phase noise, which is similar to the levels that will be seen by LISA, is suppressed by $10^7$ on the testbed.

The science phasemeter was used to measure the phase-locking performance. Figure 7 shows the relative phase noise after phase-locking, equivalent to less than a picometer$\sqrt{\text{Hz}}$ throughout the signal band. The red curve shows the measured noise when different ADCs are used for the science phasemeter and phase-locker. The difference is due to ADC sampling time jitter. The laser phase-lock is very stable and can be maintained for long periods (weeks).

4. CONCLUSION

A phasemeter has been developed which is capable of achieving the accuracy, dynamic range, and multi-tone requirements for LISA. The system can be implemented in a flight system by porting the software to a dedicated FPGA combined with a high-speed digitizer. The measurement system also performs the functions needed for laser phase-
FIGURE 6. Results from interferometer testbed. The TDI variable $\alpha$ is suppressed by $10^7$ from the laser phase noise. The black dotted line shows the LISA requirement.

FIGURE 7. Measurement of laser phase locking performance by the science phasemeter. Excess noise at low frequencies is present when independent ADCs are used, due to sampling time jitter.

locking. A breadboard measurement system has been built and tested to demonstrate the required performance. Testing in a system environment is ongoing.

ACKNOWLEDGMENTS

The authors thank Bill Folkner for many useful discussions during the development of the phasemeter. This research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.