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Ranging and phase measurement for LISA

Juan José Esteban[1], Antonio F. García[1], Johannes Eichholz[1], Antonio M. Peinado[2], Iouri Bykov[1], Gerhard Heinzel[1], Karsten Danzmann[1].

[1]Max-Planck-Institute for Gravitational Physics (Albert-Einstein-Institute) and Leibniz University of Hannover, Germany
[2]Department of signal theory, networking and communications, University of Granada, Spain

E-mail: `juan.jose.esteban@aei.mpg.de`

Abstract.
The LISA phase measurement system (PMS) will provide interferometric phase readout of the primary heterodyne signal at microcycle sensitivity, ranging measurements at sub-meter accuracy and data communication at rates of several kilobits per seconds. Our investigations are focused on inter-spacecraft laser ranging and data transfer for LISA using Direct Sequence Spread Spectrum (DS/SS) modulation onto the laser links. We present the setup of an optical experimental to test the levels of performance achievable with a single laser link as well as a new hardware prototype based on FPGA (Field Programmable Gate Array) processing to perform high-accuracy phase readout of the optical signal, ranging measurements, data communication and is suitable for clock noise demodulation and digital laser-phase locking.

1. Introduction

The Laser Interferometer Space Antenna, LISA, will be a huge unequal armlength interferometer in space for gravitational wave detection [1]. LISA will consist of three spacecraft separated by 5 million kilometers forming a triangular formation and communicating via three bidirectional laser links. As consequence of variations in the spacecraft-to-spacecraft distance, the LISA arms are unequal and time-varying (change by approximately $\pm 1\%$ over one year orbit, $\simeq 50.000\,\mathrm{km}$), resulting in a limitation of the interferometric sensitivity due to laser frequency noise. In order to suppress this effect and make LISA virtually work like an equal arm interferometer, one of the techniques planned is a post-processing algorithm on ground, known as time-delay interferometry (TDI) [2]. It combines onboard ranging measurements with phase information of the laser beams to suppress the effect of laser frequency noise by up to seven orders of magnitude. This technique relies on interspacecraft distance tracking with resolution of the order of a few meters and therefore any error in the ranging measurements will turn into an error in the outcome of the post-processing algorithm [3]. In order to achieve inter-spacecraft laser ranging and data communication, the main carrier of the laser link is phase modulated with pseudo-random noise (PRN) and the travel time can be measured via the correlation of the local and incoming PRN codes. The phase measurement system (PMS) processes the interferometric signal coming from the photodetectors on the optical bench to measure its phase with microcycle accuracy, performs ranging at sub-meter resolutions and enables data transfer at several kilobits per seconds.

In order to test the modulation scheme in a single LISA arm, an optical experiment has been built in our laboratories. Figure 1 shows the experimental setup: two offset phase-locked lasers are modulated using fibre-coupled electro-optic modulators (EOM) and injected onto a monolithic optical bench for interference. The beatnote is digitised and processed in a custom-designed PMS breadboard which implements the phase readout via a phase-lock loop (PLL) architecture and the ranging capability via a delay-lock loop (DLL) architecture.

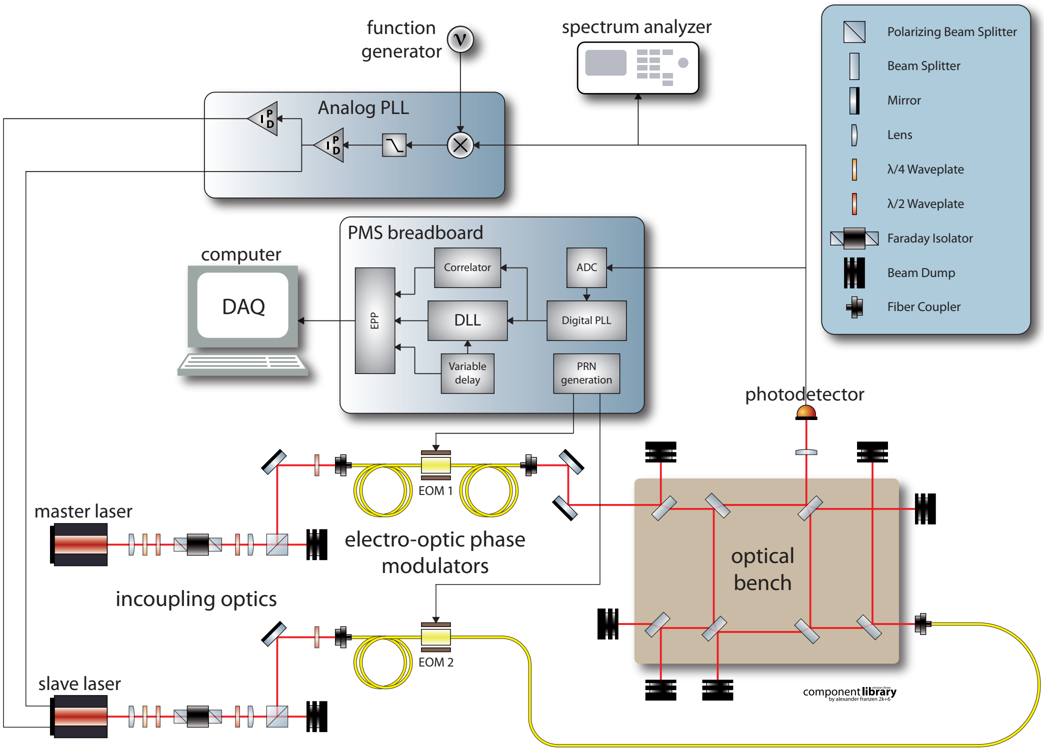

Figure 1. General schematic of the experiment setup to test the laser modulation scheme and PMS performance: two phase-locked lasers are modulated using an EOM and injected onto a Mach-Zehnder interferometer. The beatnote is detected and processed in the PMS breadboard in order to obtain phase readout, ranging measurement and data transfer.

2. Ranging and data communication

Ranging is based on the correlation properties of the pseudo-random noise (PRN) codes. There are a total of six laser beams exchanged between the LISA satellites, and therefore a PRN code has been designed for each one of them. In the LISA topology, each laser is used simultaneously in different interferometric measurements producing a beatnote modulated with more than one code. The main design driver for the codes is that after interference between any given two laser, a single PRN can be tracked separately from each other and without incurring in significant mutual interference. The set of six PRN sequences was designed by numerical optimisation and with an even length of 1024 chips[1]. The chipping rate is about 1.5 Mbps, limited by the photodectector bandwidth, and in which the data sequences are encoded at 97 Kbps. This produces

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[1] The size of the code family is a compromise between efficient use in a digital processor and the correlation properties achieved at the running chipping rate

a periodicity of the code every 200 km over the 5 million kilometer armlength, and therefore, an initial positioning system is required. The deep-space network (DNS), combined with the star tracker onboard each satellite, will provide a positioning uncertainty of about 25 km [4]. After this initial positioning, a more accurate distance determination will be achieved using the DLL architecture proposed. Note that only when the cross-correlation is made by the same PRN code with the same delay, does a peak appear in the correlation (see Figure 2). This way, the correlation peak serves as a timestamp if the start of the PRN is synchronised with the clock of the remote spacecraft.

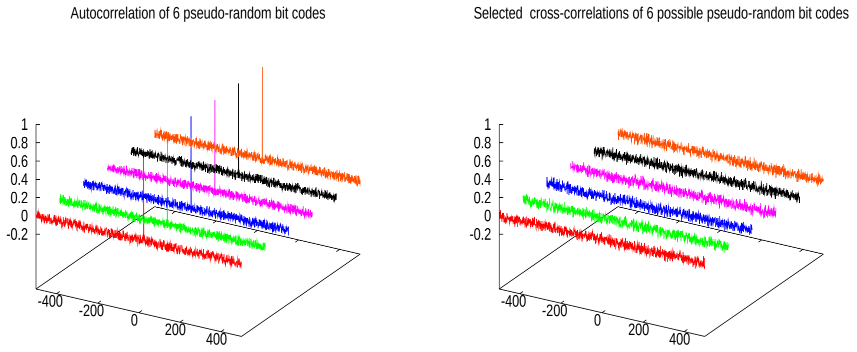

Figure 2. Autocorrelation of each pseudocode (left) and cross-correlation between a possible set of two different pseudocodes (right).

The presence of sudden phase changes modulated to the laser beam could compromise the phase stability of the LISA fringe signal. However, recent experiments pointed out that medium phase modulation could be applied without degradation of the phase fidelity of the science signal [5]. Consequently, a low-index phase modulation has been chosen using about 1% of the carrier power for ranging and data communication. Figure 3 shows the spectrum of the beatnote measured on the optical laboratory where an equivalent modulation index of m=0.16 rad was phase modulated using a EOMs.

3. Phase measurement system

The main task to be implemented by the LISA phasemeter is the phase readout of the beatnote at a required sensitivity of $2\pi \times 10^{-6}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$ on the frequency range from 0.1 mHz to 100 mHz. This task corresponds with the core processing of the PMS and is referred as the main science measurement, since the gravitational wave information is contained here. The most suitable architecture to implement this measurement is based on a digital phase-locked loop (DPLL)[6, 7] scheme and the general block diagram is represented in Figure 4: the beatnote is fed into an in-phase/quadrature (I/Q) demodulator to acquire its phase. A control loop locks the phase of a Numerically Controlled Oscillator (NCO) to the incoming beatnote. The phase measurement is formed in a floating-point unit as the sum of a raw phase estimation from the NCO and the arctangent of I and Q component. Once the phase is being processed, the PRN modulated onto the phase of the main carrier can be tracked in back-end processing using the fast residual phase error as input signal to the delay-locked loop (DLL)[8] architecture.

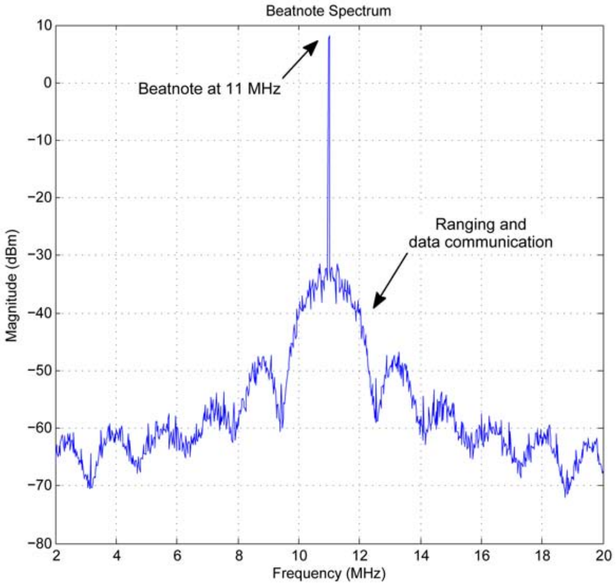

Figure 3. Spectrum of the electrical beat signal of two offset-phase locked lasers modulated by two PRN sequence with a modulation index of m=0.16 rad.

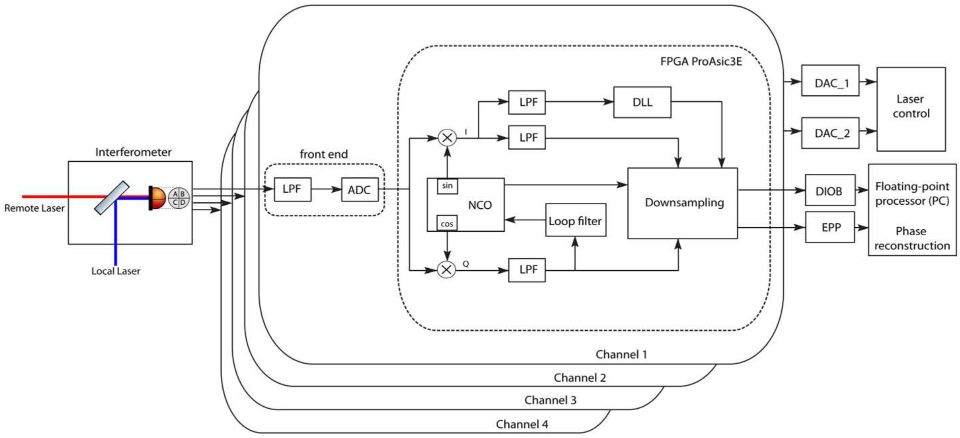

Figure 4. General PMS block diagram. FPGA: Field Programmable Gate array, ADC: Analog Digital Converter, DAC: Digital Analog Converter, LPF: Low Pass Filter, NCO: Numerically Controlled Oscillator, DLL: Delay-locked loop, EPP: Enhanced Parallel port, DIOB: Digital Input/Output board.

The DLL correlates the incoming phase signal with three versions of the same reference PRN: a punctual, an early and a late one (see block diagram in Figure 5). The early and late versions of the reference code[2] are delayed in the current implementation by plus and minus half a chip respectively, and the punctual version is not delayed with respect to the transmitted PRN. The punctual correlator is responsible for data recovery and peak detection, whereas the difference between early and late correlators is used as the error signal in a control loop to update the delay of the code generator to the input signal, thus providing tracking between the incoming and the local PRN. The control logic switches between two different modes of working:

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[2] "early" (shifted by $+\Delta/2$) and "late" (shifted by $-\Delta/2$) where $\Delta \approx 0.1\,T_c \ldots T_c$

- Acquisition mode: determines delay between the local and incoming PRN sequences at μs accuracy (one chip length). The local PRN is shifted with a coarse resolution of one code period until a peak of correlation is detected at the correct delay. Lower code period could be used, but it would increase the acquisition time. The acquition time for the current implementation is about 0.67 s.
- Tracking mode: once the acquisition is finished, it determines the timing delay with higher resolution (ns accuracy) and enables data transfer. The estimated delay at measurements rate of 1.5 kHz updates the pseudocode generator to produce the three copies of the local PRN at a resolution of 20 ns.

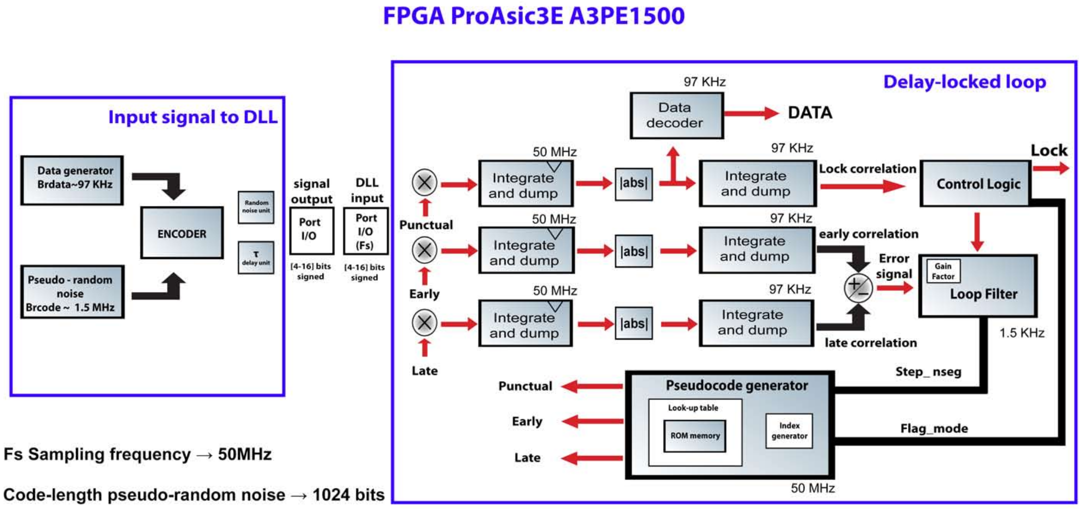

Figure 5. General block diagram of the DLL implemented in the same board as the phasemeter. The phase signal coming from the DPLL was internally simulated to provide data encoding, known shot noise and variable delay as input to the DLL.

4. Hardware

The hardware implementation of the PMS breadboard (see Picture 6) is based on a space-compatible FPGA processor running at 50 MHz, in which the DPLL and DLL architectures have been programmed and integrated. The breadboard has been designed with four independent A/D channels being able to measure in parallel the phase of each quadrant photodiodes. Additionally, the breadboard implements two independent D/A channels for digital offset phase-locking purposes and two EOM drivers for PRN modulation.

The EOMs and Mach-Zehnder interferometer used in the optical experiment are shown in Figure 7. Two Fibre-coupled EOM with frequencies up to 3 GHz have been tested in our Institute for clock noise sideband modulation[9] and are currently used for low-phase PRN modulation. The Mach-Zehnder interferometer bonded on a Zerodur-baseplate provides a stable optical bench environment with beam extraction at five points and is suitable for future testing of laser ranging with weak-light optical powers.

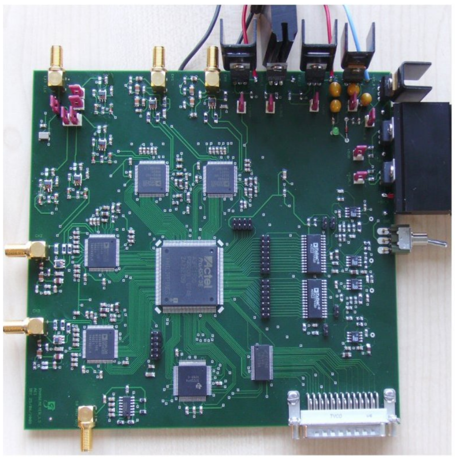

Figure 6. PMS breadboard. Main processor unit: ProAsic3E Actel FPGA with 3 Million system gates. Four input channels (AD9446-100), two output channels (AD9744-210), output interfaces: Digital Input/Output at 2 GB/s and parallel port at 1 MB/s.

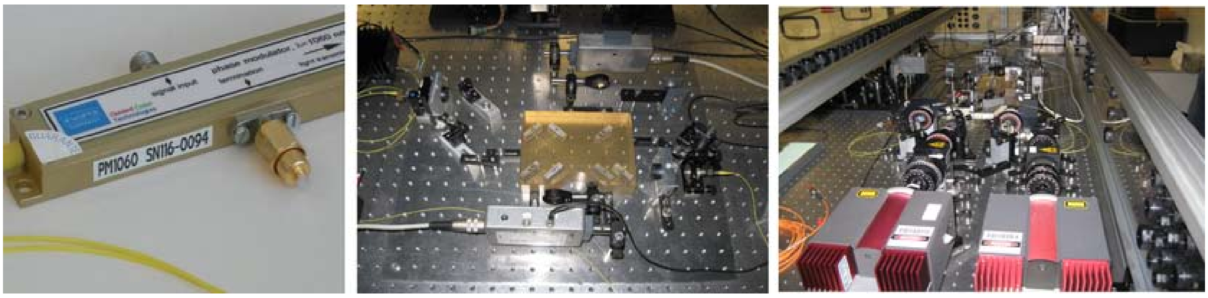

Figure 7. Fibre coupled electro-optic modulator (left), Mach-Zehnder interferometer (centre), lasers and optics (right)..

The functionality of our PMS breadboard has been verified and its performance is being tested in the laboratory[7]. The functionality of the implemented DLL architecture proposed in section 3 has been also verified achieving an ideal ranging resolution of 20 ns at a measurement rate of 1.5 kHz[10]. The system is still under active development, however simulated results show an expected distance determination of sub-meter precision with lower measurement rates and in the presence of realistic LISA-like noise sources, i.e., interference with a second PRN, data encoded and an equivalent shot noise of about $60\,\mu\mathrm{rad}/\sqrt{\mathrm{Hz}}$. The effective ranging accuracy can be improved by post-processing, taking into account optical Doppler shifts measurements in the PMS and orbit integration with Kalman filters[3].

5. Conclusions

This paper presents the optical experiments and relevant hardware components involved in the design of a delay-locked loop scheme for tracking the absolute armlength in LISA. The custom-designed Phase Measurement System breadboard can fit the architecture proposed. It functionality with optics signal is being confirmed with respect to the previous electrical testing. We thus conclude that the current experimental setup can be expected to be used to verify

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[3] This technique is similar to the applied in the Global Positioning System (GPS)

in a more realistic environment how the different modulation schemes affect the phase fidelity of the main science measurement. Besides, it can also be used to verify the phase redout of performance in a single LISA arm.

6. References

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