Optical ranging and data communication in space-based applications

Juan J. Esteban[1], Antonio F. García[1], Johannes Eichholz[1], Antonio M. Peinado[2],
Iouri Bykov[1], Joachim Kullmann[1], Gerhard Heinzel[1], Karsten Danzmann[1].
[1]Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut)
and Leibniz Universität Hannover, Germany
[2]Department of Signal theory, Networking and Communications,
University of Granada, Spain
Email: juan.jose.esteban@aei.mpg.de

***Abstract*—Ranging measurements in the radio band have been extensively used in space-based applications, for example in GNSS for navigation and GRACE for mapping the Earth's gravity field. However, the increasing demand for high-bandwidth communication and precision ranging will make optical systems ideal for these applications. Our investigations are focused on inter-spacecraft laser ranging and data communication for the LISA mission using Direct Sequence Spread Spectrum (DS/SS) modulation onto the laser links. We present the setup of an optical experiment 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. This prototype performs the phase readout of the interferometric signal at microcycle sensitivity, ranging measurements at sub-meter accuracy, data communication at rates of several kilobits per seconds and is compatible with inter-spacecraft clock noise transmission and digital laser offset-phase locking.**

I. Introduction

The Laser Interferometer Space Antenna, LISA, will be a huge Michelson interferometer in space for gravitational wave detection [1]. The LISA project is a joint ESA and NASA mission that will allow significant advances in the field of astrophysics and optical technologies. It will consist of three spacecraft separated by 5 million kilometers in a triangular formation and it will communicate via three bidirectional laser links. Each spacecraft will be equipped with two free-floating test masses that will serve as the end mirrors of the interferometer (see Figure 1). The main LISA science measurement consists of the relative pathlength variations between the free-floating test masses with a sensitivity of a few $\mathrm{pm}/\sqrt{\mathrm{Hz}}$. To obtain these position fluctuations, two offset phase-locked lasers are interfered after being reflected onto the test masses and the phase of the resulting carrier-to-carrier beatnote is measured. In addition to the main scientific measurement, the interferometry system will provide ranging measurements and data transfer by applying a Binary Phase Shift Keying (BPSK) modulation onto all laser links. In order to avoid sudden phase changes that could compromise the phase stability of the main science measurement, a low-index BPSK modulation has been chosen using about 1% of the light power.

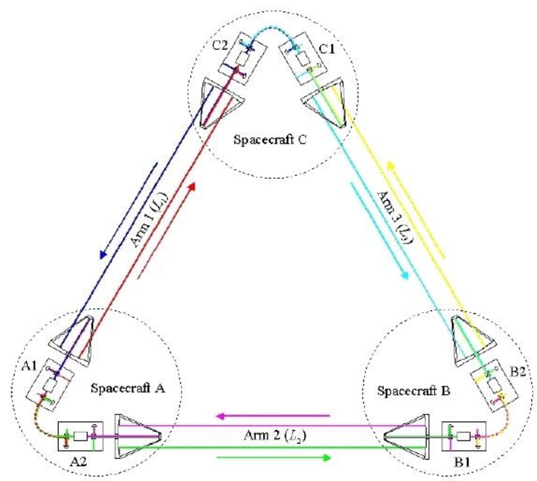

Fig. 1. The six LISA laser links: Each spacecraft is equipped with two free-floating test masses (polished platinum-gold 40 mm cube) and two telescope (40 cm-aperture) pointed to the other two satellites at an angle of 60 degrees. Each laser is transmitted to a remote spacecraft with a power of 1 W and 1064 nm wavelength. The long distance attenuates the received beam to about 100 pW.

The proposed ranging scheme is based on the correlation properties of pseudo-random noise (PRN) codes and implemented using a delay-lock loop (DLL) architecture [2][3], similar to the Global Positioning System (GPS) [4] in the radio band. To this end, the PRN sequence will be modulated into the phase of the remote laser and the inter-spacecraft distance will be measured via correlation of the demodulated carrier phase with a local copy of the original PRN code. One difference to standard DS/SS systems is that the code length is larger than the length of one data bit, such that coherent integration in the DLL is only possible for the length of one data bit. The correlation for the whole code is then completed by incoherent summation. There are a total of six laser beams exchanged between the LISA satellites, and a PRN code has been designed for each of them. In

978-1-4244-7157-7/10/$26.00 ©2010 IEEE

the LISA topology, each laser is used simultaneously in different interferometric measurements producing a beatnote modulated with more than one code. Consequently, the main design driver for the codes is that after interference between any given two lasers, 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. The chipping rate, chosen to be at 1.56 Mbps, is limited by the photodectector bandwidth and encoded with data sequences at 12 Kbps. This produces a periodicity of the code every 200 km over the 5 million kilometer armlength, and therefore an initial absolute 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 [5]. After this coarse positioning, a more accurate distance determination will be achieved using the DLL architecture proposed.

An optical experiment has been built in our laboratories to test the modulation scheme in a single LISA arm. The experimental setup and the digital signal processing architecture are outlined in Section II. Section III presents details on the actual custom-designed FPGA-based prototype used to performs interferometric phase readout of the primary heterodyne signal, ranging measurements and data communication. Measurements made with the prototype system in the optical experiment are discussed in Section IV. Finally, Section V summaries the paper and draws some general conclusions.

II. Interferometric Laser Ranging and Data Transfer

Only about 100 pW of the emitted laser light arrives at the other end of the arm due to diffraction losses of the beam after propagation over the huge inter-spacecraft distance. Figure 2 shows a schematic of the offset-phase locking technique for a LISA arm. The received laser is phase-locked to the local laser and returns a high power phase replica. When the transponded laser arrives back at the original spacecraft, it is interfered with a portion of the original laser beam, and their phase difference is recorded by the phase measurement system (PMS). The Doppler shift produced by orbital motion of the spacecraft (up to 15 m/s) leads to an offset frequency in the range between 2 to 20 MHz. Each spacecraft measures the phase of the resulting beatnote with respect to its on-board clock at microcycles precision. Only one spacecraft is used to communicate to ground via DSN at roughly 100 kbps for 8 hours every 2 days. The science data are exchanged between spacecraft, and stored onboard during periods of no communication [6]. The inter-spacecraft clock synchronisation, which is needed to achieve the desired overall LISA sensitivity, is performed by applying a 2 GHz sideband phase modulation in the laser link using 10% of the light power [7].

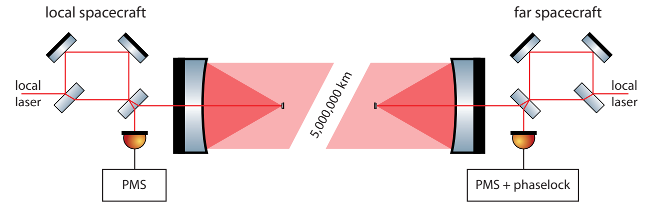

Fig. 2. Schematic of the laser offset-phase locking for a single LISA arm.

Figure 3 shows the experimental setup for a laser link: two 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 DLL architecture.

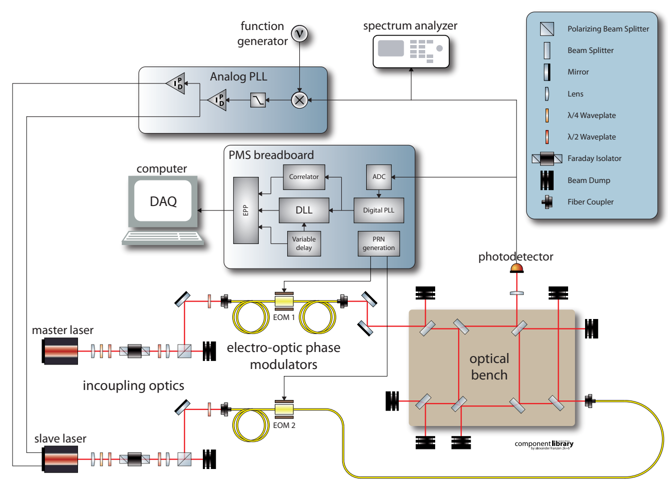

Fig. 3. General schematic of the experiment setup to test the laser modulation scheme and PMS performance: two phase-locked lasers are modulated using an EOM and injected into a Mach-Zehnder interferometer. The beatnote is detected and processed in the PMS breadboard in order to obtain phase readout, ranging measurements and data transfer.

A. Digital signal processing

1) Phasemeter architecture: The main task of the LISA phasemeter is the phase readout of the beatnote at a required sensitivity of $2\pi \times 10^{-6}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}$ in the frequency range from $0.1\,\mathrm{mHz}$ to $100\,\mathrm{mHz}$. The most suitable architecture to implement this measurement is based on a digital PLL scheme [8], [9]. The general block diagram for such a system is presented 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 the I and Q components.

In parallel, the PRN modulated onto the phase of the main carrier can be tracked using the fast residual phase error as input signal to the DLL.

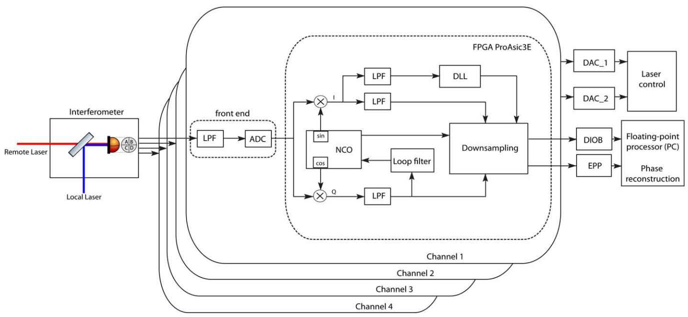

Fig. 4. General phasemeter block diagram. FPGA: Field Programmable Gate Array, ADC: Analog Digital Converter, DAC: Digital Analog Converter, LPF: Low Pass Filter, NCO: Numerically Controlled Oscillator, DLL: Delay-lock loop, EPP: Enhanced Parallel Port, DIOB: Digital Input/Output Board.

2) Ranging and data transfer architecture: The DLL correlates the incoming phase signal with three versions of the same reference PRN: a punctual, an early and a late one. The early and late versions of the reference code[1] are delayed in the current implementation by plus and minus half a chip, respectively, while the punctual version is kept synchronous 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. A control logic switches between two different modes of operation:

- Acquisition mode (Figure 5): 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. A lower code period could be used, but it would increase the acquisition time. The acquisition time for the current implementation is about 0.67 s based on the time it takes for a full scan through all offsets.

- Tracking mode (Figure 6): once the acquisition is finished, the tracking mode determines the timing delay with higher resolution (ns accuracy) and enables data transfer. The estimated delay updates the pseudocode generator to produce the three copies of the local PRN at a resolution of 20 ns. The measurement rate is determined by the required time to process partial correlation of a code-length (1.5 kHz for a full code-length correlation time) and is transmitted to the on-board computer with a downsampled rate of 3-10 Hz.

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

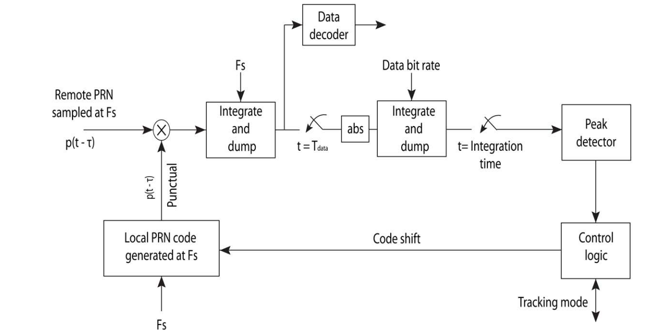

Fig. 5. Equivalent circuit to acquire code delay of the incoming PRN.

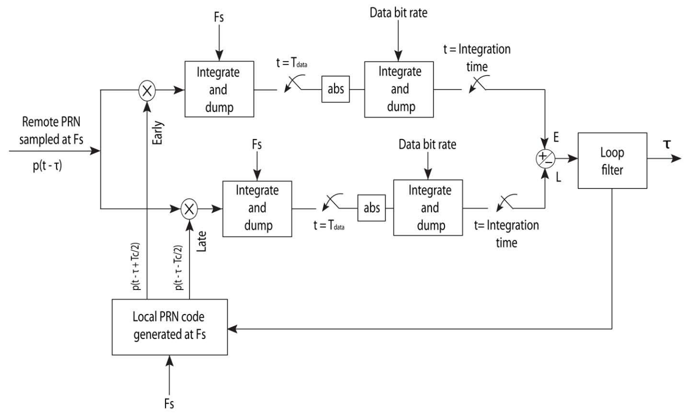

Fig. 6. The early-late delay lock loop with a delay difference between early and late reference signals of one chip period.

III. Hardware

The hardware implementation of the electronic breadboard (see Picture 7) is based on a space-compatible FPGA processor running at 50 MHz, in which the PLL and DLL architectures have been programmed and integrated. The breadboard has been designed with four independent A/D channels able to measure in parallel the phase of each quadrant photodiode. Additionally, the breadboard implements two independent D/A channels for digital offset phase-locking purposes.

The EOMs and the Mach-Zehnder interferometer used in the optical experiment are shown in Figure 8. The phase fidelity of the EOMs was tested at the Albert Einstein Institute (AEI) for clock noise sideband modulation[10] and they are currently used for low-depth PRN phase modulation. The Mach-Zehnder interferometer, bonded on a Zerodur-baseplate, provides a stable optical bench environment with beam extraction at five points.

IV. Preliminary results

The functionality of the implemented DLL architecture proposed in section II-A2 was verified in a weak light environment and in the presence of LISA-like noise sources, i.e., interference with a second PRN and encoded data. Figure 9

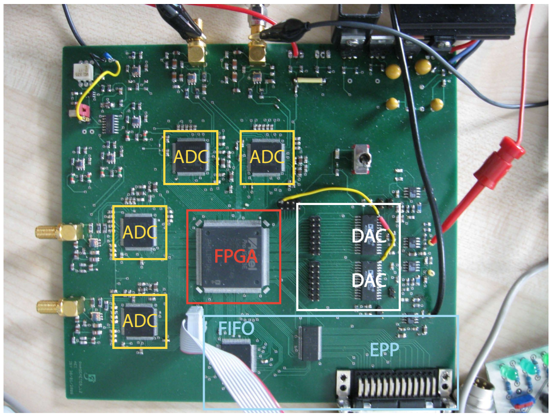

Fig. 7. PMS breadboard. Main processor unit: ProAsic3E Actel FPGA with 3 million system gates. Four input channels (AD9446-100), two output channels (AD9744-210), output interfaces: Digital Input/Output at 2 GB/s and parallel port at 1 MB/s.

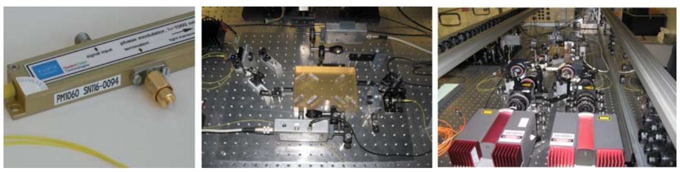

Fig. 8. Fibre coupled electro-optic modulator (left), Mach-Zehnder interferometer (centre), lasers and optics (right).

shows the standard deviation of the estimated delay with respect to the averaging time. Both the master laser at roughly 100 pW and the slave laser at 1 mW are phase modulated with two different data-encoded PRN signals. After interference the resulting beatnote is demodulated by the phasemeter. The tracked signal is a time-varying PRN with an equivalent inter-spacecraft velocity of 100 m/s, which is an order of magnitude above the 15 m/s that is predicted for LISA. The ranging measurements were obtained taking into account four different code-length correlations. Experimental results demonstrate a ranging accuracy of 45 cm at 10 Hz for a data rate of 12 Kbps. Investigations are ongoing to improve the effective ranging accuracy by post-processing, taking into account optical Doppler shifts measurements in the phasemeter and orbit integration with Kalman filters.

V. Conclusions

This paper has provided an overview of the inter-spacecraft laser ranging capabilities and presented a new hardware implementation based on two main architectures. A digital phase-locked loop for control of the carrier tracking, and a delay-locked loop for control of the code tracking. The custom-designed breadboard can fit the architecture proposed, and its functionality with heterodyne interferometry has been verified with LISA-like noise sources. The designed system is suitable for investigations on additional LISA technologies; inter-spacecraft clock noise transmission or digital laser offset phase-locking. The implemented system may also have other

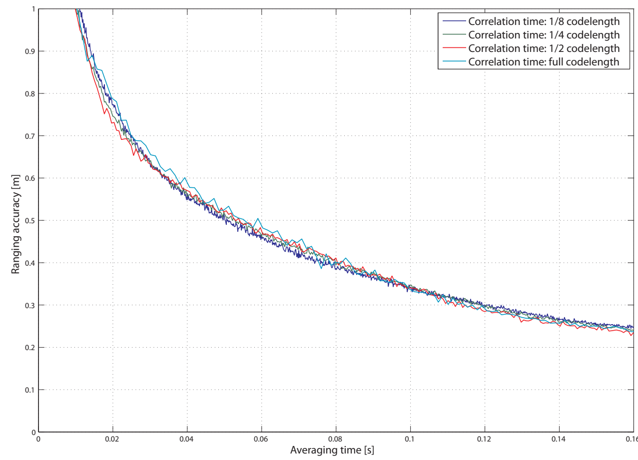

Fig. 9. Standard deviation of the optical ranging measurement in weak light environment with respect to the averaging time and in the presence of LISA-like noise sources, i.e., interference with a second PRN and data encoded.

space-based applications which demand similar requirements, including the GRACE follow-on mission [11], a future inter-planetary mission, or potentially for optical ground interferometers to isolate optical signals based on their delay [12].

References

[1] The LISA Study Team. *Laser Interferometer Space Antenna for the Detection and Observation of Gravitational Waves: Pre-Phase A Report*. Max-Planck-Institute for Quantum Optics, 1998.

[2] Esteban J.J, Garcia Marin A.F, Bykov I, Heinzel G, and Danzmann K. Free-space laser ranging and data communication. *IEEE Conf Proc*, pages 275–281, 2009.

[3] Esteban J.J, Bykov I, Garcia Marin A.F, Heinzel G, and Danzmann K. Optical ranging and data transfer development for lisa. *J. Phys.: Conf. Series*, (154), 2009.

[4] Misra P and Enge P. *Global positioning system, signals, measurements, and performance*.

[5] Folkner W. M. Lisa orbit selection and stability. *Class. Quamtum Grav.*, (18):4053–4057, 2001.

[6] *Laser Interferometer Space Antenna: Sciencecraft Description*. LISA-SC-DD-0001. NASA Goddard Space Flight Center, 2009.

[7] Klipstein W, Halverson P.G, Peters R, Cruz R, and Shaddock D.A. Clock noise removal in lisa. *AIP Conference Proceedings: 6th International LISA Symposium*, (873):312318, 2006.

[8] Shaddock D, Ware B, Halverson P, Spero R, and Klipstein B. Overview of the lisa phasemeter. *AIP Conf Proc*, (873):654–660, 2006.

[9] Bykov I, Esteban J.J, Garcia Marin A.F, Heinzel G, and Danzmann K. Lisa phasemeter development: Advanced prototyping. *J. Phys.: Conf. Series*, (154), 2009.

[10] Simon B, Troebs M, Sheard B, Heinzel G, and Danzmann K. Phase noise contribution of EOMs and HF cables. *J. Phys.: Conf. Series*, (154), 2009.

[11] Dehne M, Guzman Cervantes F, Sheard B, Heinzel G, and Danzmann K. Laser interferometer for spaceborne mapping of the earth's gravity field. *J. Phys.: Conf. Series*, (154), 2009.

[12] Shaddock D.A. Digitally enhanced heterodyne interferometry. *Opt Lett*, (22):3355–3357, 2007.