A Cyclic Matched Filter Approach To Delay Space Mapping For Digital Interferometry With Applications to Optical Phased Arrays

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INTRODUCTION

THIS PROJECT is a continuation of work done in the previous semester on solving the Delay Space mapping problem for Digital Interferometry (DI) [1]. DI is a technique in optical metrology that allows for multiple interferometric measurements to be performed with a single metrology scheme using code-division techniques adapted from spread spectrum communications [2]. An example DI scheme for distributed vibrometry is presented in Figure 1, the purpose of such a scheme is to concurrently measure micrometre scale vibrations of multiple back-reflectors in an optical fibre. To achieve this an Electro-Optic Modulator is used to encode the phase of an interferometer's signal arm at a depth of ζ with a Pseudo-Random Binary Sequence (PRBS). The interferometric returns from each back-reflector are recombined together with a phase-stable Local Oscillator (LO) arm which is shifted up in frequency by a "heterodyning frequency" f_H before detection [2].

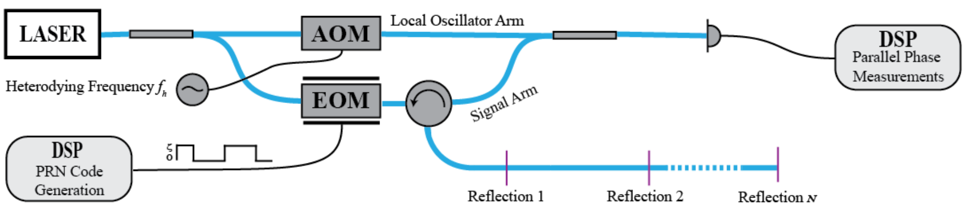

Fig. 1. Schematic Diagram of an Example Digital Interferometry Scheme for distributed vibrometry.

An approximation of the signal that we expect at the photodetector under the assumption that the local oscillator power is significantly greater than the optical power of the reflections being measured is given by Equation 1. Each V_i is an amplitude, and each $\phi_i(t)$ is a phase signal we want to eventually measure. $c(t)$ is the PRBS modulated onto the signal arm and V_{DC} is a DC offset. The essence of the delay space mapping problem is to estimate the 'delays' $\tau_1, ..., \tau_N$ from samples of such a photodetector voltage signal to facilitate the decoding of each phase signal $\phi_i(t)$. This phase signal can then be used to discriminate changes in distance on the order of the wavelength of light being used.

$$\begin{aligned} V_{\text{PD1}}(t) &= V_1 \cos\left(2\pi f_L t - \phi_1(t) - \zeta c(t-\tau_1)\right) + V_2 \cos\left(2\pi f_H t - \phi_2(t) - \zeta c(t-\tau_2)\right) + ... \\ &\qquad ... + V_N \cos\left(2\pi f_H t - \phi_N(t) - \zeta c(t-\tau_N)\right) + V_{\text{DC}} \end{aligned} \tag{1}$$

In an evolution of previous work deploy a cyclic correlation [3] based digital matched filter [4] to exploit the periodicity of PRBSs and produce a 'map' of the delay space which gives information about the signal amplitude at all possible delays. In doing so we rely on the code-generation linear-feedback-shift-registers (LFSRs) and sampling clocks being matched in frequency to perform the process depicted in Figure 2. The frequency matching is required to ensure the code period can be given as an integer number of samples, permitting the use of the cyclic cross-correlation to perform the matched filtering.

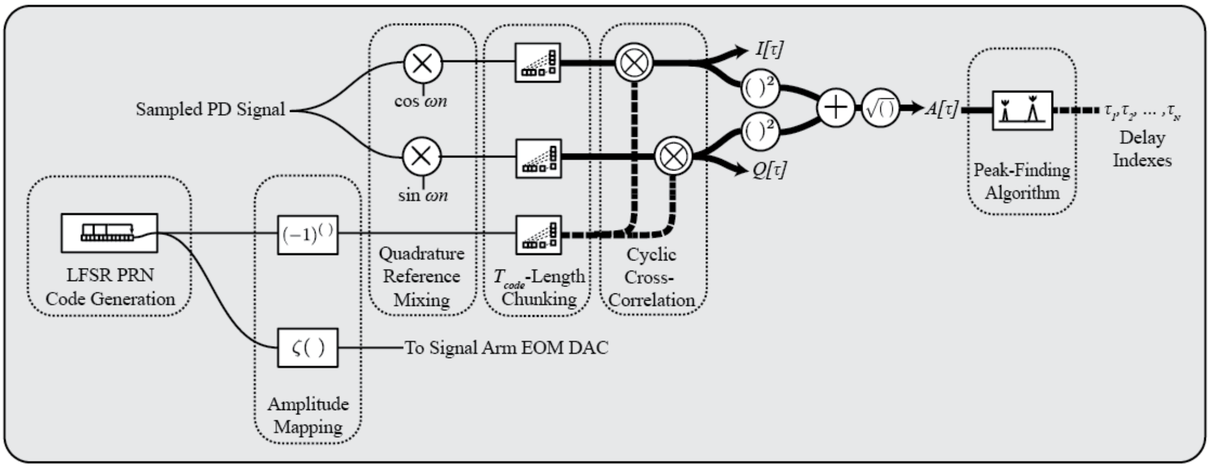

Fig. 2. Schematic diagram of the proposed delay space mapping DSP pipeline. $A[\tau]$ is the amplitude quadrature measurement for DI signals matching delay τ, likewise $Q[\tau]$ is the phase quadrature. $A[\tau]$ is the amplitude-at-delay measurement.

The aim of this project is to implement the proposed technique for a real DI scheme. In this case for a 4-emitter internally sensed optical phased array as depicted in Figure 3. The experiments will attempt to map the delay space of the back reflections on the optical emitter heads, pushing towards shallow encoding depths and shorter code lengths.

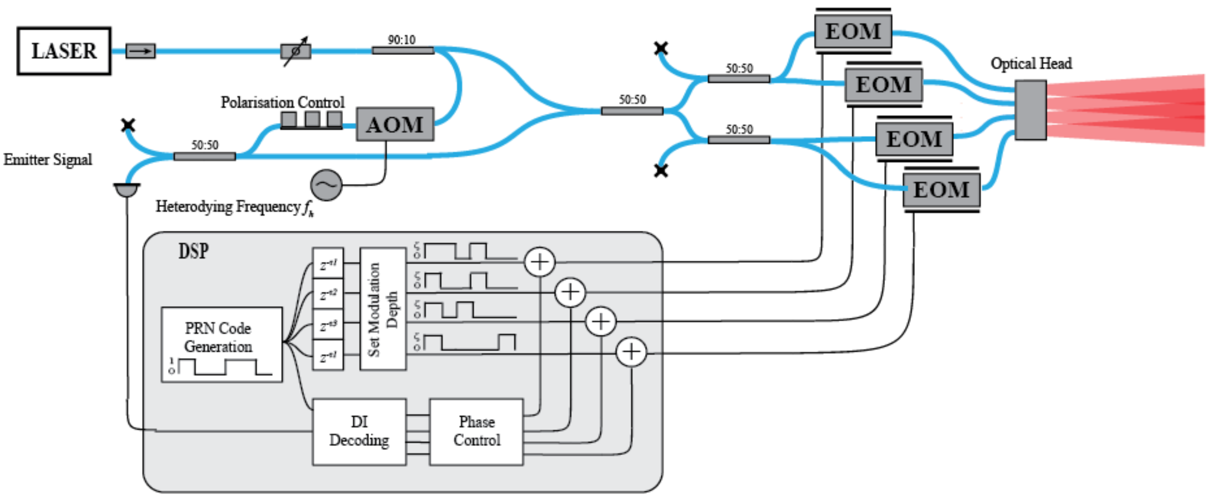

Fig. 3. Schematic Diagram of an example Internally Sensed 4-Element Linear Optical Phased Array with a phase control feedback loop.

WORK COMPLETED TO DATE

Literature Review Progress

A Draft Literature review has been completed but will be subject to future revisions. It encompasses the following topics:

- Digital Interferometry Fundamentals
- Internally Sensed Optical Phased Arrays and Breakthrough Starshot
- Fast Fourier Transforms
- Matched Filters
- Field Programmable Gate Arrays (With emphasis on the programming thereof with NI LabView)

The content in the Fast Fourier Transforms section will be reduced from it's current iteration to allow for inclusion of discussions of the GPS code acquisition algorithms from which the method presented draws significant inspiration from.

Paper Draft Progress

A draft journal paper with working title 'A Technique for Single-Shot Delay-Space Mapping and Phase Measurement in Digital Interferometry using a Cyclic Matched Filter Approach' is currently in progress for submission in Week 8. The paper is to contain a detailed overview of the technique presented in Figure 2, including how phase measurements for every single possible delay can be obtained by computing $\phi_i = \arg(I[\tau_i] + jQ[\tau_i])$. The figures to be presented in this paper will be similar to that presented previously in [1] but results will be from simulations of the new matched filter approach developed after the submission of [1]. The draft paper will be in an Optica journal format and cover the following topics:

- Introduction to Interferometry
- Digital Interferometry, its Applications and the Delay Space mapping problem
- Matched Filters and Code Acquisition algorithms
- The proposed FFT-based delay space mapping algorithm
- Simulation results

Experimental Progress

Current experimental progress has advanced to the point of successful application of the technique presented in Figure 2 to map the delay space of a four emitter internally sensed OPA of the architecture depicted in Figure 3. An image of the delay space map obtained can be seen in Figure 4. It was determined that averaging the results of multiple delay space snapshots in a way akin to the pulse integration techniques used in pulsed radar systems improved the peak prominence [5]. The cause of the odd behaviour obscuring some of the peaks seen in Figure 4 before averaging is yet to be determined and investigation of this may form a part of the paper, the current hypothesis is that at low modulation depths we get insufficent supression of unencoded beatnote components with the current short 31 chip code. The current computational architecture involves performing the mixing stage on an FPGA and then bit-interleaving the results of the two mixed signals and the reference code together to be transported to the host CPU as a block of length T_{code} samples. The host CPU then de-interleaves and performs the appropriate cyclic cross correlations with length T_{code} FFTs and IFFTs before computing the delay space from the results.

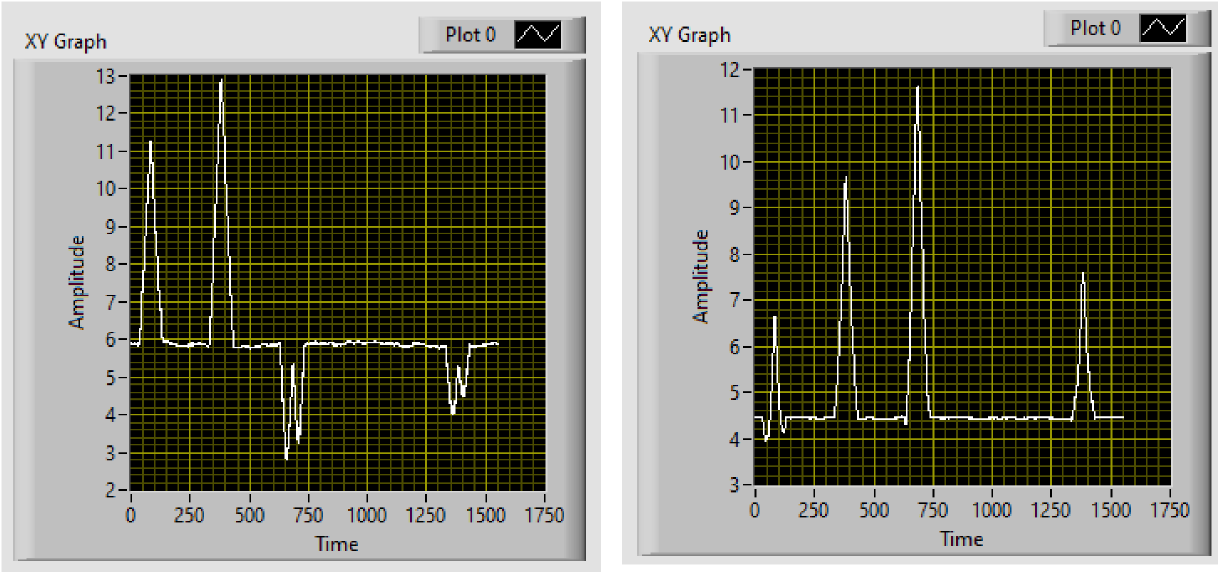

Fig. 4. Image of successful delay space map for an internally sensed OPA. (Left) map of the delay space from a single acquisition. (Right) Average of 10 delay space maps from 10 acquisitions.

Indicative Timeline for Remaining Work

The following is an indicative timeline for the remaining work in the project.

Week	Items	Deliverables
7	Continuously Updating Delay Space Map	Mid-Sem Report
8	Debug Previous Week's Work	Draft Theory/Simulation Paper
9	Attempt to operate at data-rate with FFTs on FPGA	
10	Debug Previous, Attempt to simulate signal from ≥ 16 Emitters	
11	Attempt Ranging. Seminar Slide Writing. Final Report Writing	Seminar Slides
12	Final Report Writing	Final Report

Issues Affecting the Project

The main issue affecting this project has been the continual discovery of relevant literature that has resulted in constant re-framing of the Paper and the Report. The first of these was the discovery of matched filters as described in [4] and second was the discovery of FFT-based GPS code audition algorithms as described in [6]. This has significantly delayed the writing of the draft paper. Further, the literature review has been difficult to write in that to avoid re-treading too much ground previously covered in [1] the review is forced to neglect spending too much time explaining many of the basics, to account for this may require a comprehensive set of appendicies in the final report.

REFERENCES

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