Electronic Phase Delays

- A First Step Towards A Bench-Top Model of LISA -

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Overview

Current Work

- What is Electronic Phase Delay (EPD)?
- Using EPD to make a “Synthetic Interferometer”

Future Work

- Upcoming experiments
- The bench-top LISA model

Introduction I -
A Simple Model of A Single LISA Arm

- Laser field

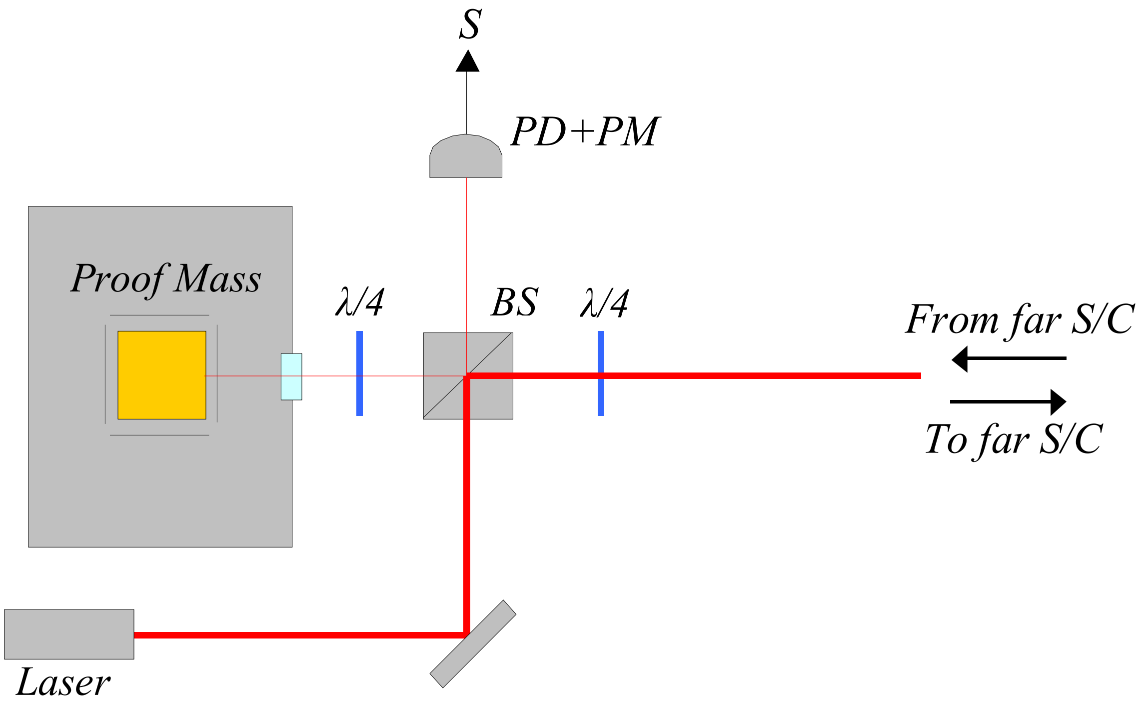
$$E(t) = E_0 \exp\{i[\omega t + \phi(t)]\}$$

- Phase Meter (PM) Signal

$$S(t) \propto \phi(t) - \phi(t - \tau_{RT})$$

τ_{RT} ❺ round-trip light travel time

- Simplifying Assumptions
  - far S/C acts as perfect optical transponder (mirror)
  - stationary S/C (no Doppler shifts)



Introduction II - The Problem

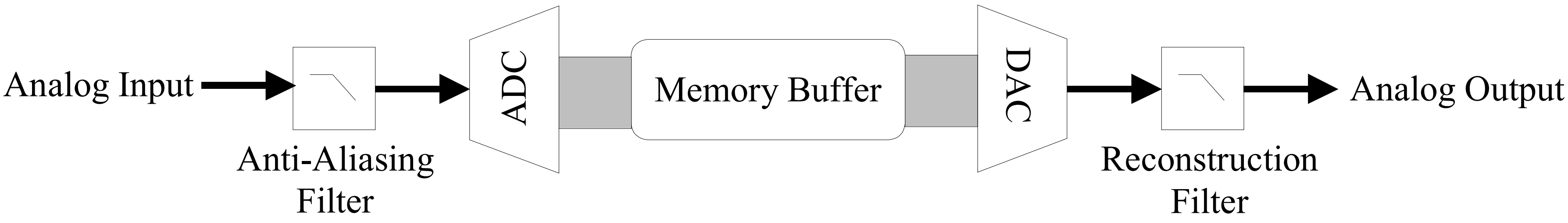
The large Optical Path Lengths (OPLs) in LISA correspond to $\tau_{RT} \sim 33$s. It is virtually impossible to create physical OPLs of this size in the laboratory.

Solution: We only need to delay the *phase* of the laser.

- **demodulate it with a stable oscillator (another laser)**
- **digitize the difference phase**
- **store it in a buffer**
- **regenerate the signal**

} Electronic Phase Delay (EPD)

Implementation of Electronic Phase Delay (EPD)



Analog Input

Anti-Aliasing Filter

ADC

Memory Buffer

DAC

Reconstruction Filter

Analog Output

Three Steps

- Digitize input signal
- Store in a FIFO memory buffer for the desired time.
- Regenerate analog signal

Current Iteration

- MicroStar DAP5216a Data Processing Card
- 200kS/s
- 16-bit
- signals ❣ 30kHz are reproduced well

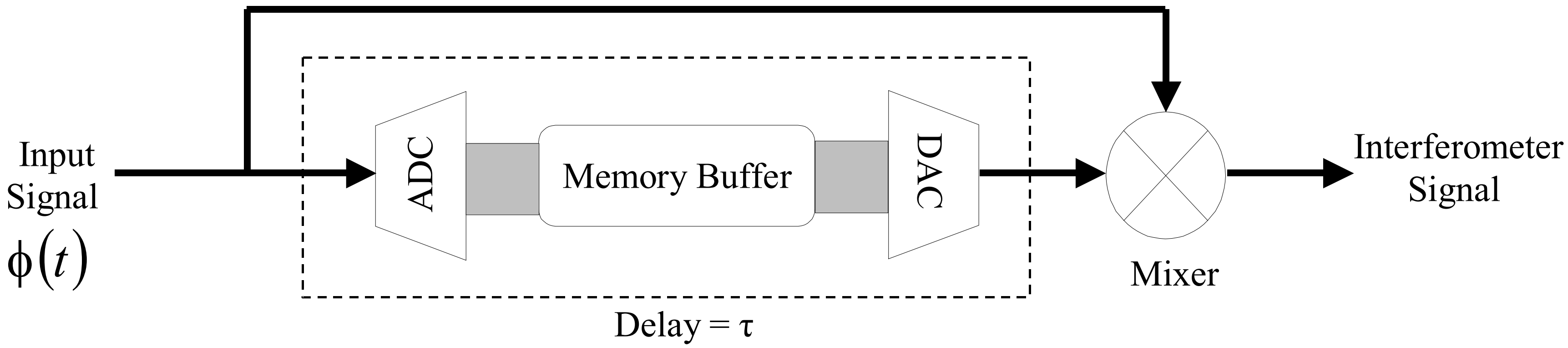
Limitations

- Digitization Rate (limits bandwidth)
- Digitization Precision (noise)

Future Technologies

- Increase digitization rate so that signals up to 20MHz can be delayed.

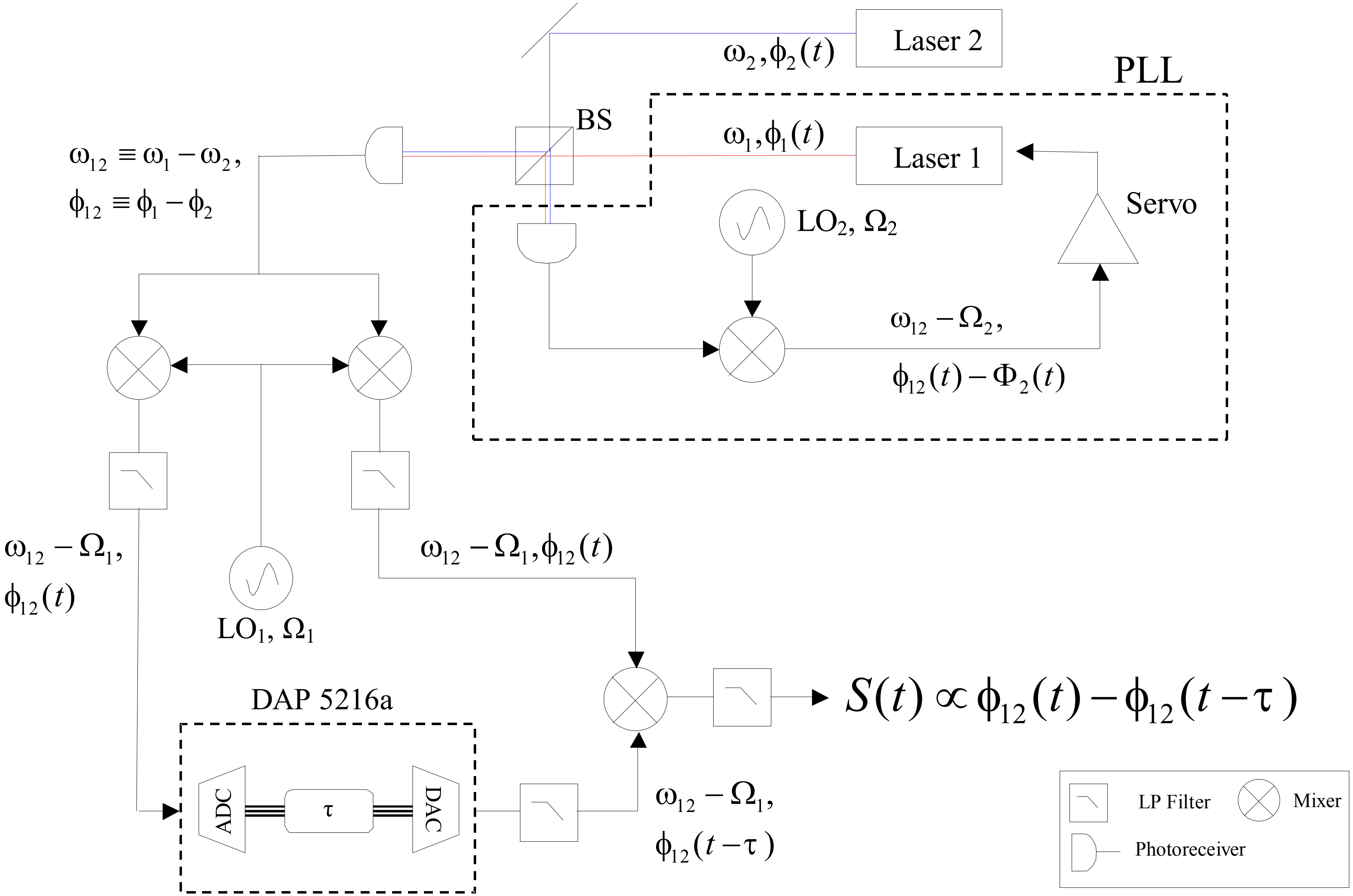
Using EPD to Make a Synthetic Interferometer



Mixer Output, $S \propto \phi(t) - \phi(t - \tau)$

Equivalent to an interferometer with one long arm having a delay of τ

Demonstration of a Synthetic Interferometer



Response To Frequency Step

- Time delay

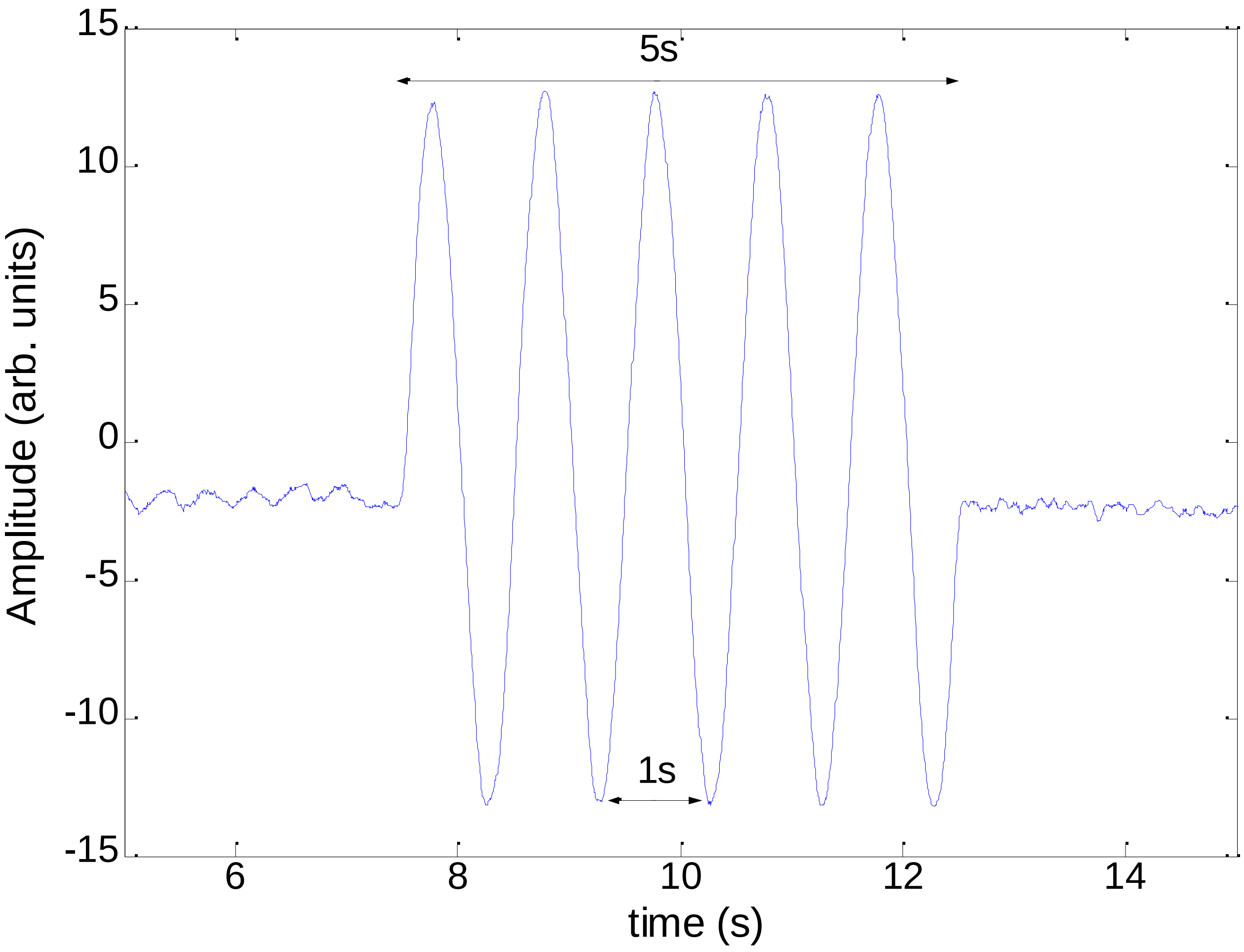
  $\tau = 5s$

- Step change of 1Hz on Laser 1

(Achieved by stepping LO_2)

- Observed Response

  1Hz oscillation lasting for 5s.



Frequency Response

- Time delay

  $\tau = 1s$

- Frequency Ramp on Laser 1

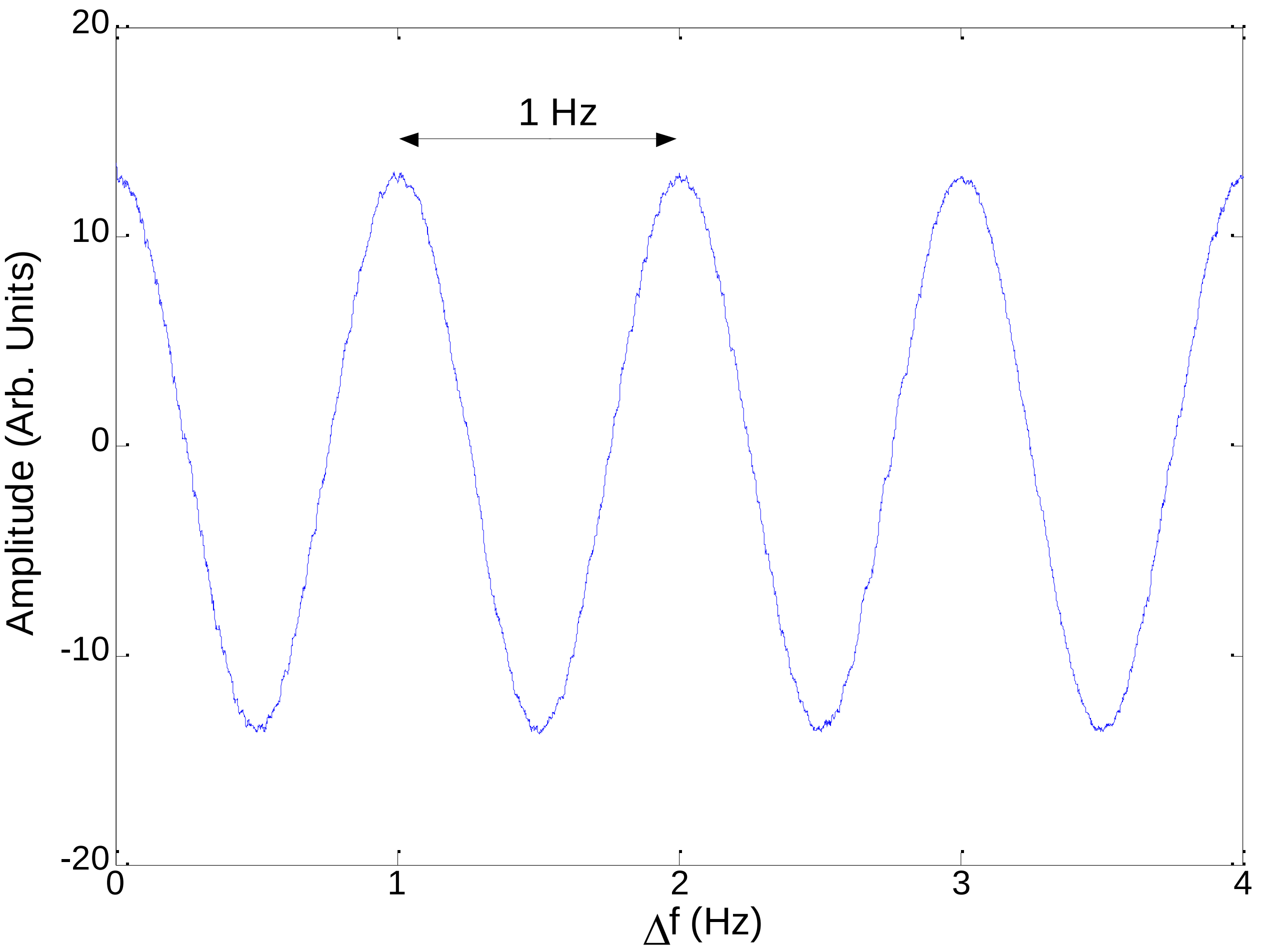
  (by modulating LO_2)

  $\Omega_2 = 2\pi\left(20.03MHz + \Delta f\right)$

  $\Delta f = \left(100mHz/s\right)\times t$

- Observed Response

  Sinusoidal amplitude variations with a frequency spacing of $1/\tau = 1$Hz



Response to Phase Modulation I - Theory

- Mixer Output

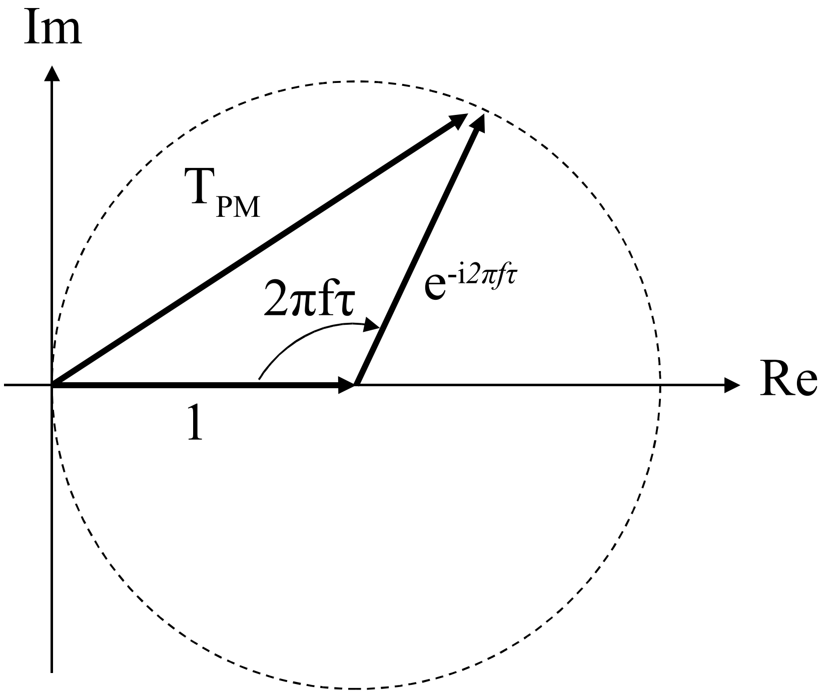
$$S(t) \propto \phi_{12}(t) - \phi_{12}(t-\tau)$$

- Fourier Transform

$$\tilde{S}(2\pi f) \propto \tilde{\phi}_{12}(2\pi f)\left(1 - e^{-i2\pi f\tau}\right)$$

- Transfer Function

$$T_{PM}(2\pi f) \equiv \frac{\tilde{S}(2\pi f)}{\tilde{\phi}(2\pi f)} \propto \left(1 - e^{-i2\pi f\tau}\right)$$



$$\left|T_{PM}(2\pi f)\right| \propto \left|\sin(\pi f\tau)\right|$$

$$\angle T_{PM}(2\pi f) = \tan^{-1}[\cot(\pi f\tau)]$$

Zeros at f_0 ❺ n / τ

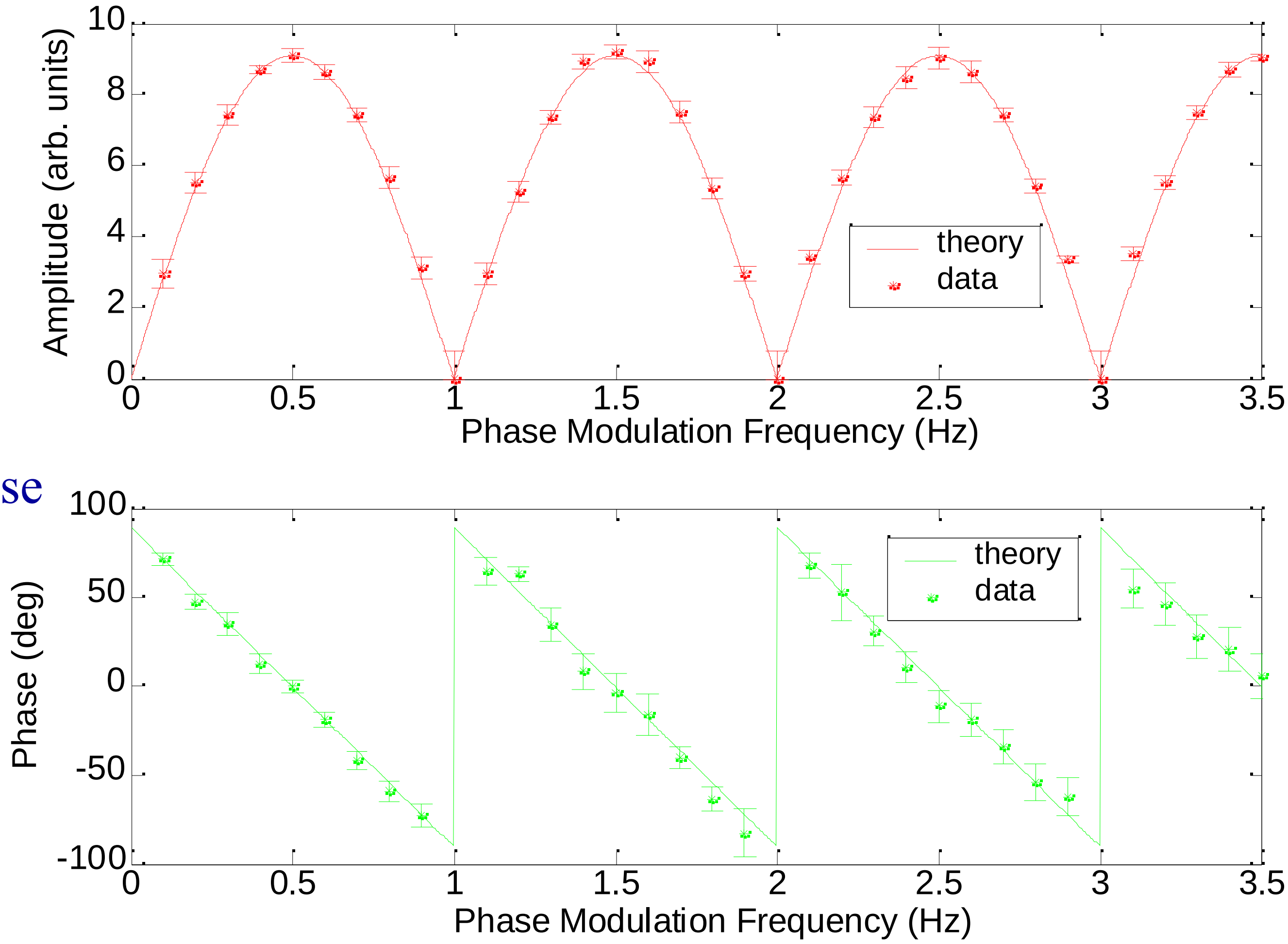
Phase Discontinuity from –90° to +90° at f_0

Response to Phase Modulation II - Results

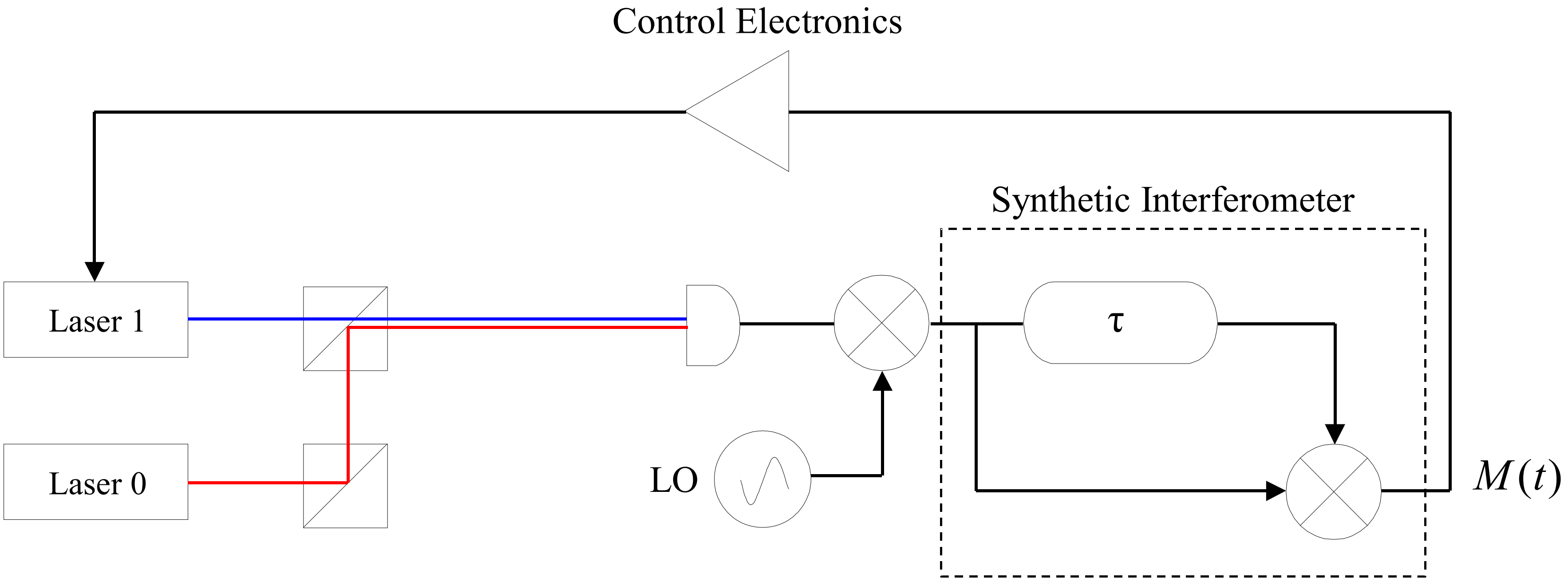
- Time delay

  $\tau = 1s$

- PM on Laser 1
  - Sinusoidal at a frequency of f_{PM} with a modulation depth of 20^{o}.
- Observed Response
  - No response at $f_{PM} = n/\tau$, $n = 1,2,3\ldots$
  - 180^{o} phase discontinuity at $f_{PM} = n/\tau$



The Next Step I – Arm Locking



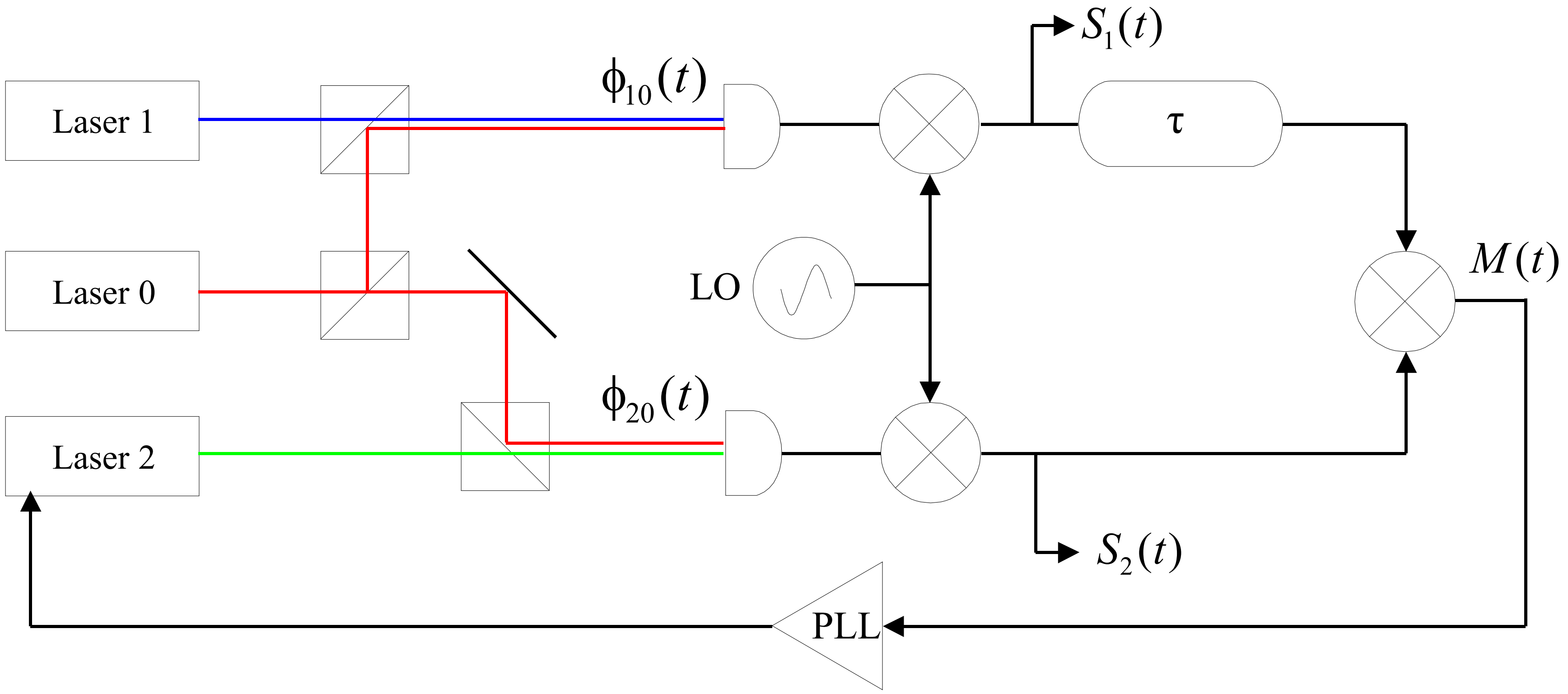
Interferometer Signal

$$M(t) \propto \phi_{10}(t) - \phi_{10}(t-\tau)$$

Lock laser phase difference to interferometer zero

$$\phi_{10}(t) = \phi_{10}(t-\tau)$$

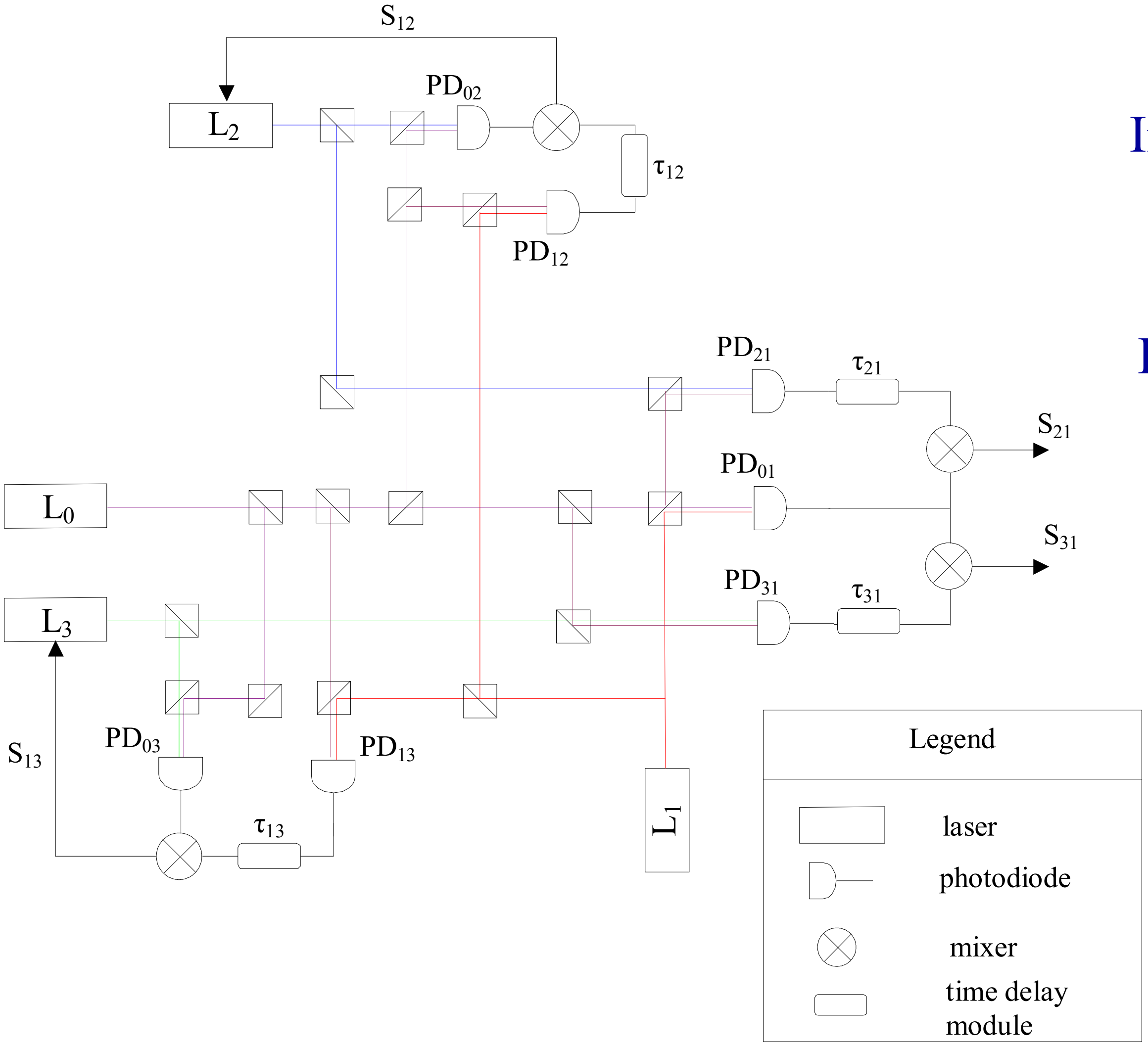
The Next Step II – "TDI" With a Single LISA Arm



Phase Lock $M(t) = 0 \Rightarrow \phi_{20}(t) = \phi_{10}(t-\tau)$

Experimental Test $\angle S_2(t) = \phi_{20}(t) \overset{?}{=} \angle S_1(t-\tau) = \phi_{10}(t-\tau)$

The Next Step III – TDI with Two Arms



Interferometry Signals on S/C 1

$$S_{21}(t)\ \&\ S_{31}(t)$$

Experimental Test of TDI

$$\begin{aligned}&S_{21}(t)-S_{21}(t-\tau_{13}-\tau_{31})\\&-S_{31}(t)+S_{31}(t-\tau_{12}-\tau_{21})\\&=0?\end{aligned}$$

Long Term – Getting to a model LISA

- Incorporate additional features

- clock noise

- Doppler shifts

- bench motion

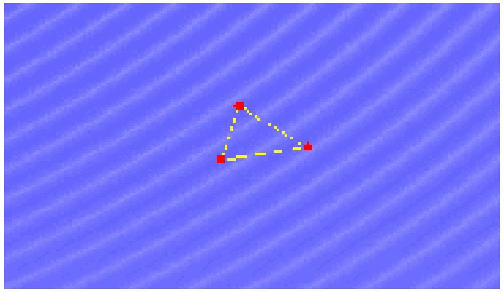
- Add 3^{rd} arm

- Add GW signals

- Incorporate data reduction algorithms

- …?

Take it for a test drive!



Host a "Mock Data Challenge" in which we inject a GW signal and then attempt to extract it.

Thanks/Questions

The LISA crew at UFL

(front row, left to right) Ira Thorpe, Shannon Sankar, Rodrigo Delgadillo, Derek Mulder (standing) Rachel Parks, Guido Mueller

Frequency Response - 2

- Time delay

$$\tau = 5s$$

- FM on Laser 1

(by modulating LO_2)

$$\Omega_2 = 2\pi\left(20.03MHz + \Delta f\right)$$

$$\Delta f = \left(100mHz/s\right)\times t$$