Testbed for Validating Second-Generation TDI and Clock Noise Correction for LISA

Karin Kruuse

Reid Ferguson, Daniele Vetrungo, Guido Müller

Outline of the Talk

- LISA interferometry
- About previous LISA simulators
- Overview of our proposed LISA testbed
  - Its purpose and goals
  - Status of the current purely electronic testbed
  - Putting together an optical input

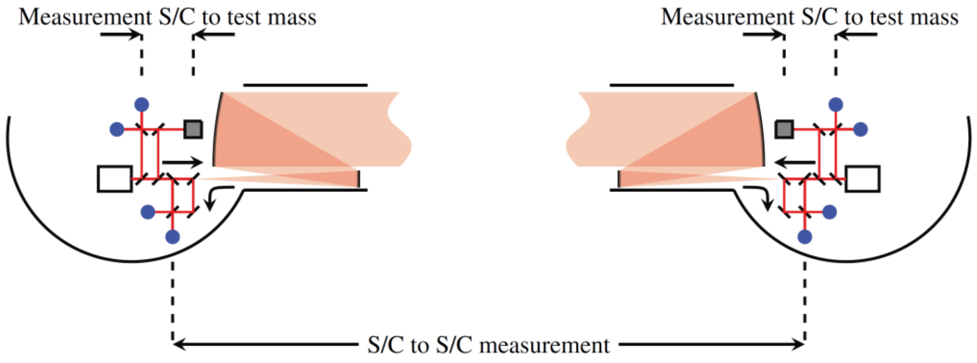
The Satellites

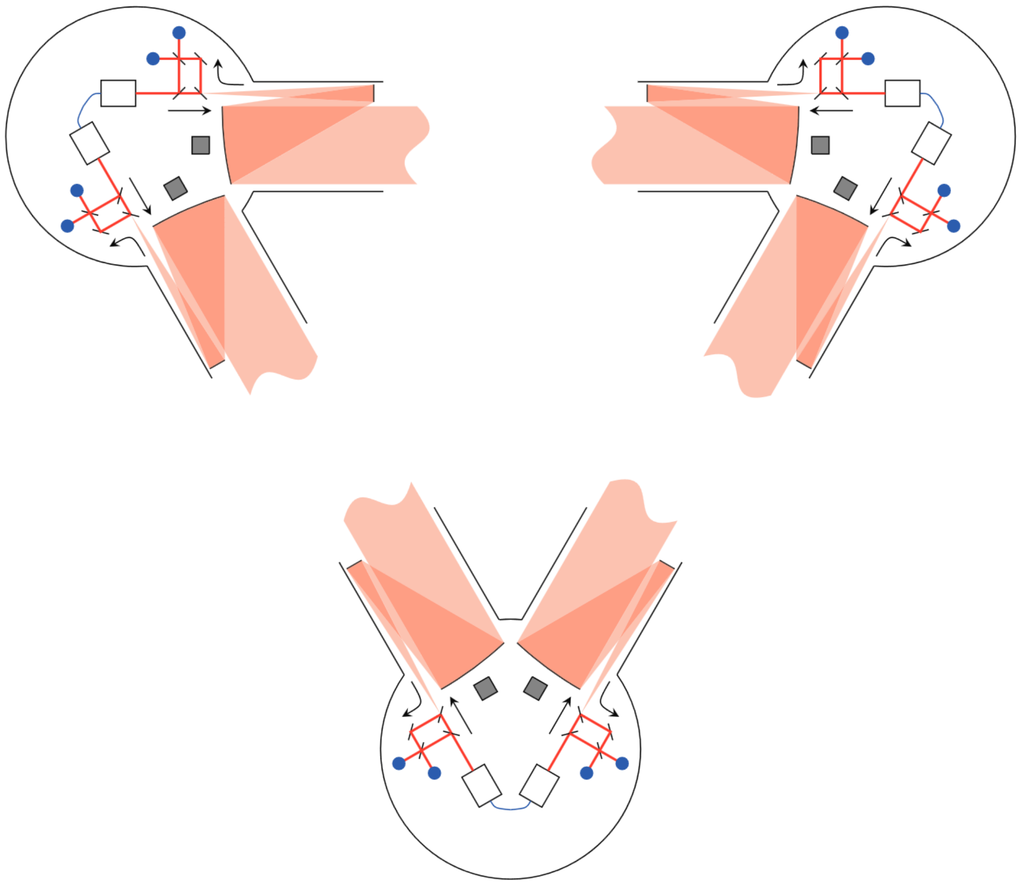
Three satellites surrounding six test masses in free fall

Each satellite houses two lasers, two optical benches and a phasemeter.

Each optical bench houses three interferometers.

The test mass to test mass distances are measured in three parts – this is the so-called split interferometry used in LISA.

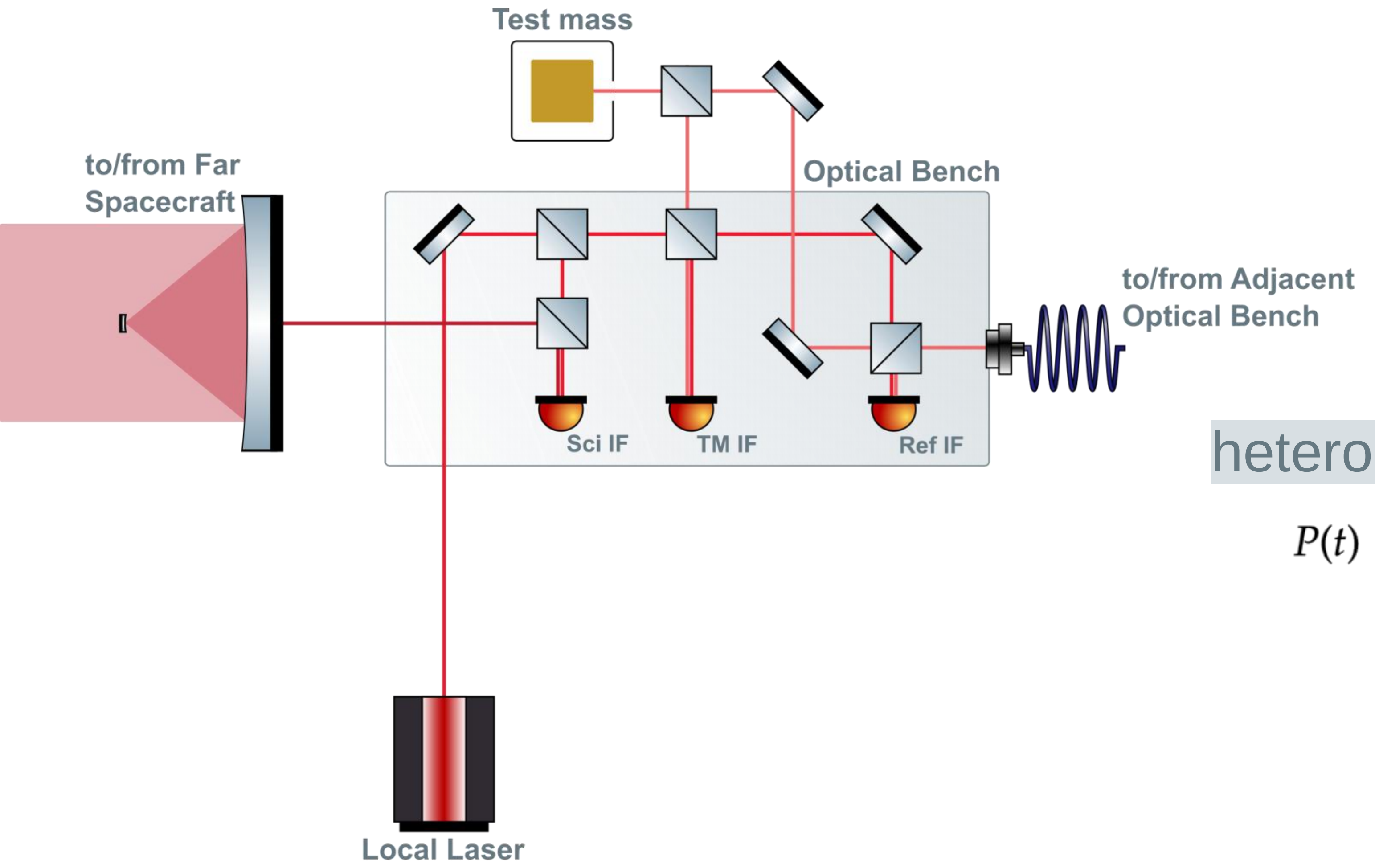




Jennrich, 2010

Internals of a LISA Spacecraft

LISA interferometric metrology system



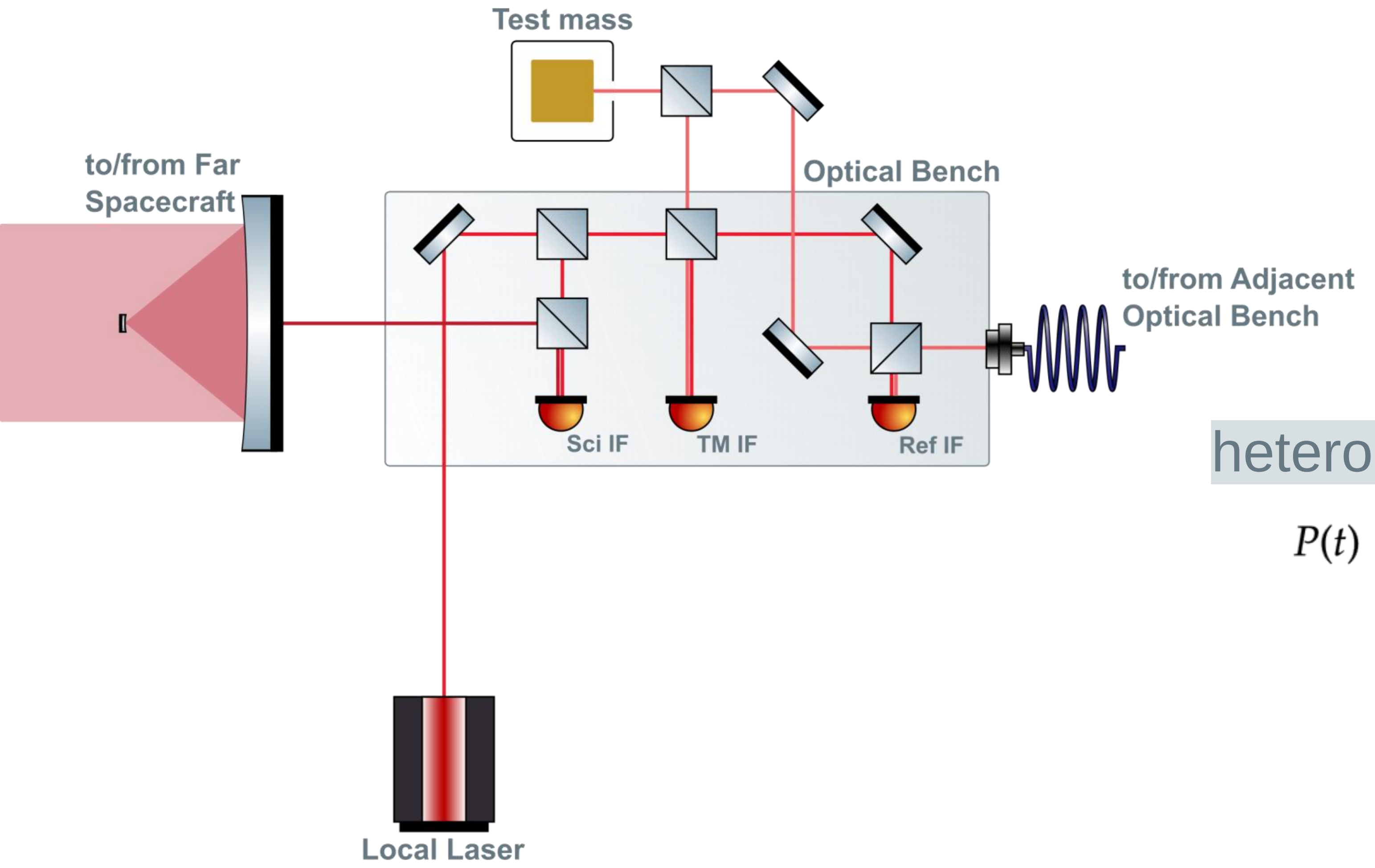
heterodyne interferometry

$$
\begin{aligned}
P(t) &\propto |E_1(t) + E_2(t)|^2 = \\
&= E_1^2 + E_2^2 + 2E_1E_2\cos((\omega_1 - \omega_2)t)
\end{aligned}
$$

$$E_i(t) = E_i \exp(j\omega_i t)$$

Internals of a LISA Spacecraft

LISA interferometric metrology system



heterodyne interferometry

$$P(t) \propto |E_1(t) + E_2(t)|^2 =$$

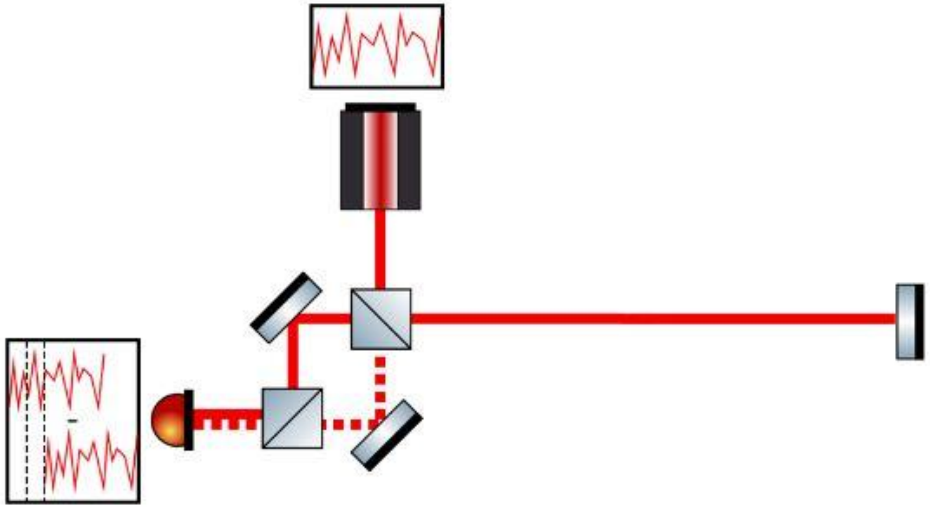
Beatnote

$$= E_1^2 + E_2^2 + \boxed{2E_1E_2\cos((\omega_1 - \omega_2)t)}$$

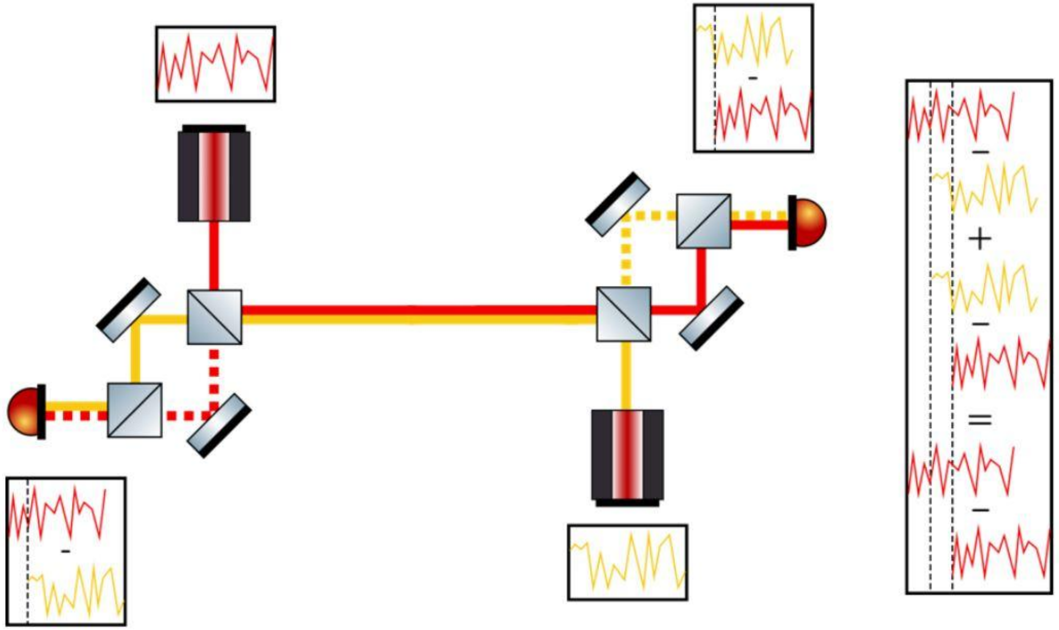
$$E_i(t) = E_i \exp(j\omega_i t)$$

Solution: Time Delay Interferometry

Time Delay Interferometry (TDI) is a cluster of methods to construct virtual equal arms in post-processing.



Transponder signal

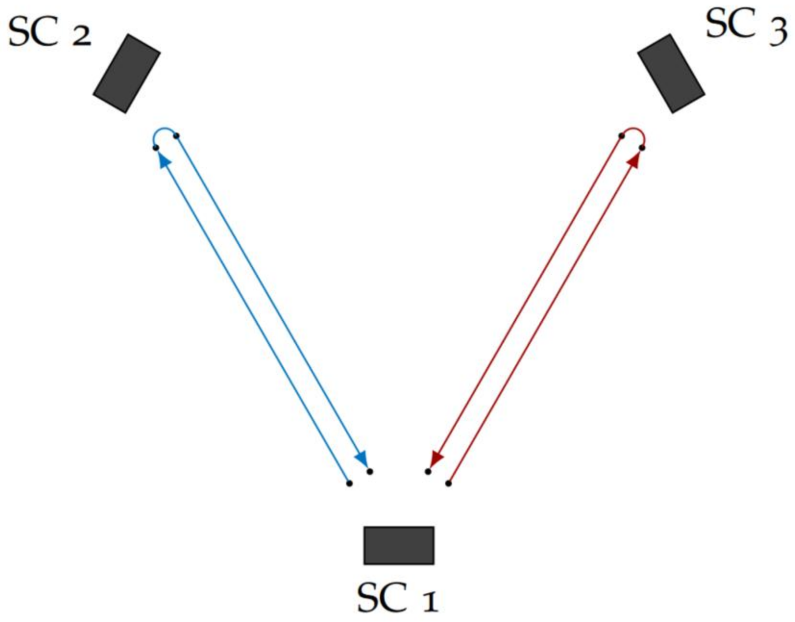


Virtual transponder signal

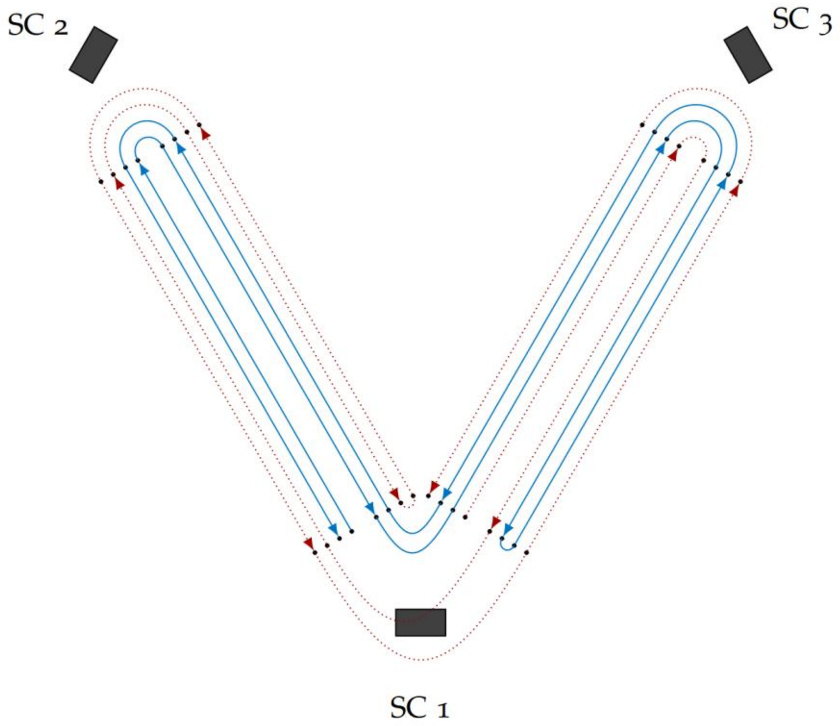
Hartwig, 2021

Solution: Time Delay Interferometry

Time Delay Interferometry (TDI) is a cluster of methods to construct virtual equal arms in post-processing.



0th generation TDI X combination, equal unchanging arm lengths



In practice, 2nd generation combinations should suppress noise enough to meet the requirement.

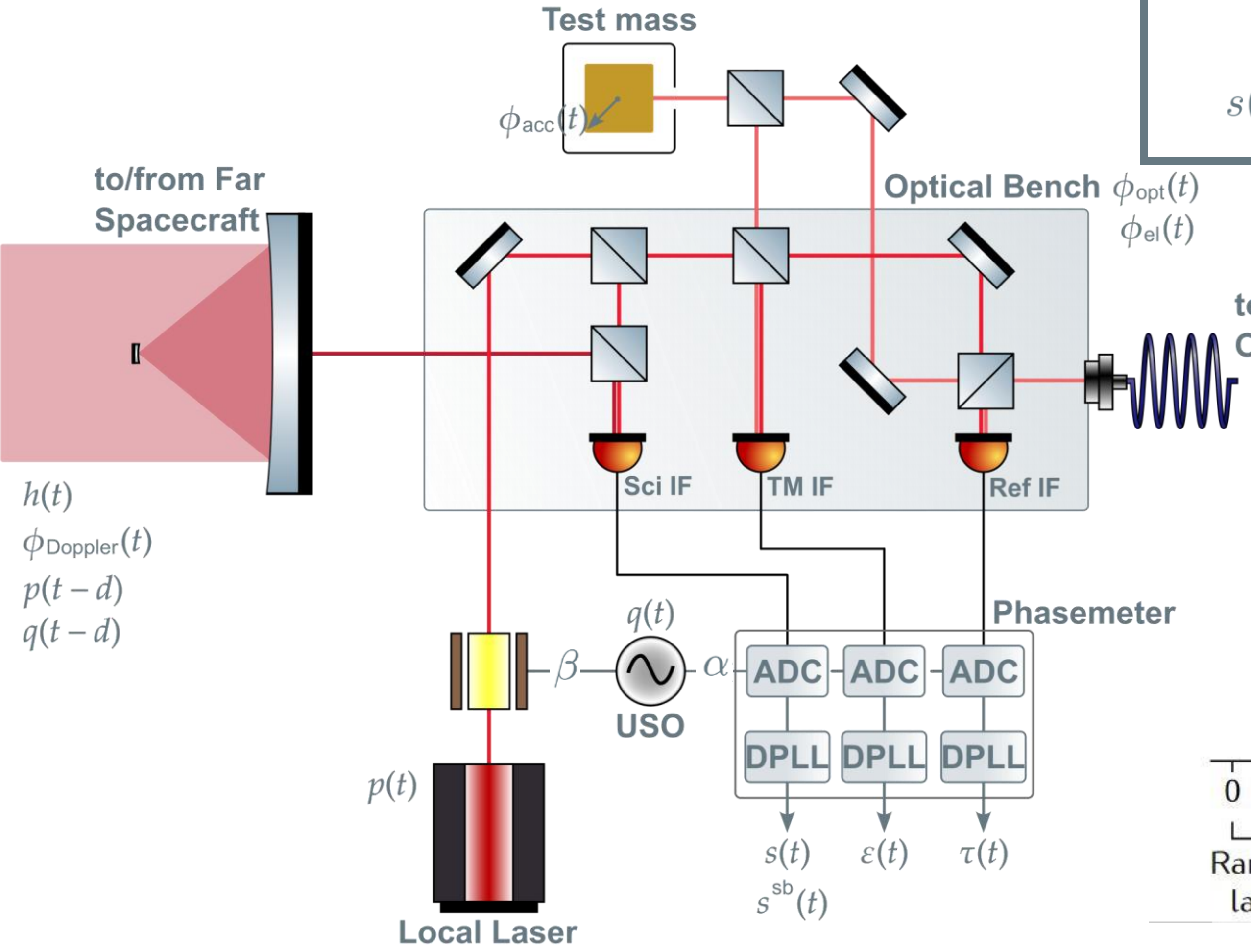
Hartwig, 2021

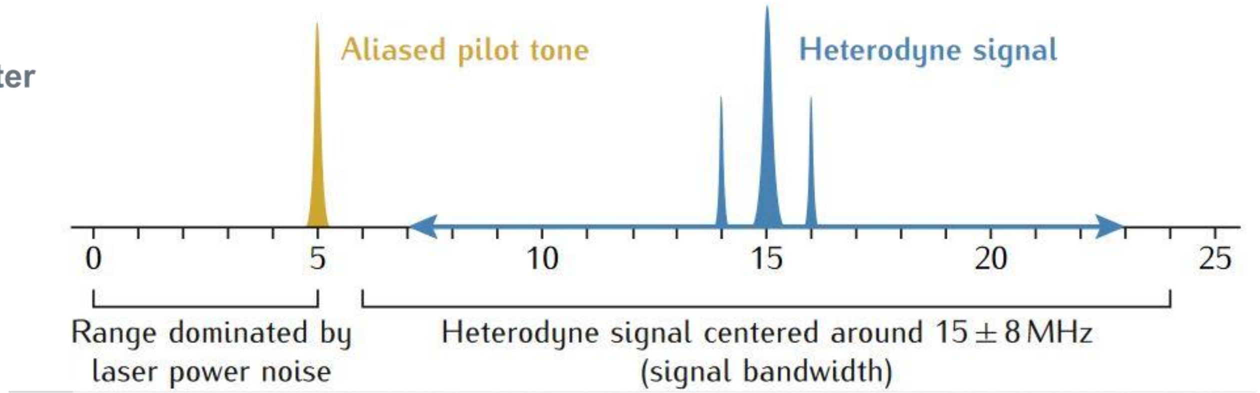
Solution: The Sidebands

After demodulation, considering laser noise and clock jitter:

$$s(t) = p_1(t) + p_2(t - d_{12}) + \alpha_1 q_1(t)$$

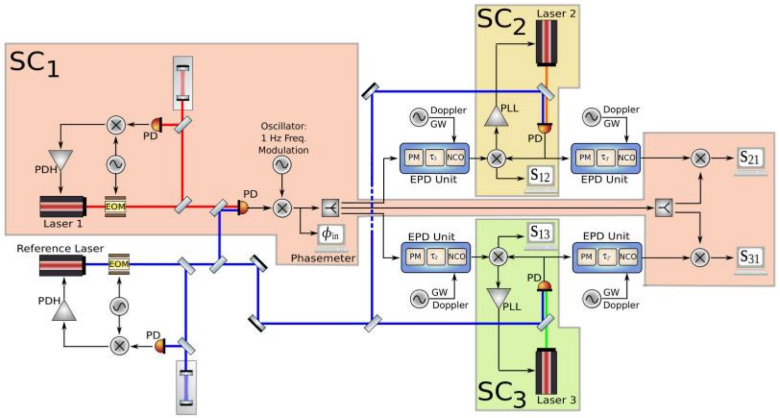
$$s(t)^{\mathrm{SB}} = p_1(t) + p_2(t - d_{12}) + \beta_1 q_1(t) + \beta_2 q_2(t - d_{12}) + \alpha_1^{\mathrm{SB}} q_1(t)$$



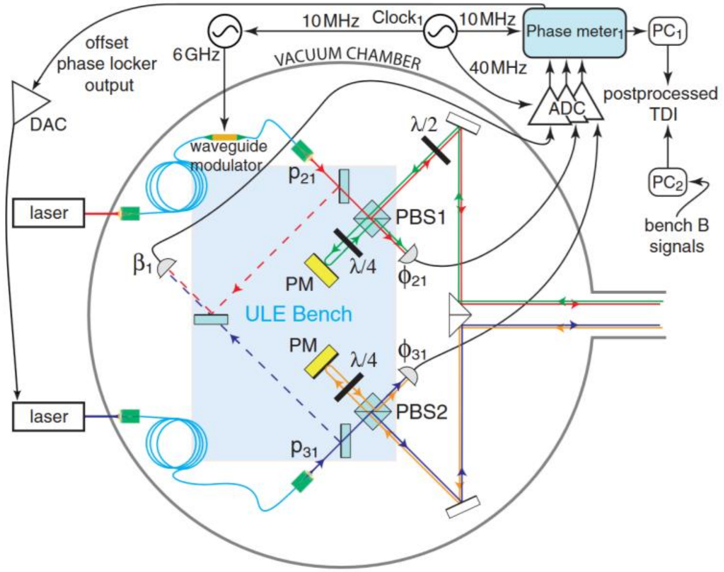


Lisa metrology system-final report, 2014

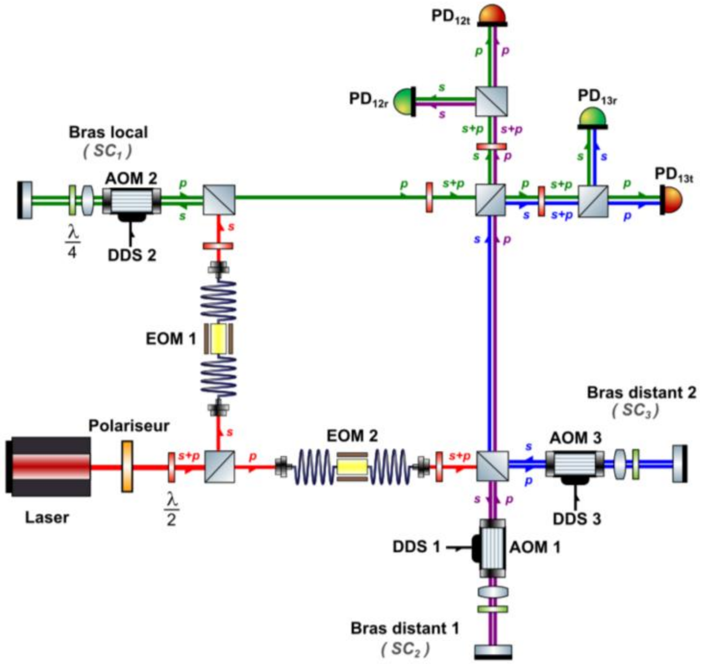
Previous Experiments



Mitryk, 2012: Laser Noise Mitigation through Time Delay Interferometry for Space-based Gravitational Wave Interferometers Using the UF Laser Interferometer



De Vine et al., 2010: Experimental Demonstration of Time-Delay Interferometry for LISA, JPL



Vidal, 2023: Validation expérimentale des performances interférométriques de LISA, Paris

Laser noise, No Clock Jitter, Realistic Delay

Laser noise, Clock jitter, No delay

Laser noise, Clock Jitter, Delay

MiniLISA

MiniLISA is a hardware testbed that aims to simulate LISA's signal chain and test whether we can recover a gravitational wave signal from a realistic, noisy system.

To start with, we want to test the combination of second generation TDI and the clock noise removal post-processing methods on experimental data.

MiniLISA could also offer a substitute to modelled noise sources included in current data analysis.

Current Status

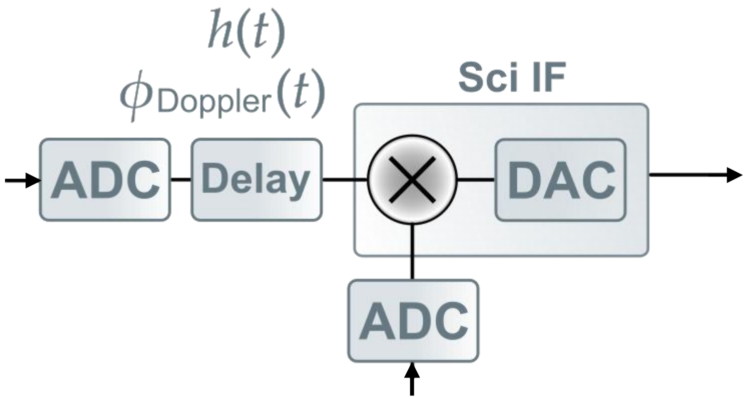
A fully electronic implementation of the interferometry system together with a delay and gravitational wave injection has already been developed and is being tested.

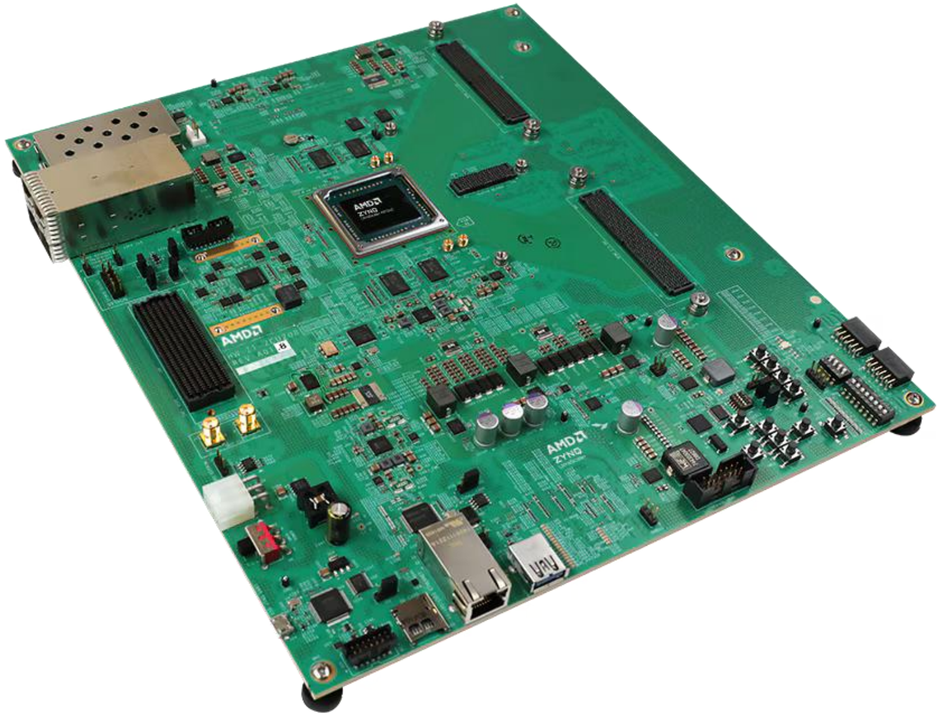
- Time varying delays
- Doppler shifts for both the carrier and sidebands
- Gravitational wave injection

The Delay Line

The center of the experiment is the delay line.

The added varying delays, gravitational wave signals and Doppler shifts are controllable via a Python-based interface.





AMD Zynq™ UltraScale+™ RFSoC ZCU208 Evaluation Kit

Signal Processing on the Delay Line

The evaluation board includes enough to take in two photodetector readings and output the corresponding LISA-like beatnote as an electrical signal.

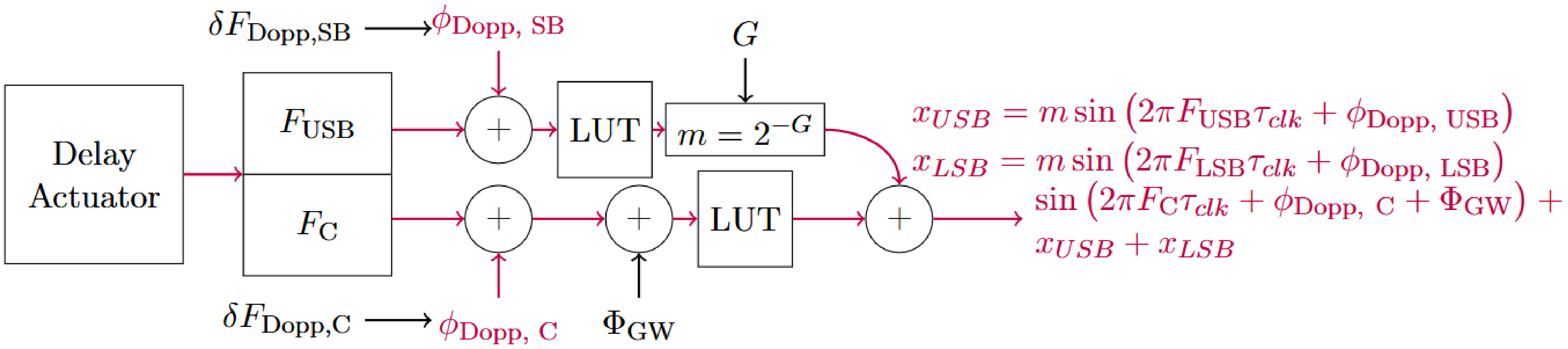


Figure 3: Block diagram of Doppler- and GW-derived phase modulation of the carrier after the delay.

Credit: Reid Ferguson

Delay Line Noise Measurement

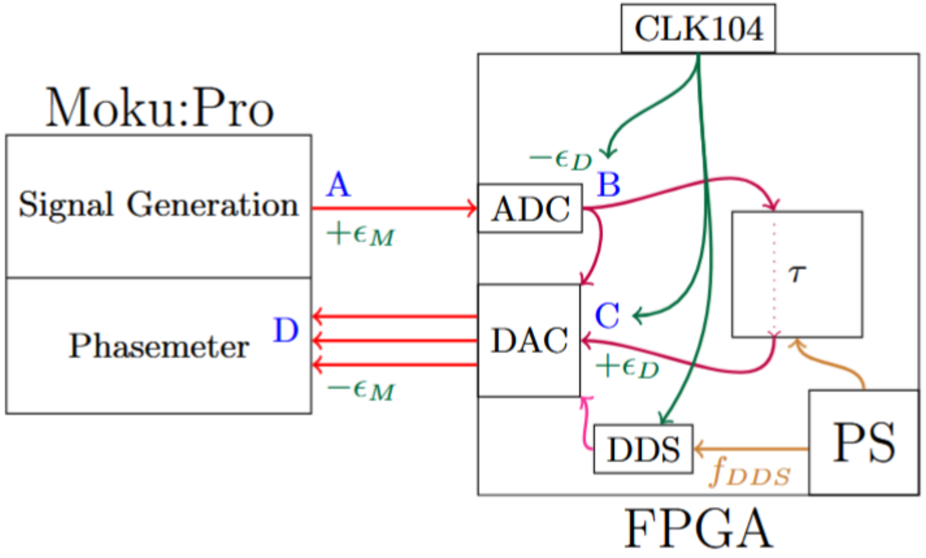
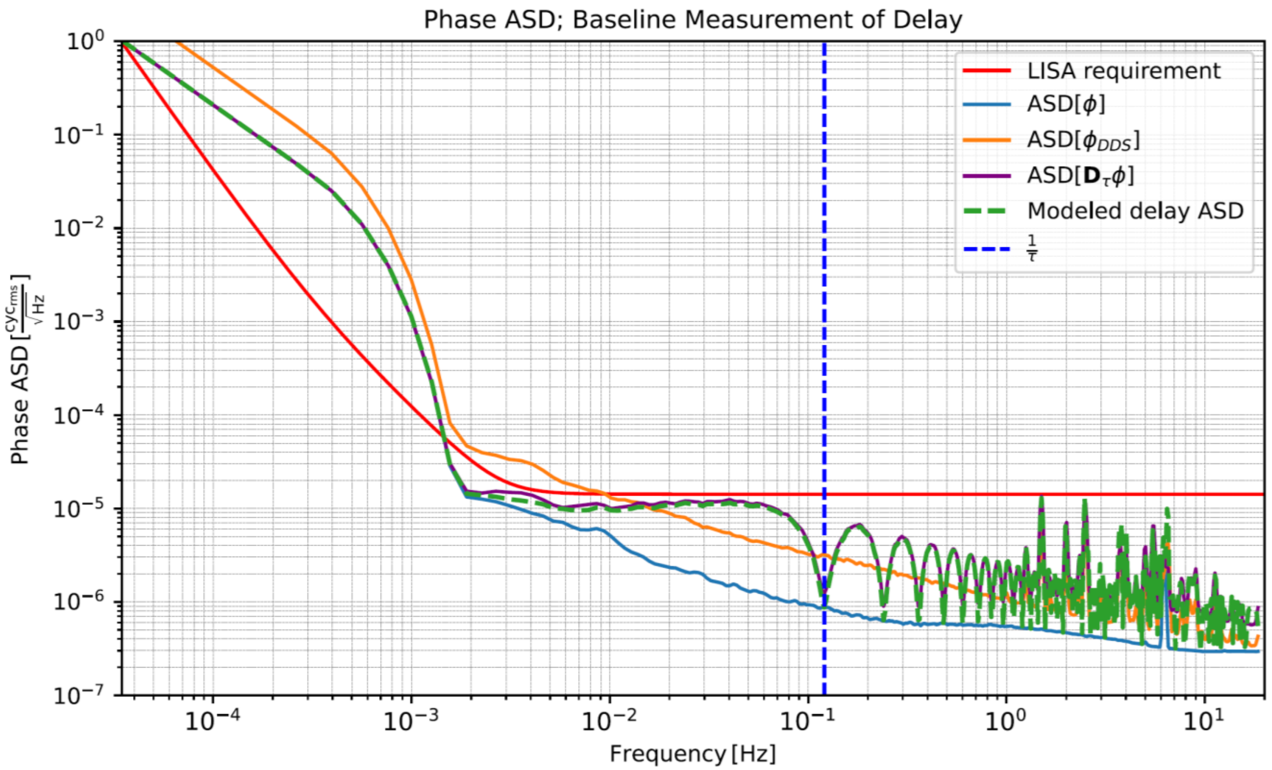


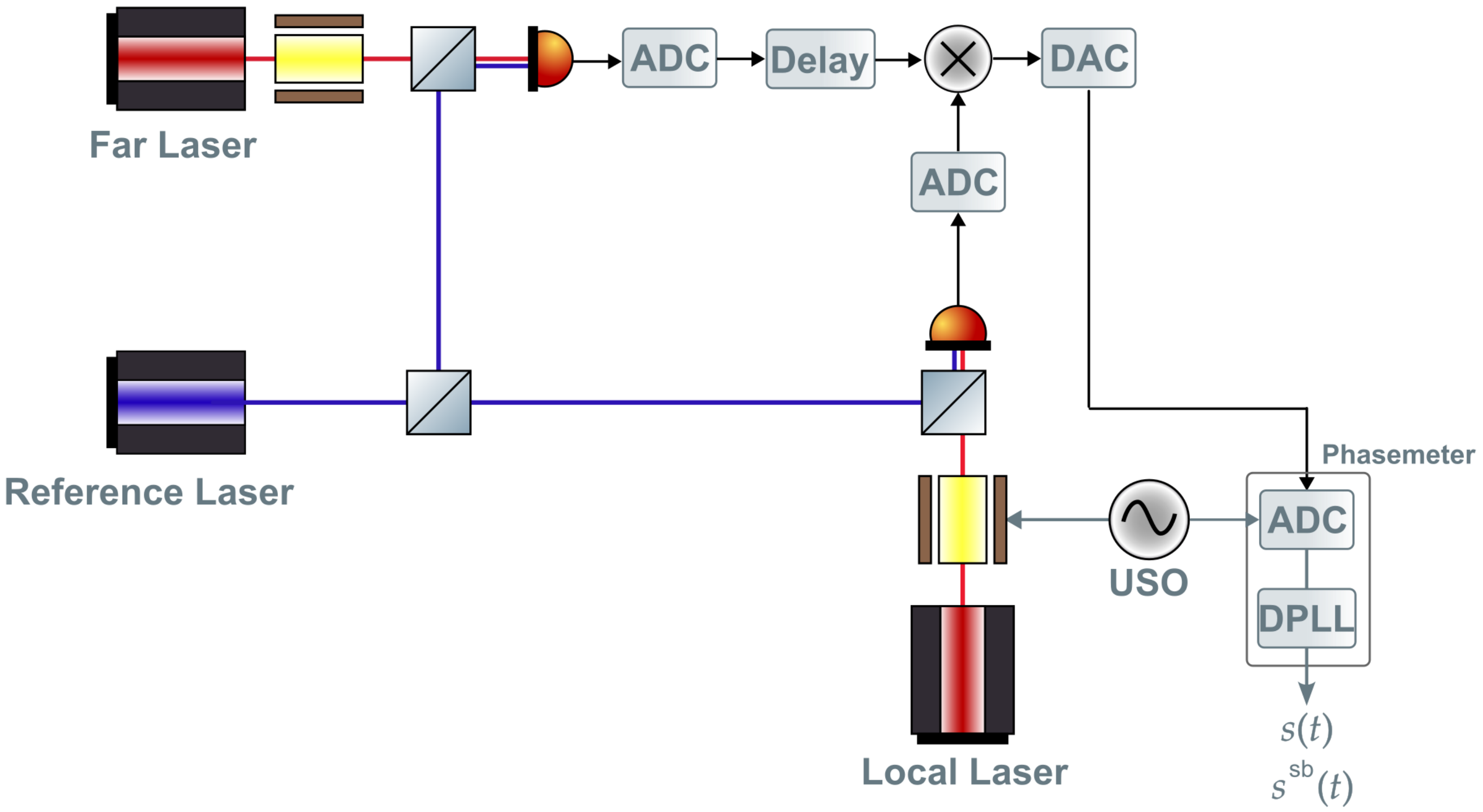
FIG. 6: Block diagram of single delay line performance test, including clocking effects.



Credit: Reid Ferguson

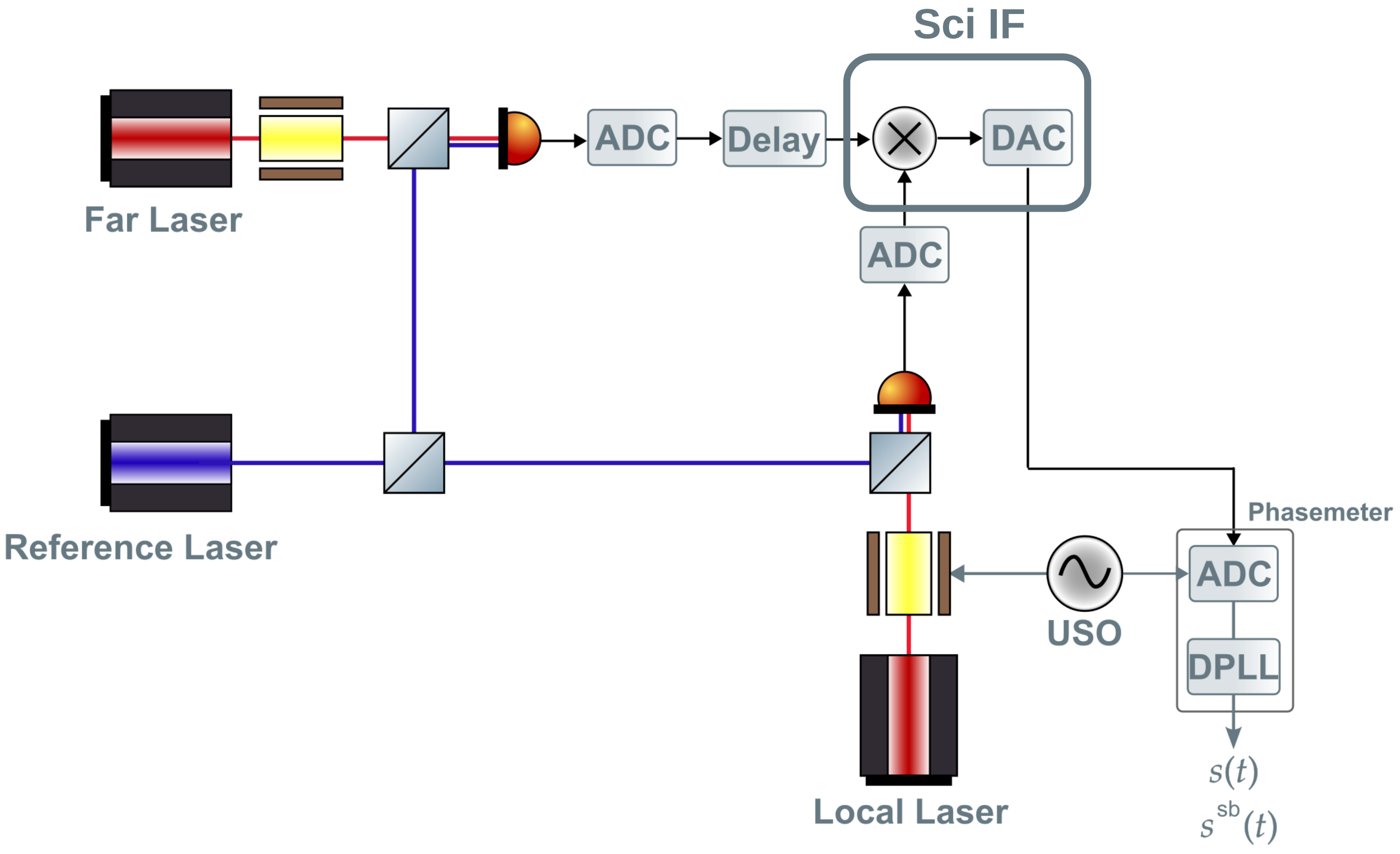
Phase Measurement with an Optical Input

Set up for generating one LISA-like science interferometer readout.



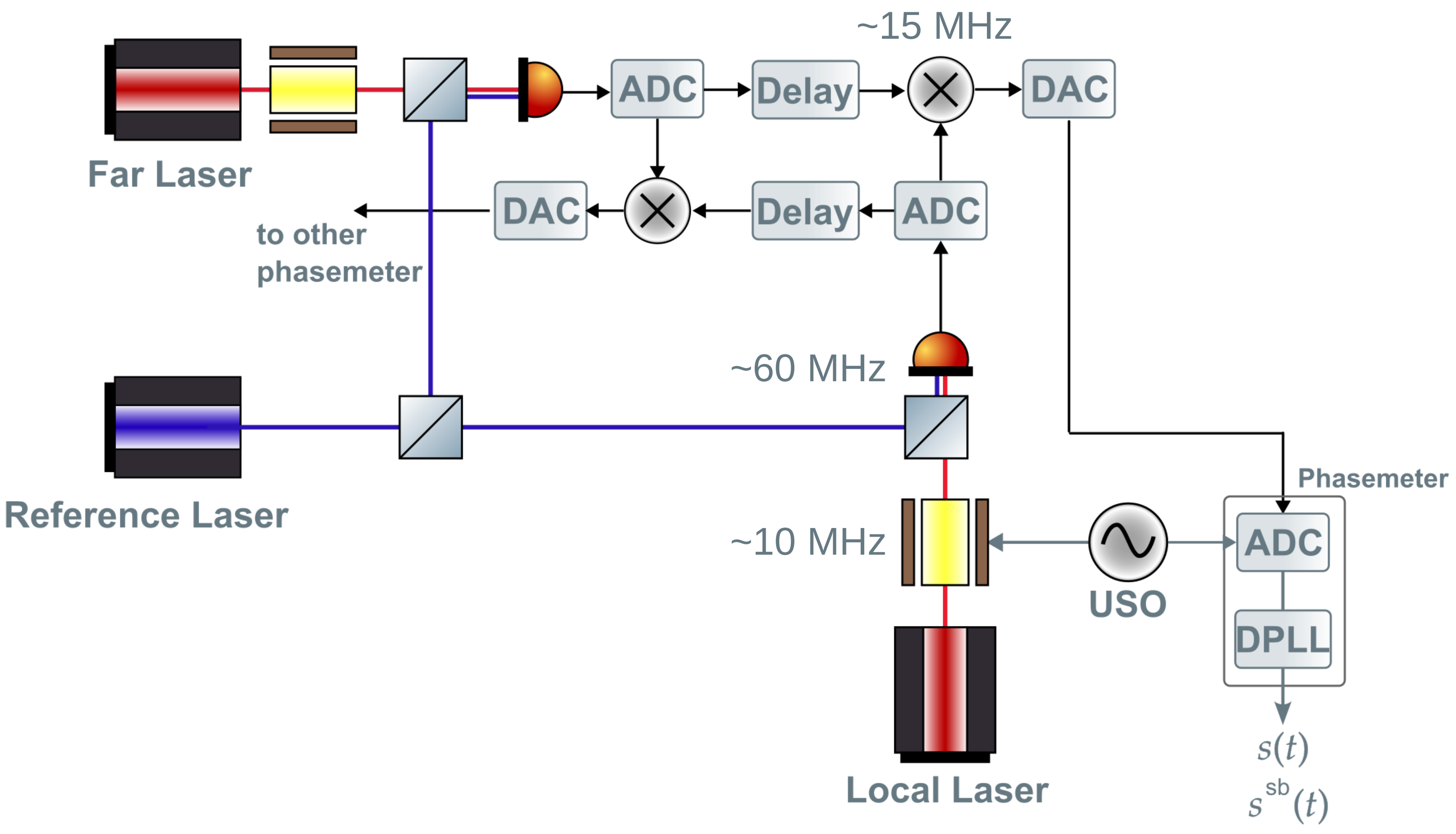
Phase Measurement with an Optical Input

Set up for generating one LISA-like science interferometer readout.



Phase Measurement with an Optical Input

Set up for generating one LISA-like arm link.



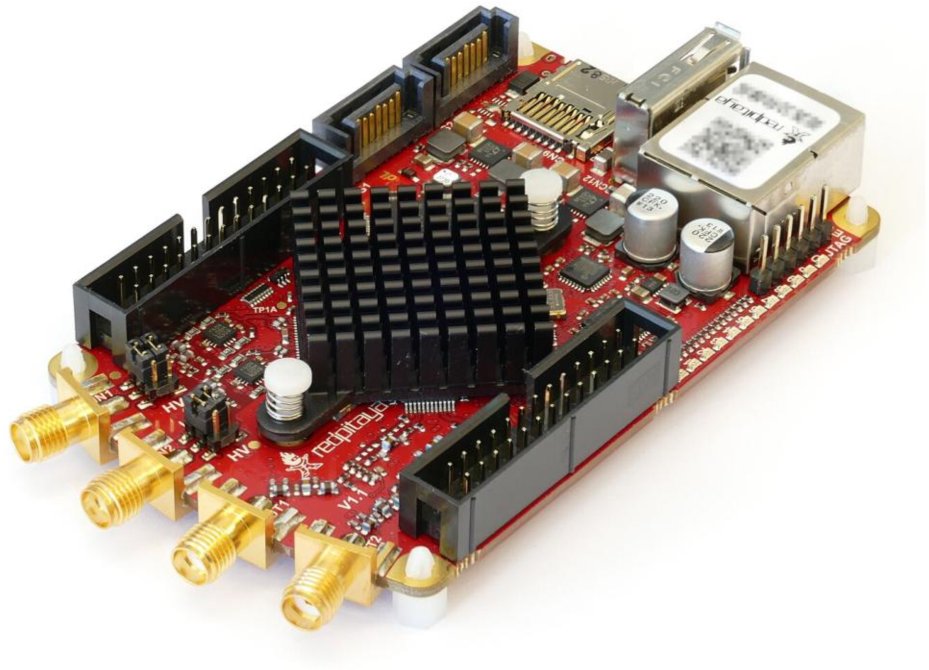
The Phasemeters

Red Pitaya running LISA gateware

Not space-qualified, but enables MHz phase readout

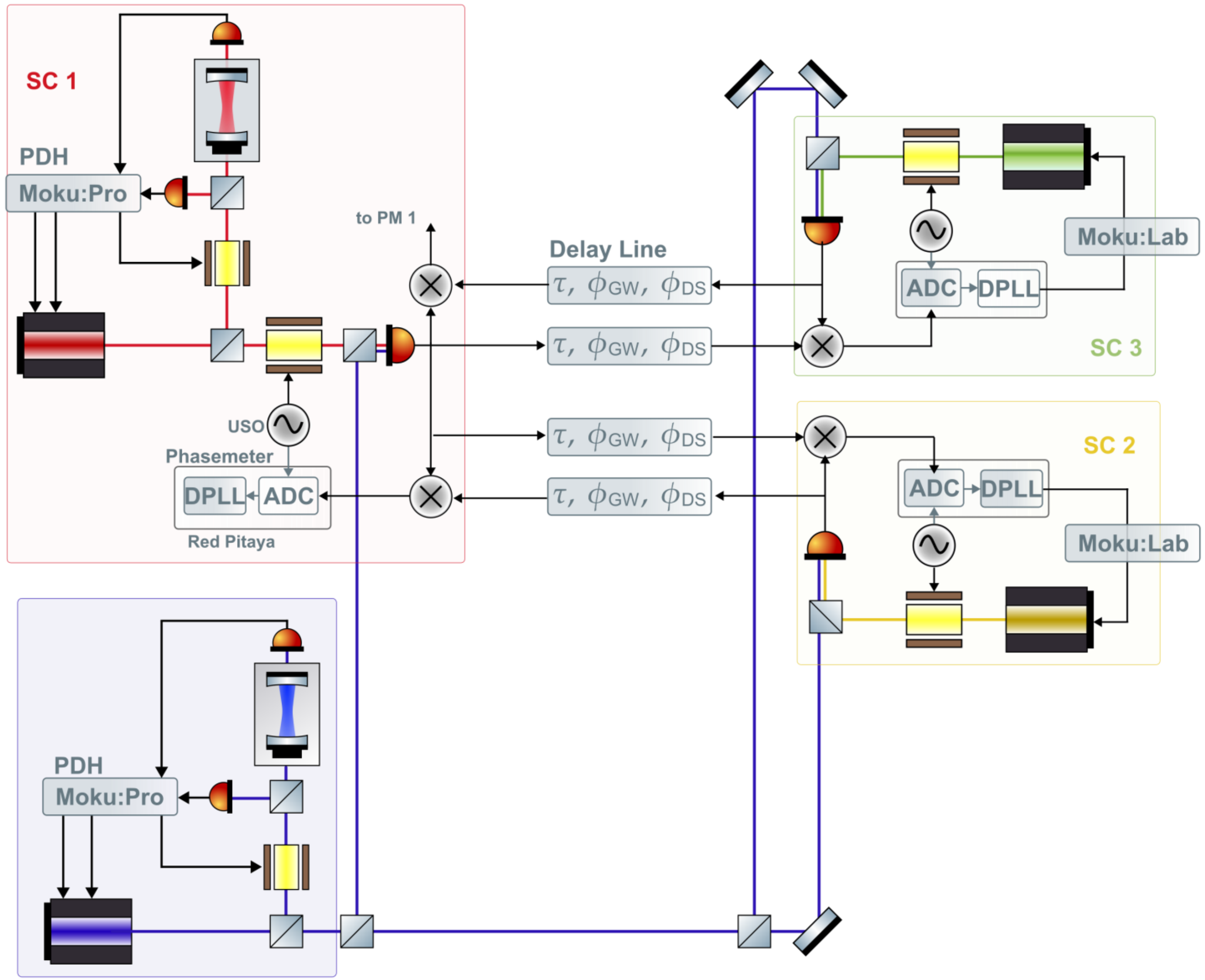
ADC is noisier than LISA’s frontend, but pilot tone correction helps

Each board has two inputs and two outputs.



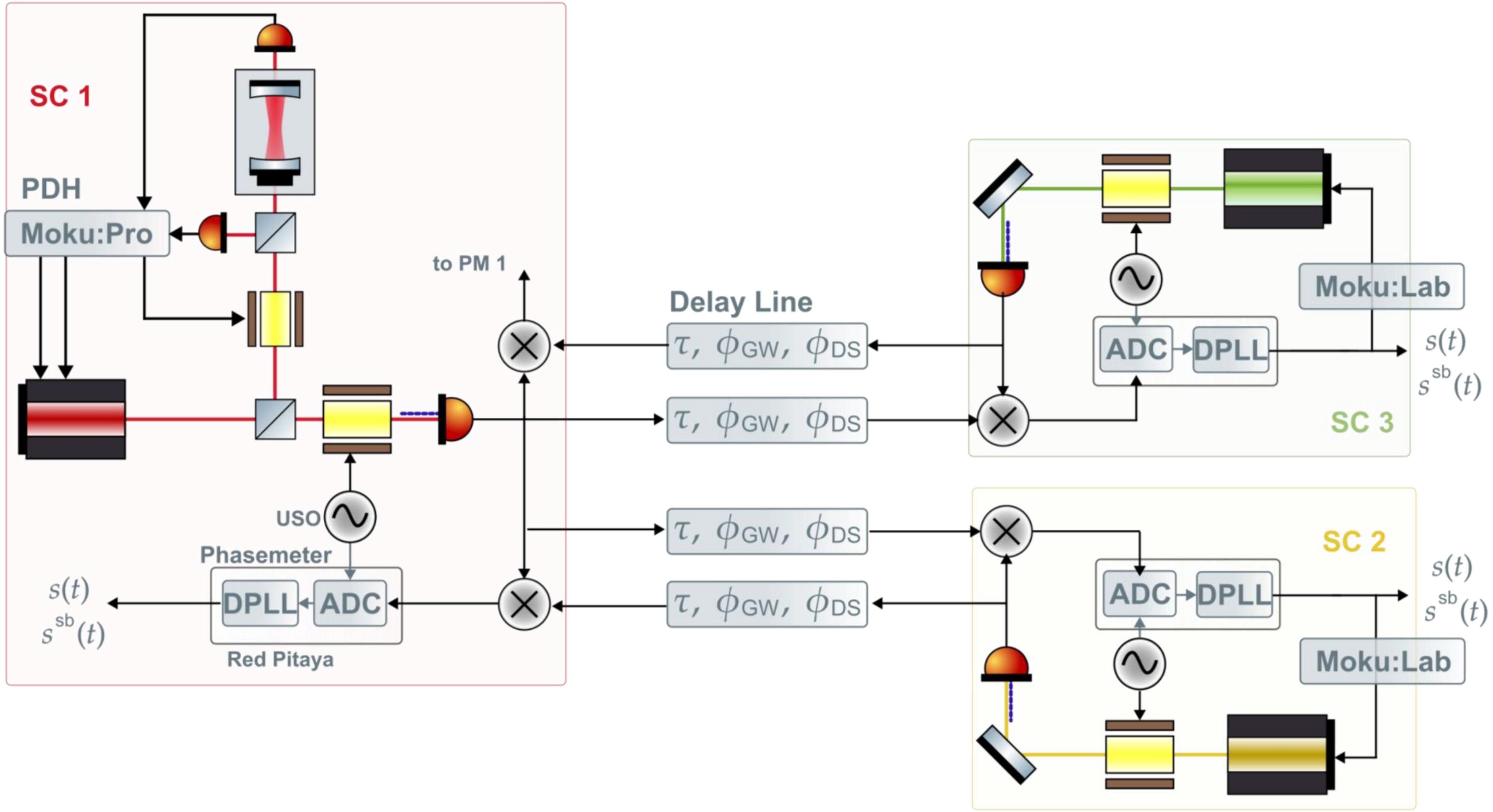
Red Pitaya

Two-arm Testbed



Reference Oscillator

Two-arm Testbed



Possible Additions

- More true-to-LISA clock noise transfer
  - Needs some more studying
- Third arm link
  - Needs frequency planning
- Test mass acceleration noise

Thank you for listening!