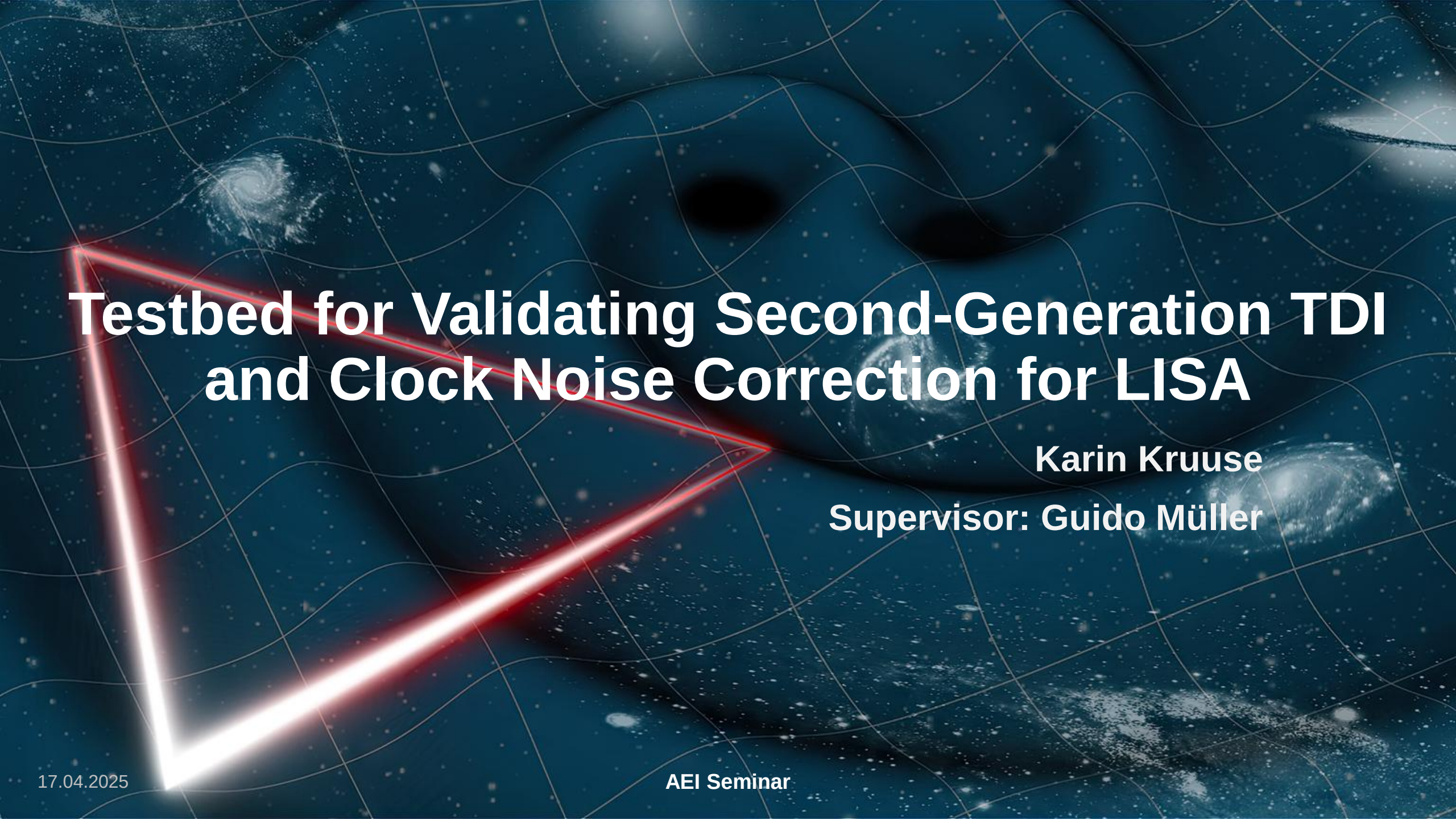


Testbed for Validating Second-Generation TDI and Clock Noise Correction for LISA

Karin Kruuse

Supervisor: 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

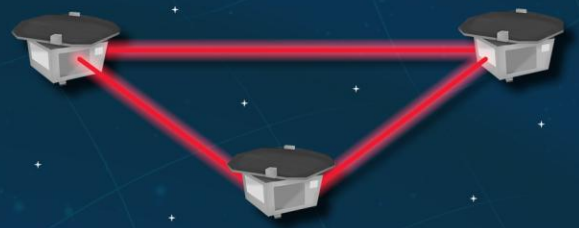
THE SPECTRUM OF GRAVITATIONAL WAVES

esa

Observatories & experiments

Ground-based experiment

Space-based observatory



Pulsar timing array

Cosmic microwave background polarisation

Timescales

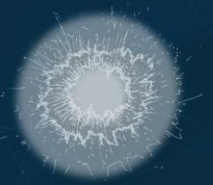
milliseconds | seconds | hours | years | billions of years

Frequency (Hz)

100 | 1 | 10^{-2} | 10^{-4} | 10^{-6} | 10^{-8} | 10^{-16}

Cosmic fluctuations in the early Universe

Cosmic sources

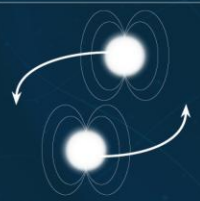


Supernova

Pulsar

Compact object falling onto a supermassive black hole

Merging supermassive black holes



Merging neutron stars in other galaxies

Merging stellar-mass black holes in other galaxies

Merging white dwarfs in our Galaxy

#lisa

ESA | NASA lisa

LISA

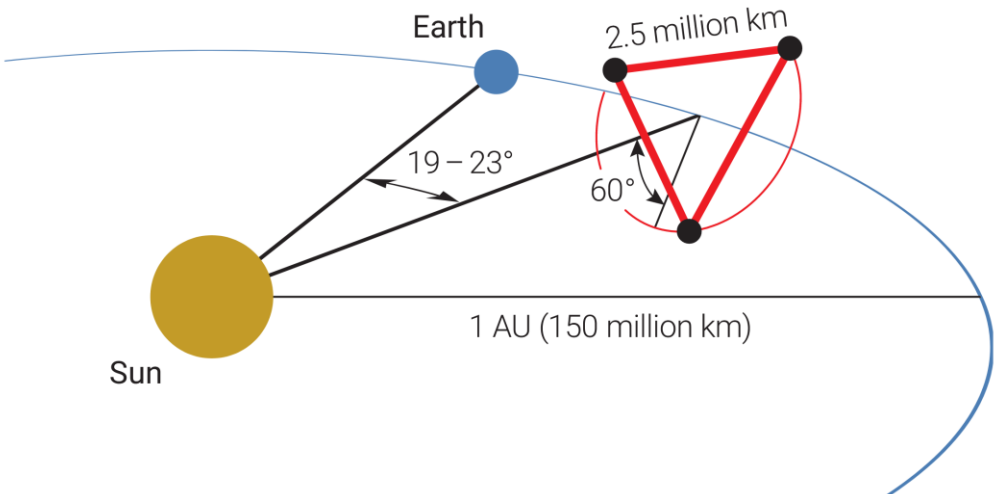
Space-based gravitational wave detector

No seismic noise and longer arm length improve sensitivity.

The arm-lengths are unequal and time-varying

→ which means laser noise won't cancel out

→ and the laser fields experience Doppler shifts in the range from -10 to 10 MHz



Amaro-Seoane et al., 2017

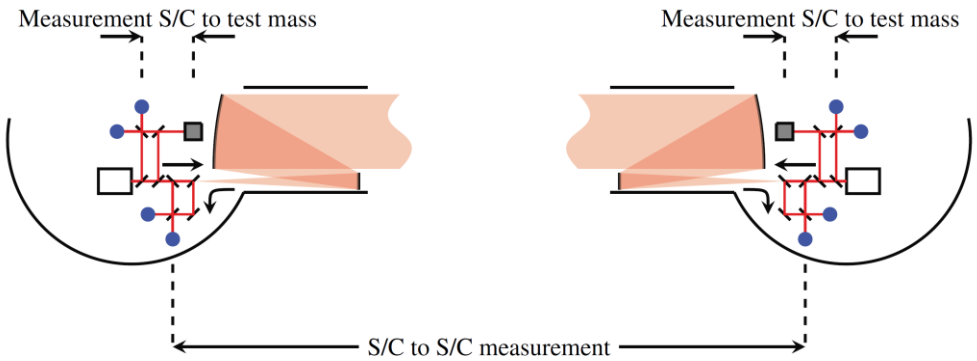
The Satellites

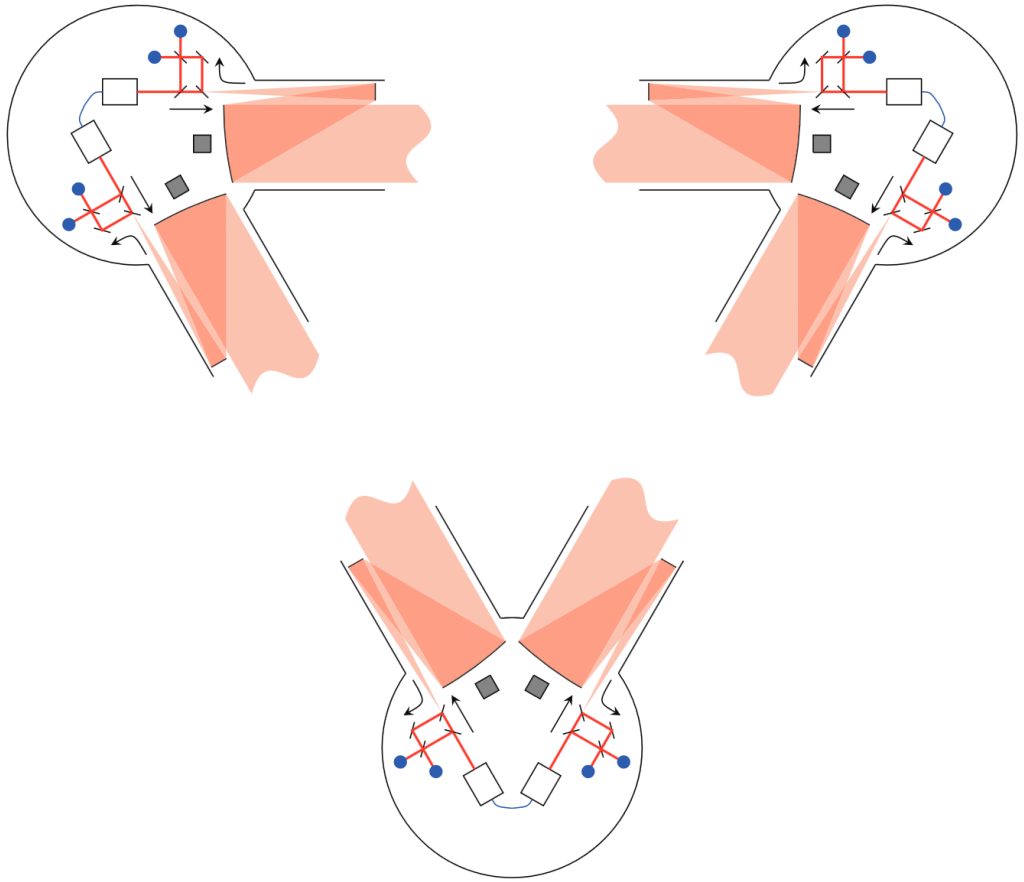
Three satellites surrounding six test masses in free fall

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.

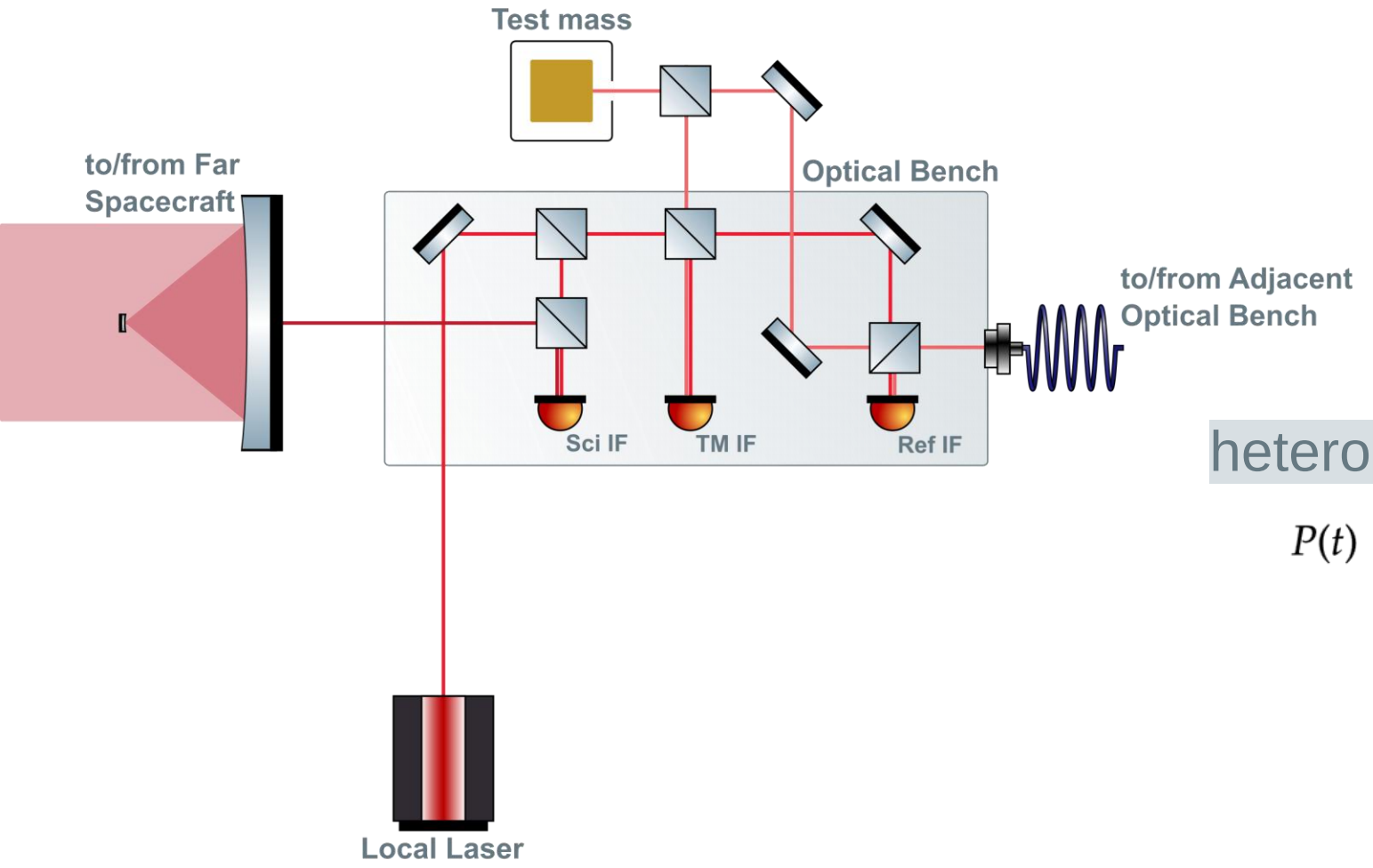




Jennrich, 2010

Internals of a LISA Spacecraft

LISA interferometric metrology system



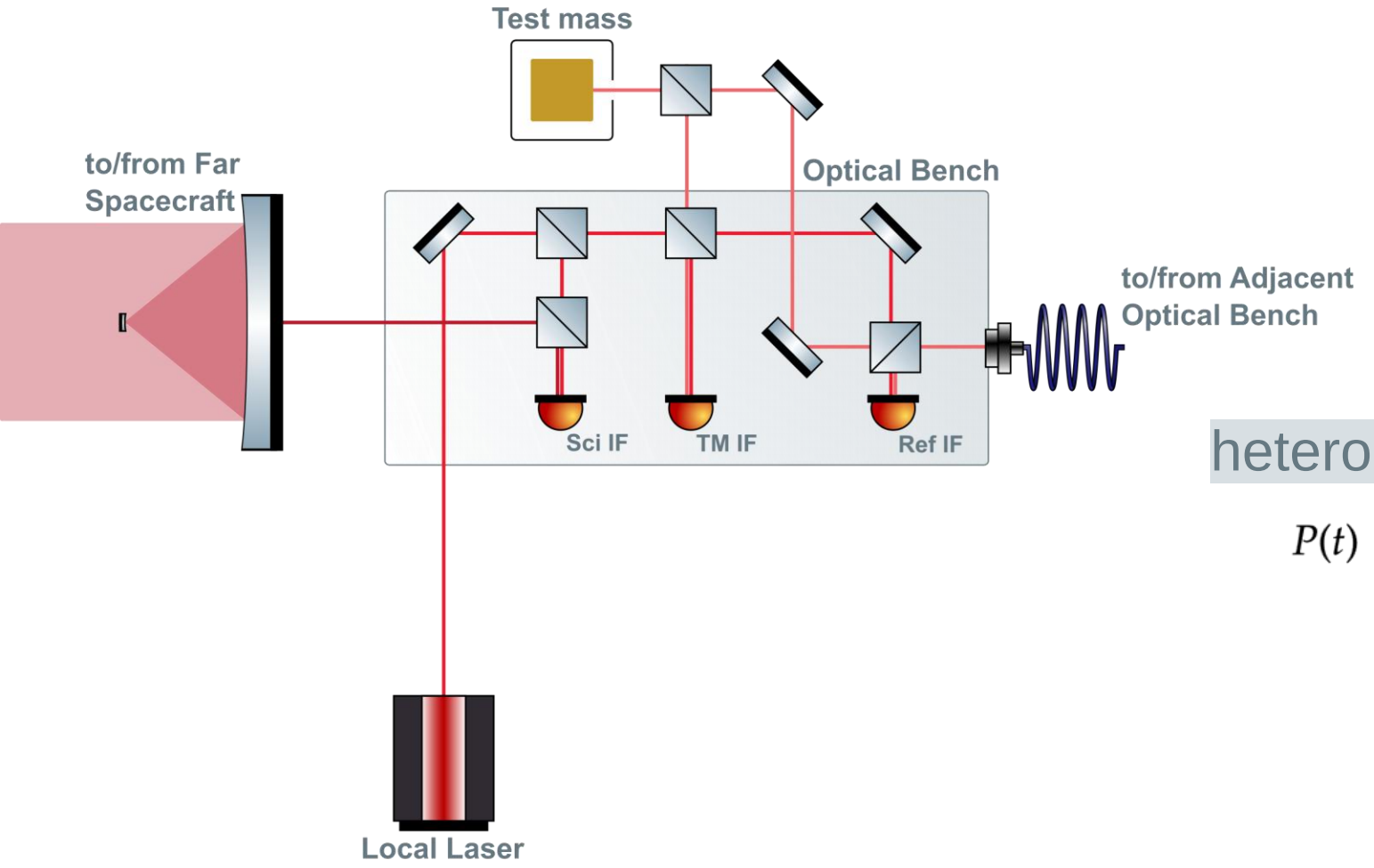
heterodyne interferometry

$$P(t) \propto |E_1(t) + E_2(t)|^2 = \\ = E_1^2 + E_2^2 + 2E_1E_2\cos((\omega_1 - \omega_2)t)$$

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

Internals of a LISA Spacecraft

LISA interferometric metrology system

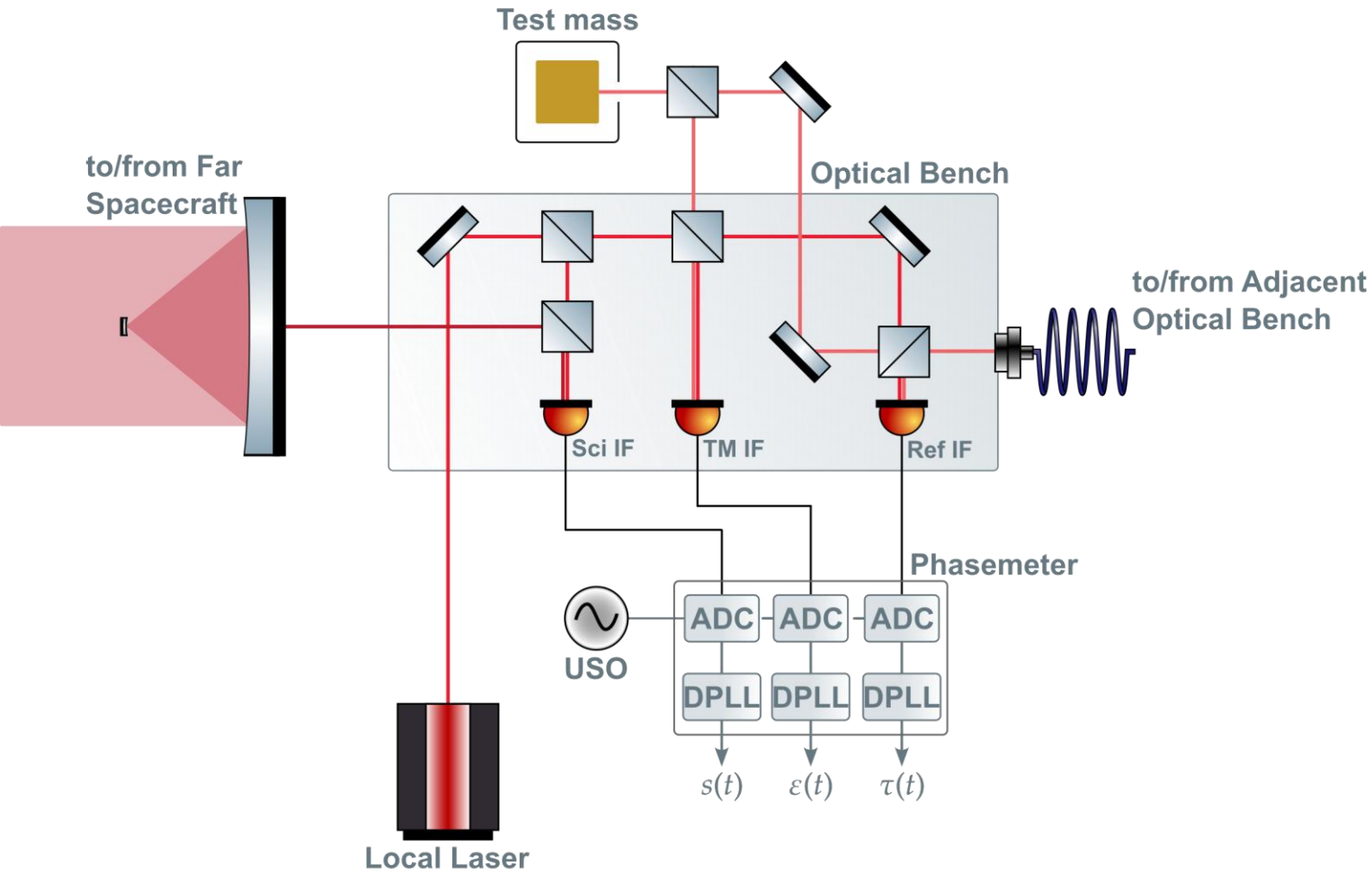


heterodyne interferometry

$$P(t) \propto |E_1(t) + E_2(t)|^2 = \quad \text{Beatnote}$$
$$= E_1^2 + E_2^2 + \boxed{2E_1E_2\cos((\omega_1 - \omega_2)t)}$$

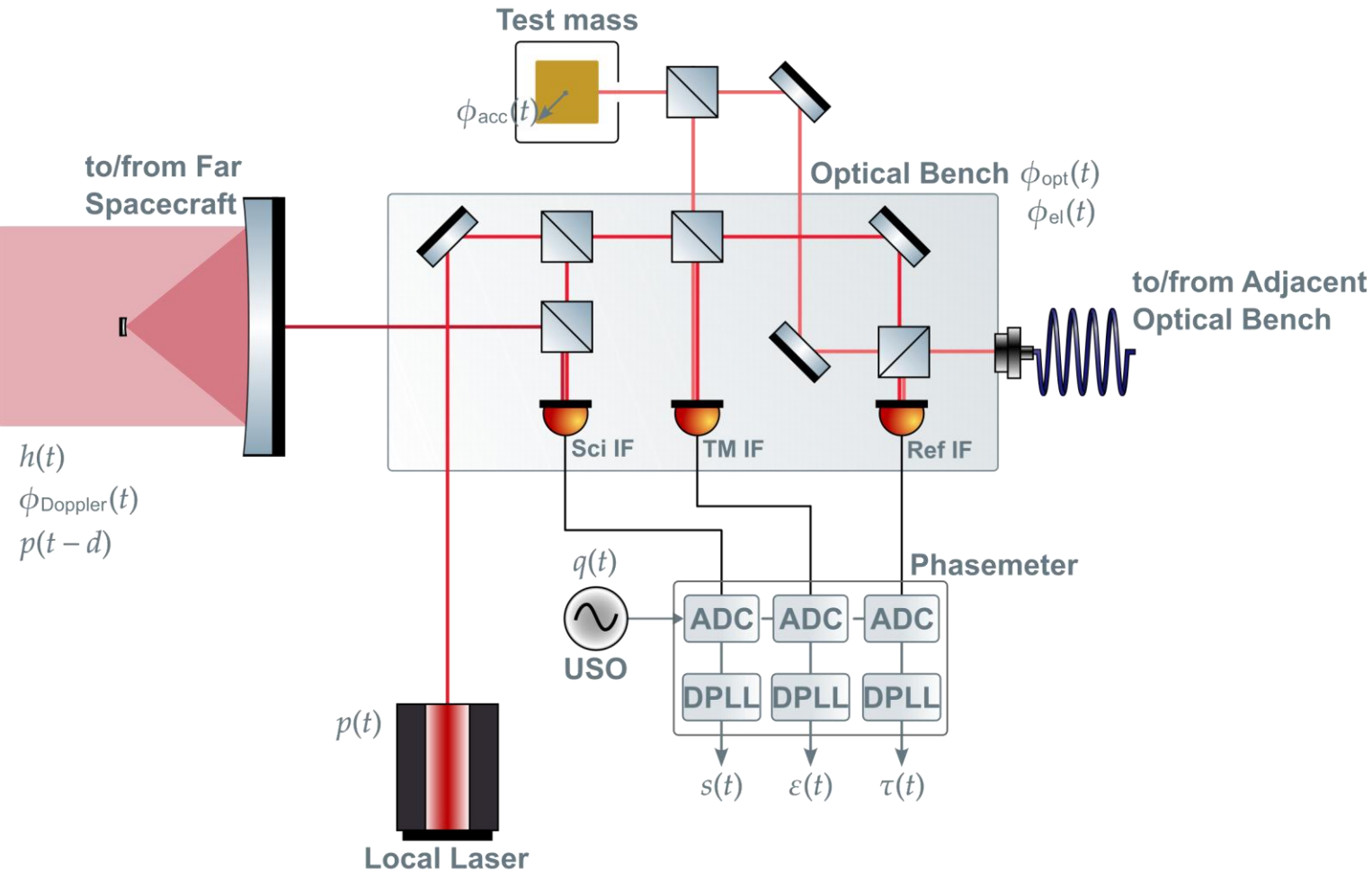
$$E_i(t) = E_i \exp(j\omega_i t)$$

Internals of a LISA Spacecraft



USO – Ultra Stable Oscillator

Internals of a LISA Spacecraft



GW Signal	$h(t)$
Doppler Shift	$\phi_{\text{Doppler}}(t)$
Laser Noise	$p(t)$
Clock Jitter	$q(t)$
Acceleration noise	$\phi_{\text{acc}}(t)$
Optical Path Length Noise	$\phi_{\text{opt}}(t)$
Electrical Noises	$\phi_{\text{el}}(t)$

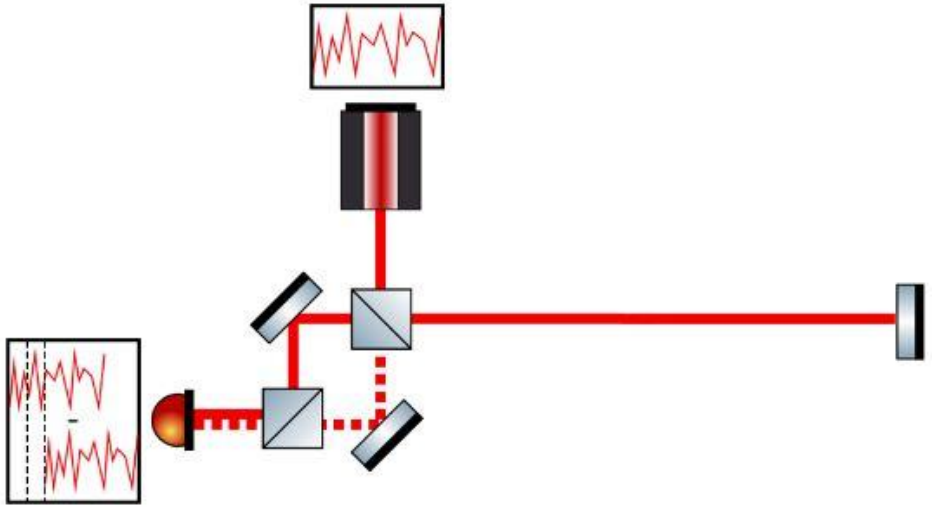
Problem: Laser Noise

MHz beatnotes must be measured at µcycle precision.

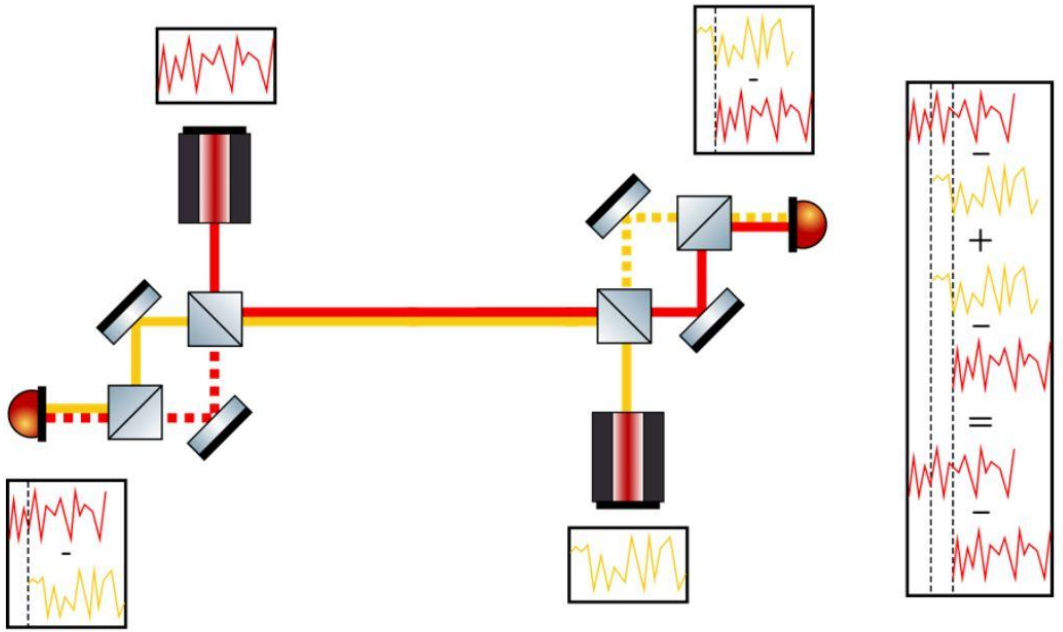
The pre-stabilised laser noise levels coupled into the beatnotes are expected to be orders of magnitude higher.

Solution: Time Delay Interferometry

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



Transponder signal

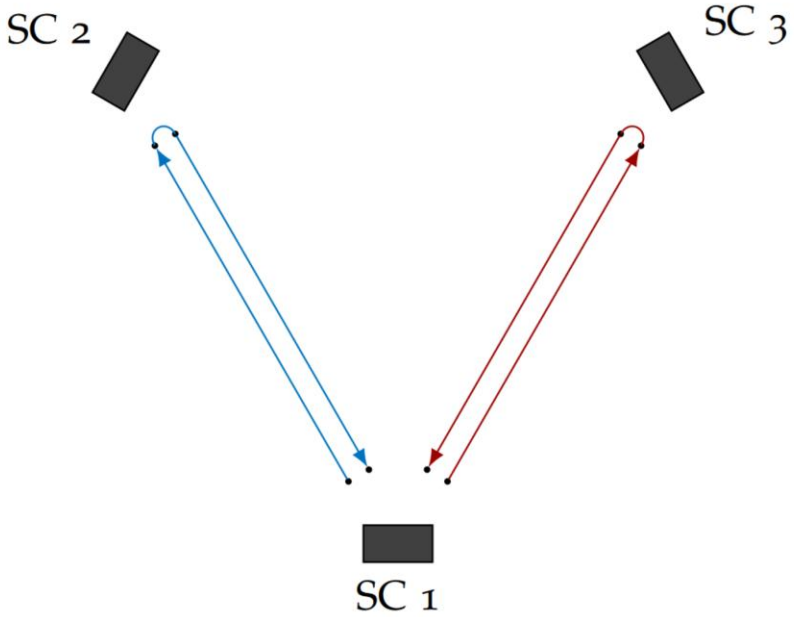


Virtual transponder signal

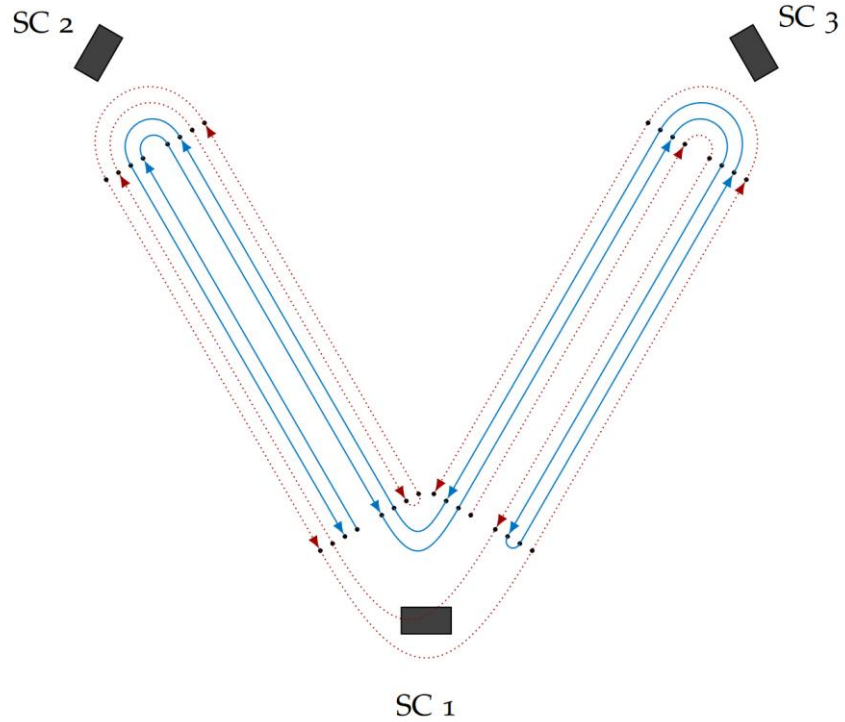
Hartwig, 2021

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

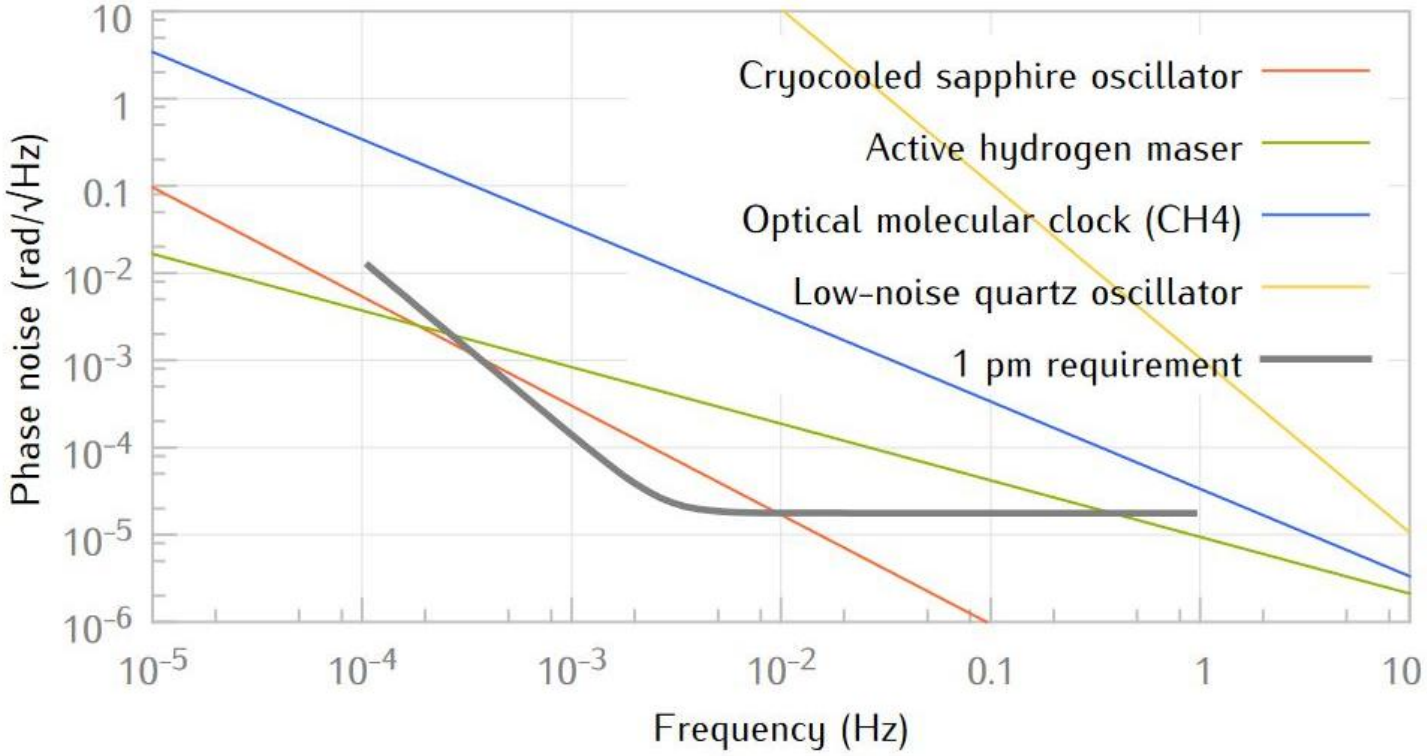


In practice, 2nd generation combinations should suppress noise enough to meet the requirement.

Hartwig, 2021

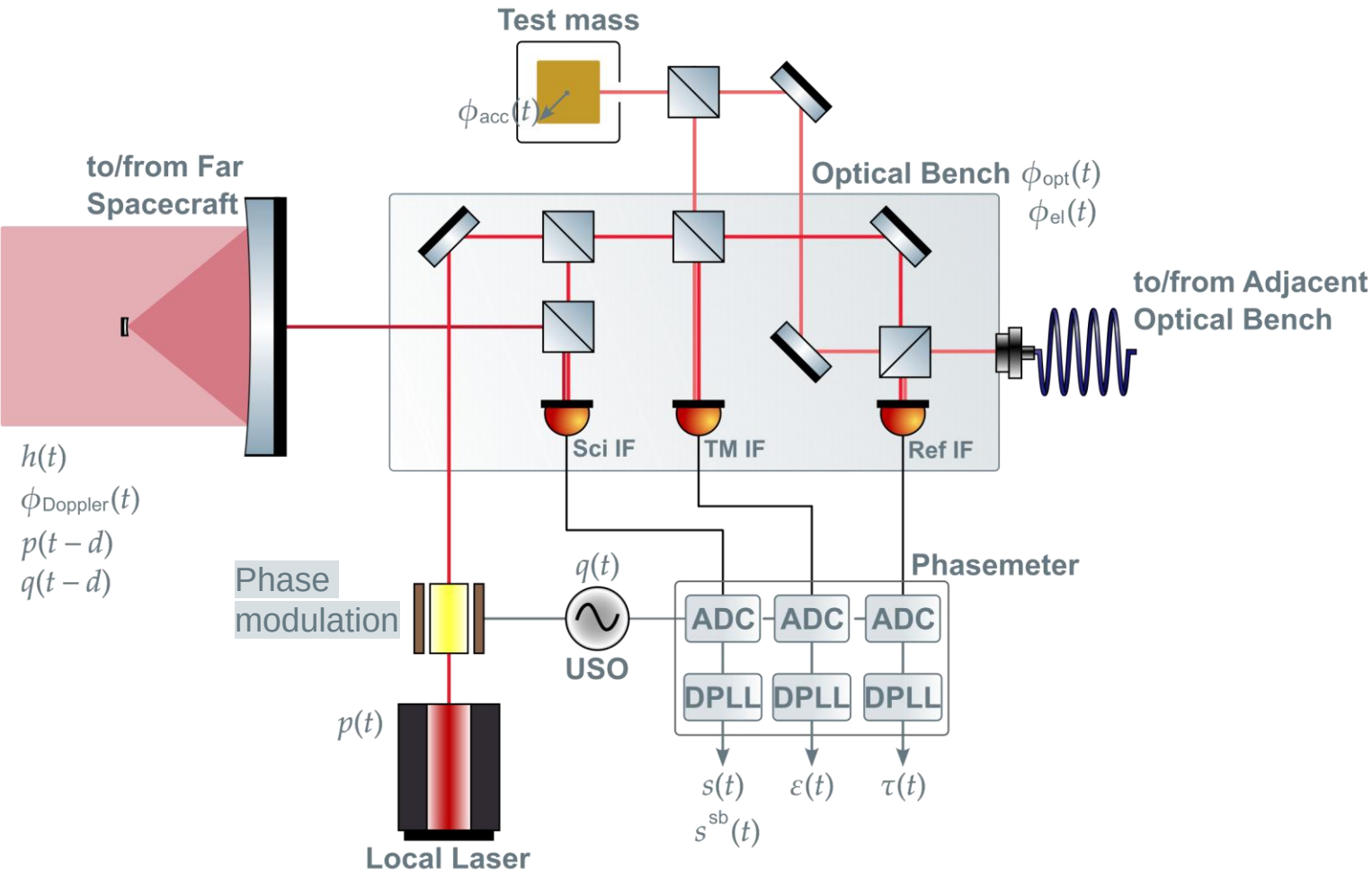
Problem: Clock Jitter

Top of the notch clock performance (2014)

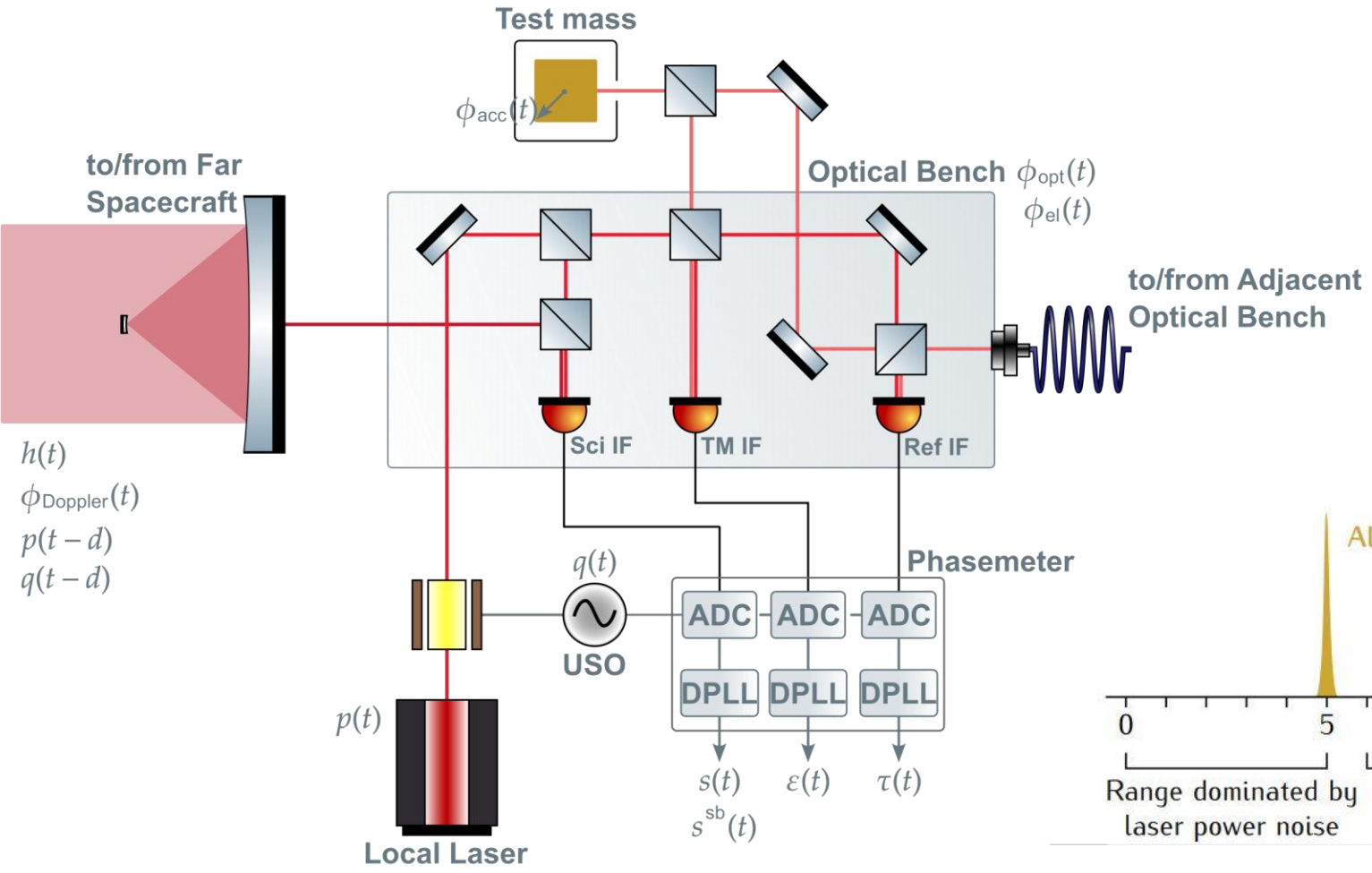


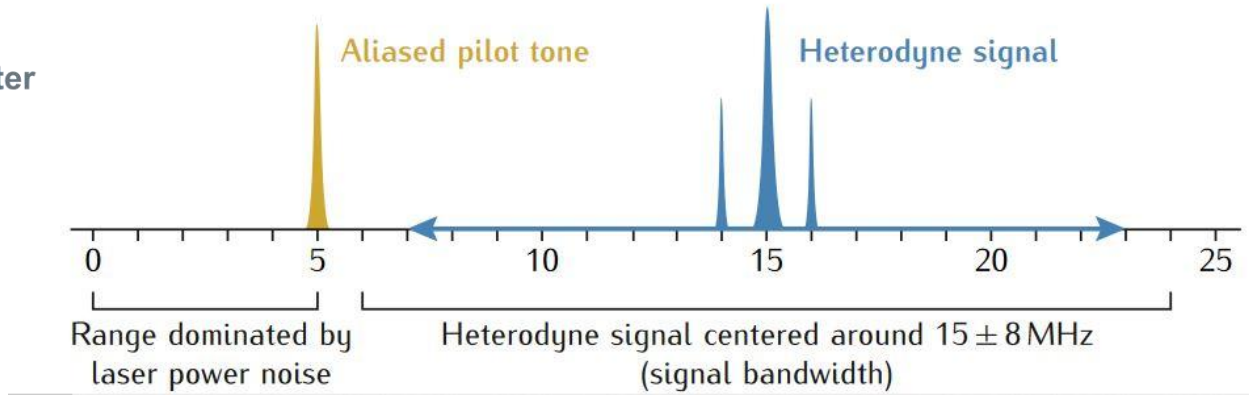
Lisa metrology system-final report, 2014

Solution: The Sidebands



Solution: The Sidebands





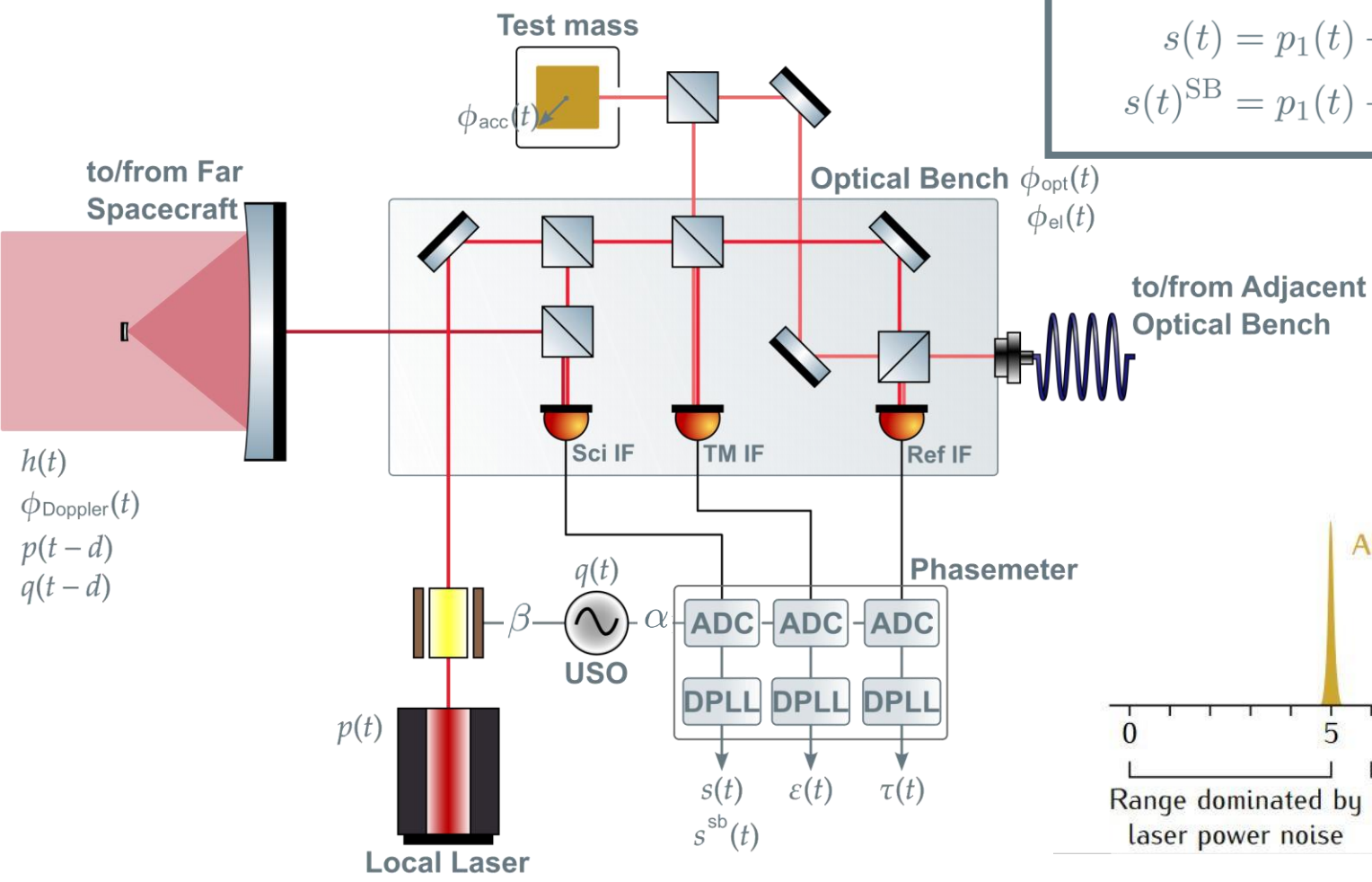
Lisa metrology system-final report, 2014

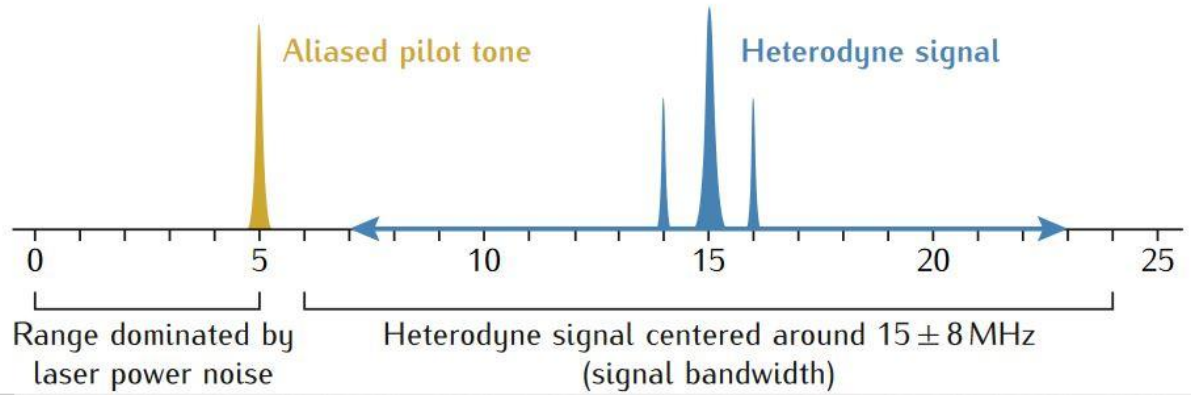
Solution: The Sidebands

After demodulation, considering laser noise and clock jitter:

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

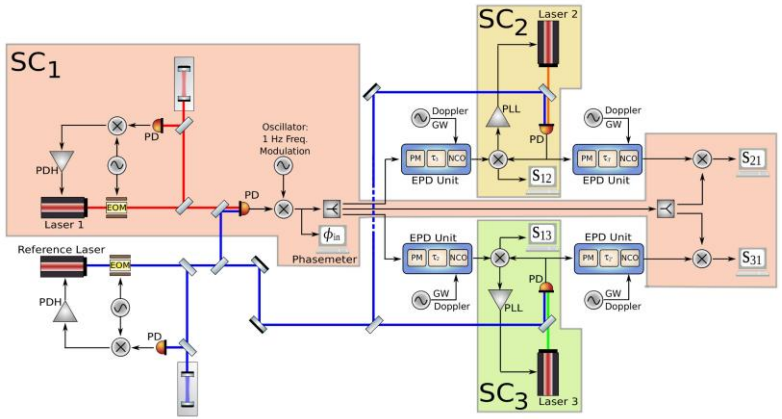
$$s(t)^{\mathrm{SB}} = p_1(t) + p_2(t - d_{12}) + \beta_1 q_1(t) + \beta_2 q_2(t - d_{12}) + \alpha_1^{\mathrm{SB}} q_1(t)$$





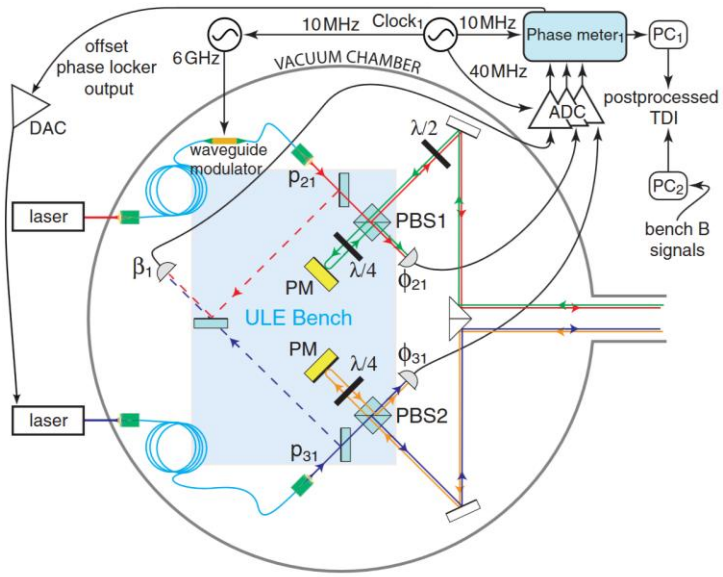
Lisa metrology system-final report, 2014

Previous Experiments



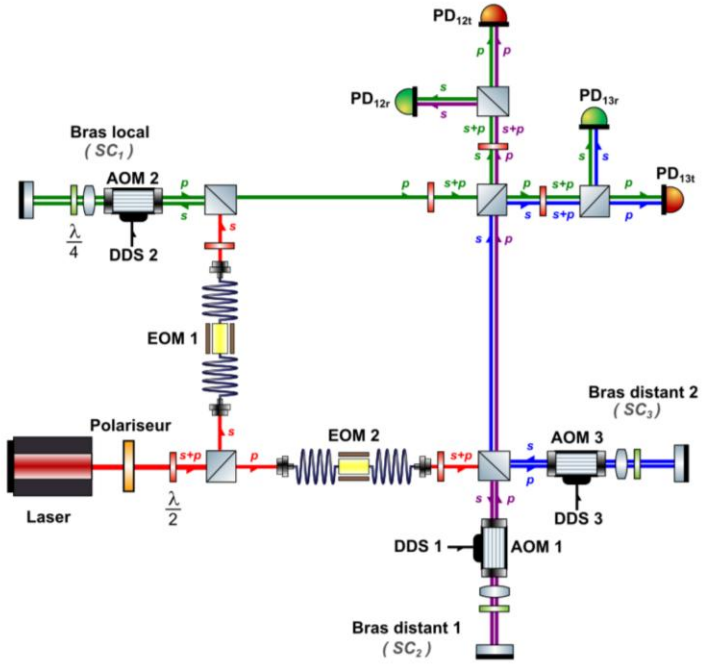
Mitryk, 2012: Laser Noise Mitigation through Time Delay Interferometry for Space-based Gravitational Wave Interferometers Using the UF Laser Interferometer

Laser noise, No Clock Jitter, Realistic Delay



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

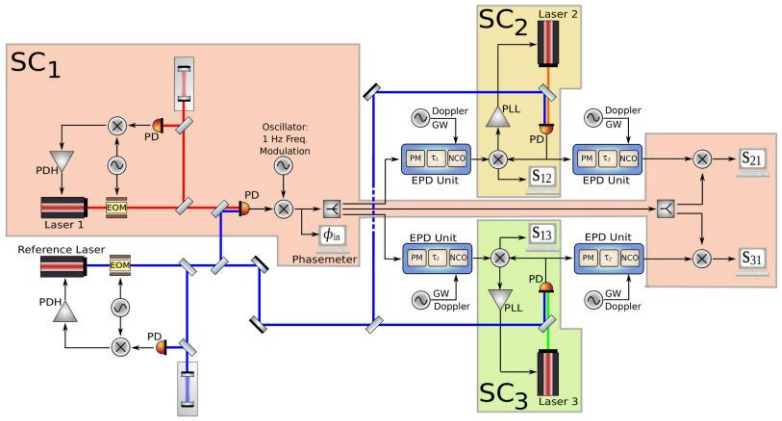
Laser noise, Clock jitter, No delay



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

Laser noise, Clock Jitter, Realistic Delay

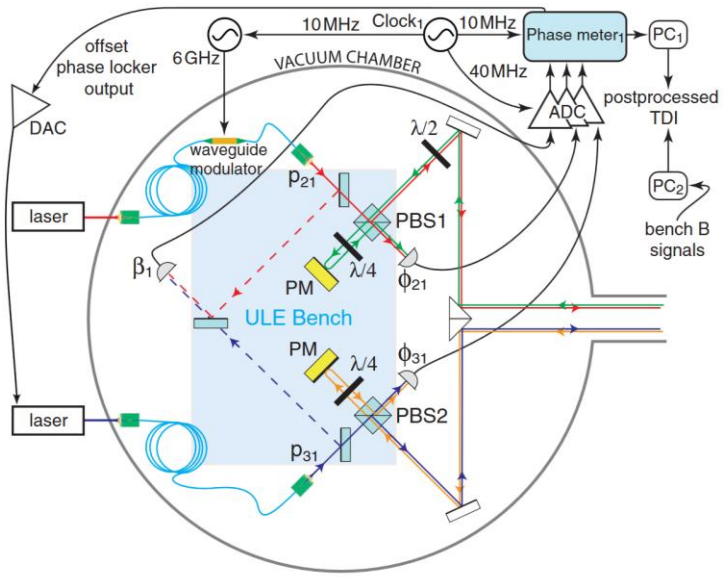
Previous Experiments



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

Laser noise, No Clock Jitter, Realistic Delay

Predecessor to our testbed, limited by the technology of the time



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

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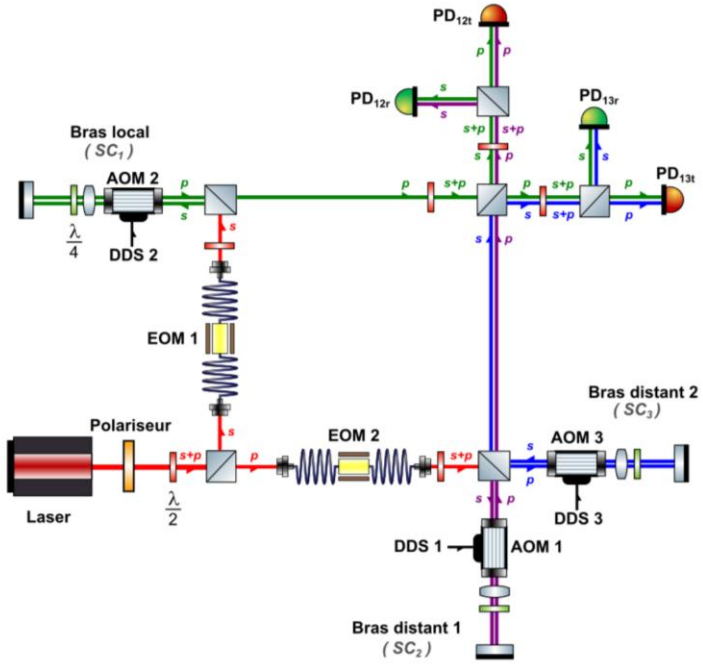


Vidal, 2023: Validation expérimentale des performances interférométriques de LISA, Paris

Laser noise, Clock Jitter, Delay

Previous Experiments

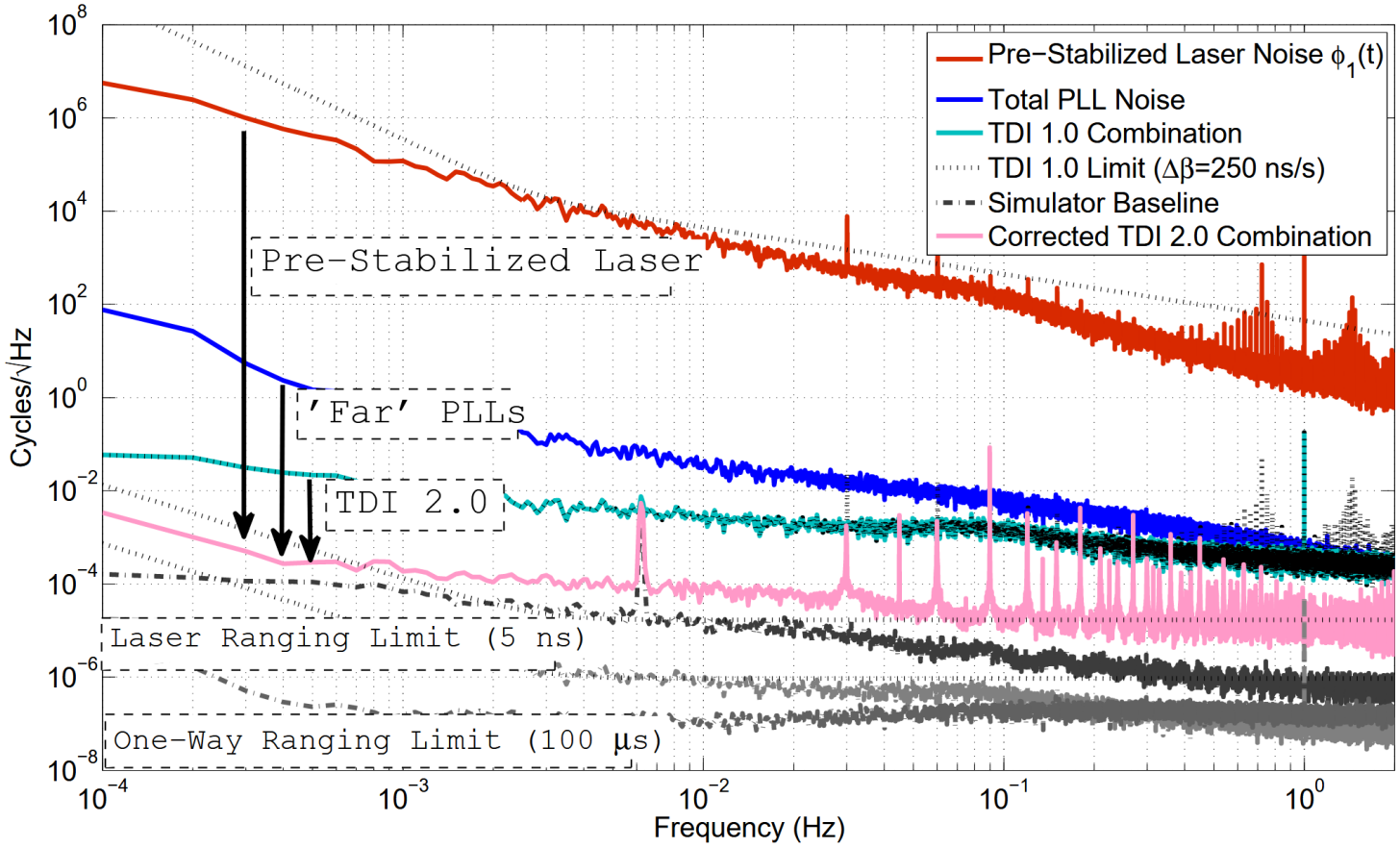


Figure 7-10. Dynamic LISA-like experimental results

Mitryk, 2012

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

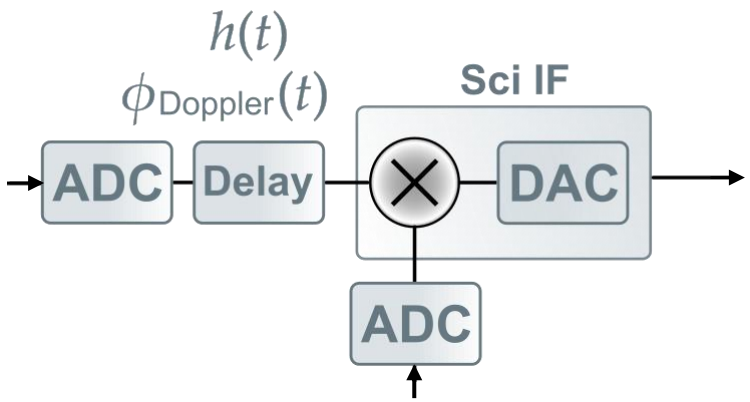
A fully electronic implementation of the interferometry system together with a delay and gravitational wave injection has already been developed and is being tested.

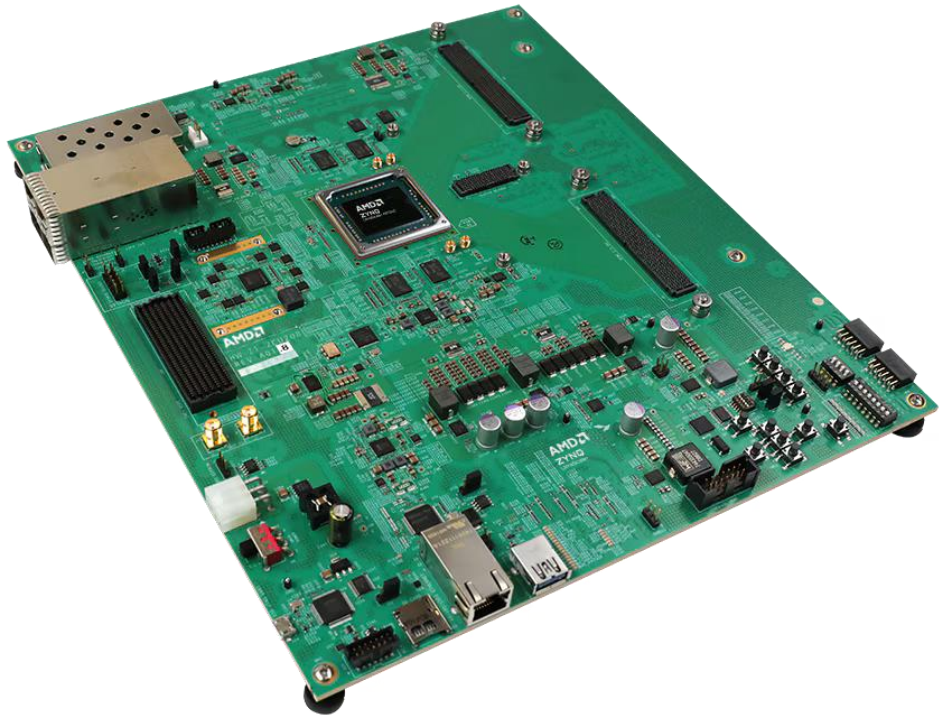
- Time varying delays
- Doppler shifts for both the carrier and sidebands
- Gravitational wave injection

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.

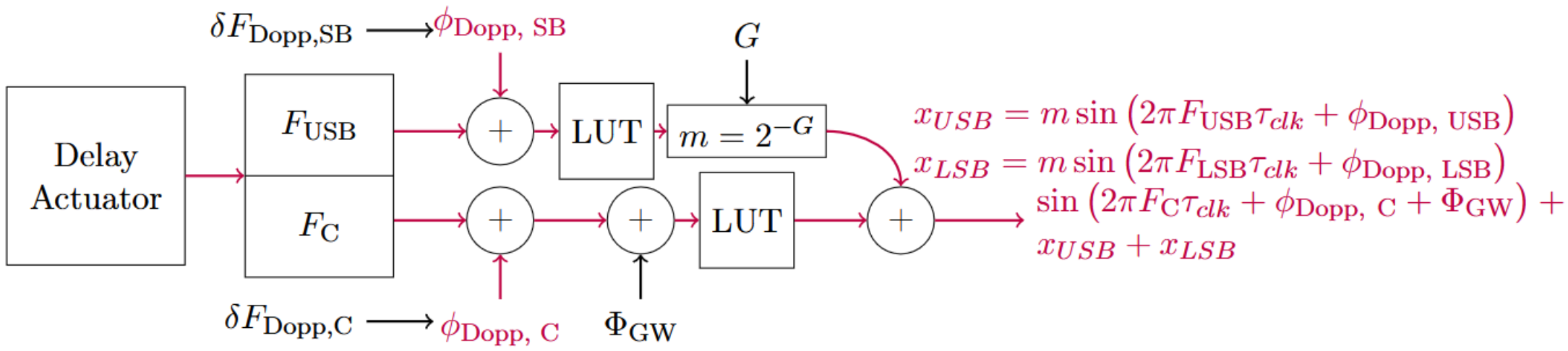


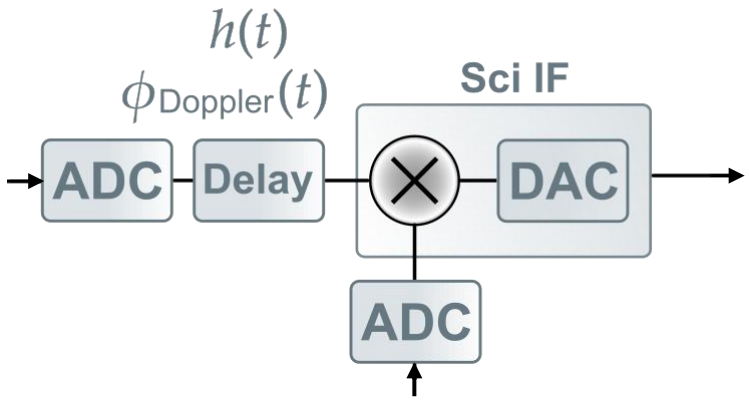
Figure 3: Block diagram of Doppler- and GW-derived phase modulation of the carrier after the delay.

Credit: Reid Ferguson

Delay Line Performance

Main noise source is the clock jitter, which couples into the phase measurement.

This won't be suppressed by TDI or clock noise removal and an extra measurement is likely needed.



Delay Line Noise Measurement

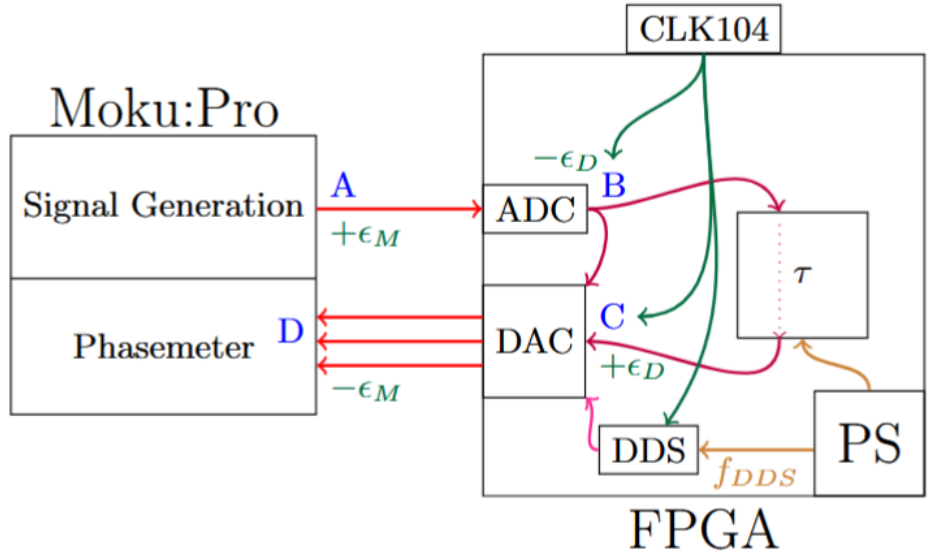
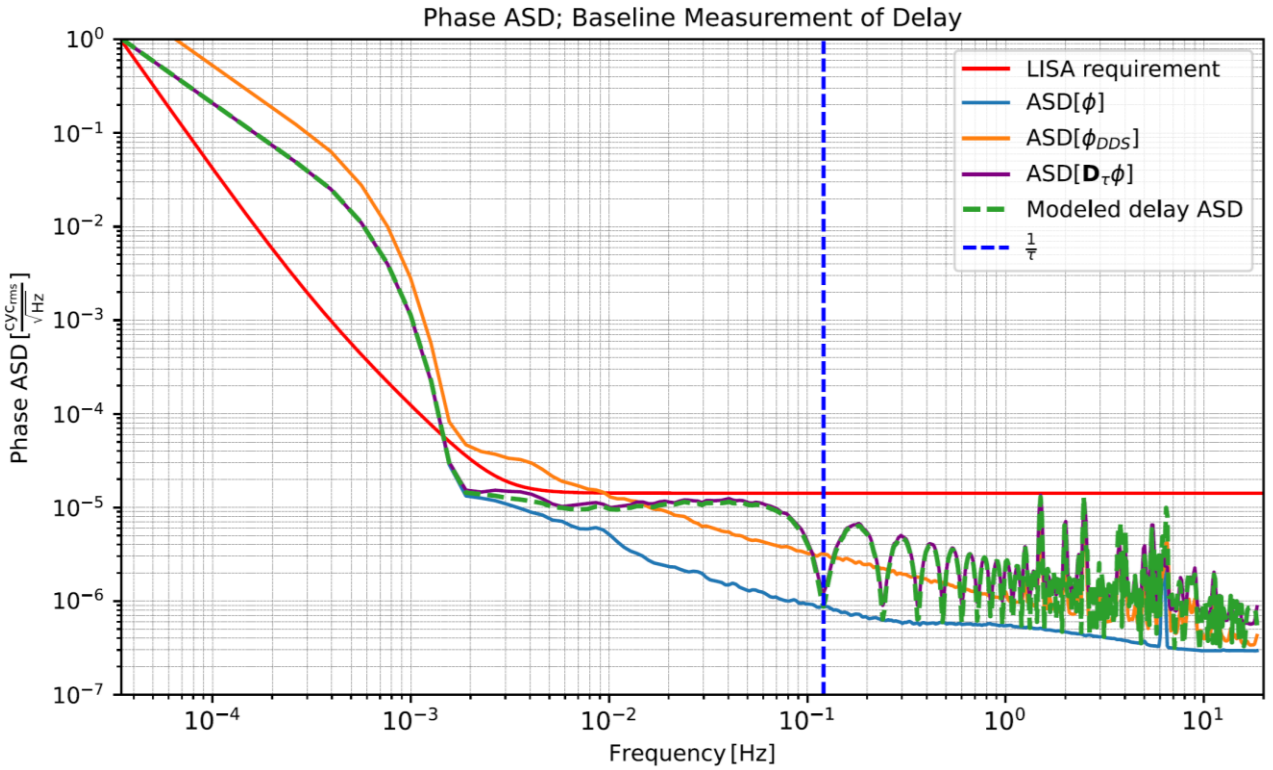


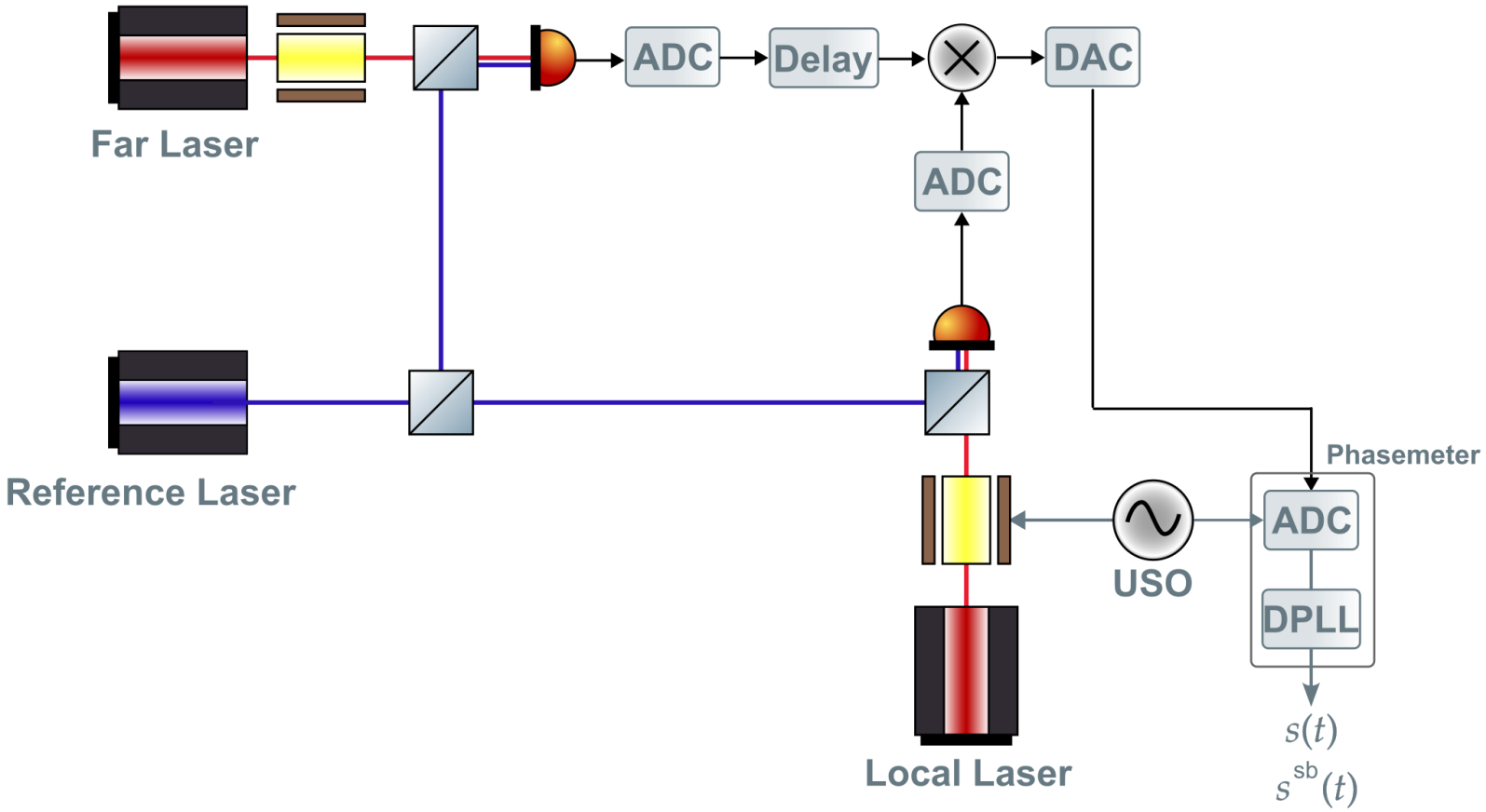
FIG. 6: Block diagram of single delay line performance test, including clocking effects.



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

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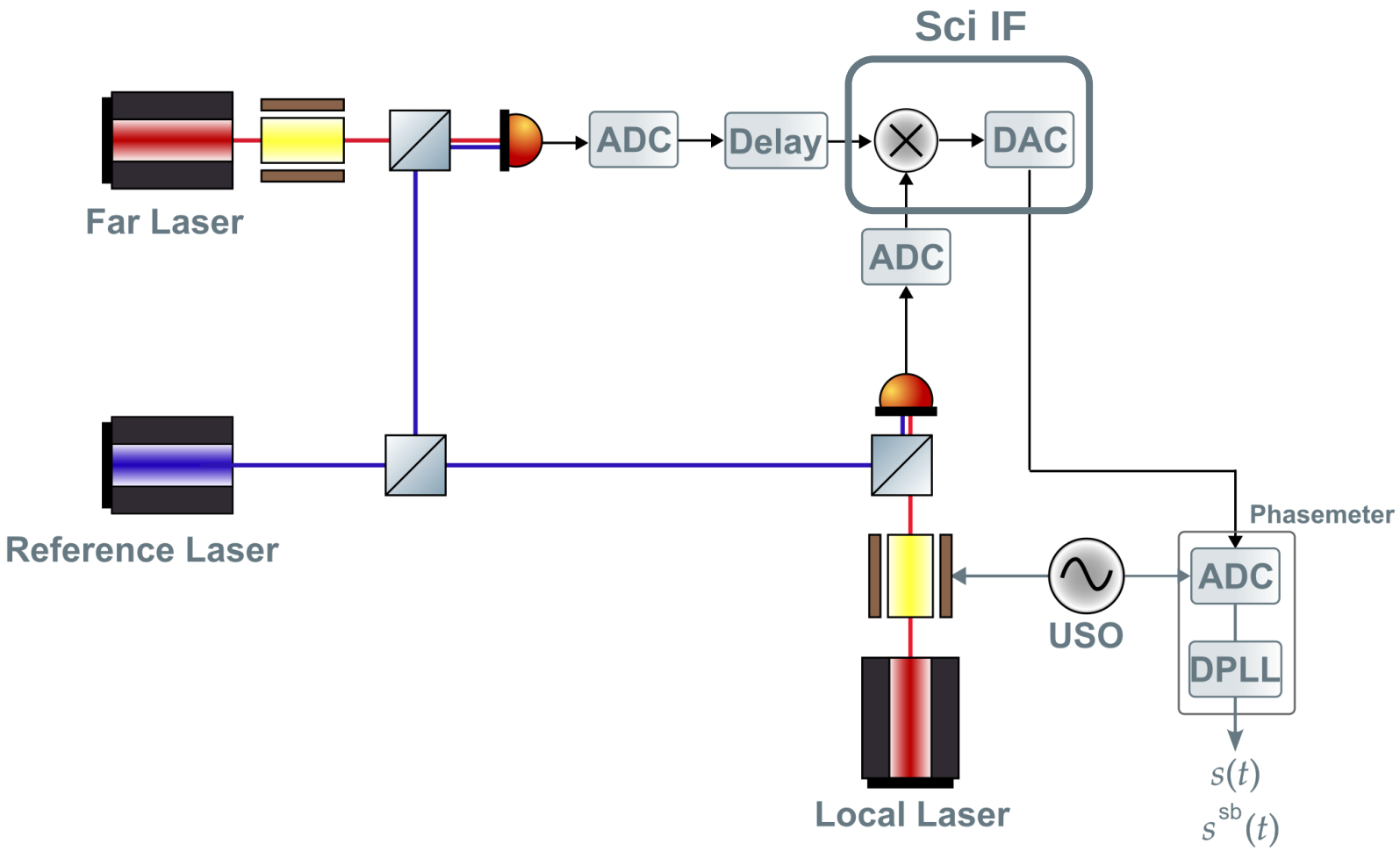
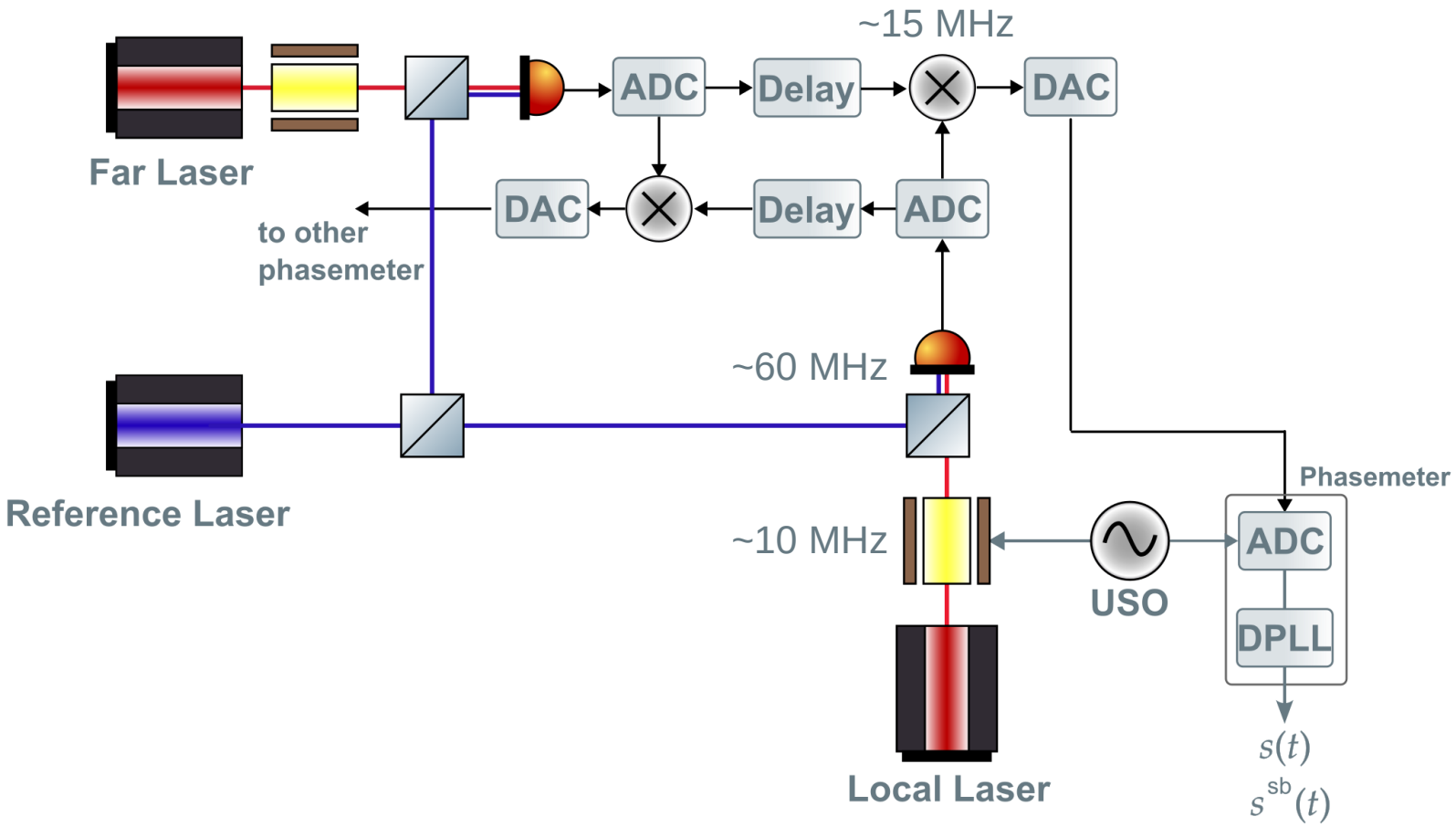


Phase Measurement with an Optical Input

Set up for generating one LISA-like arm link.

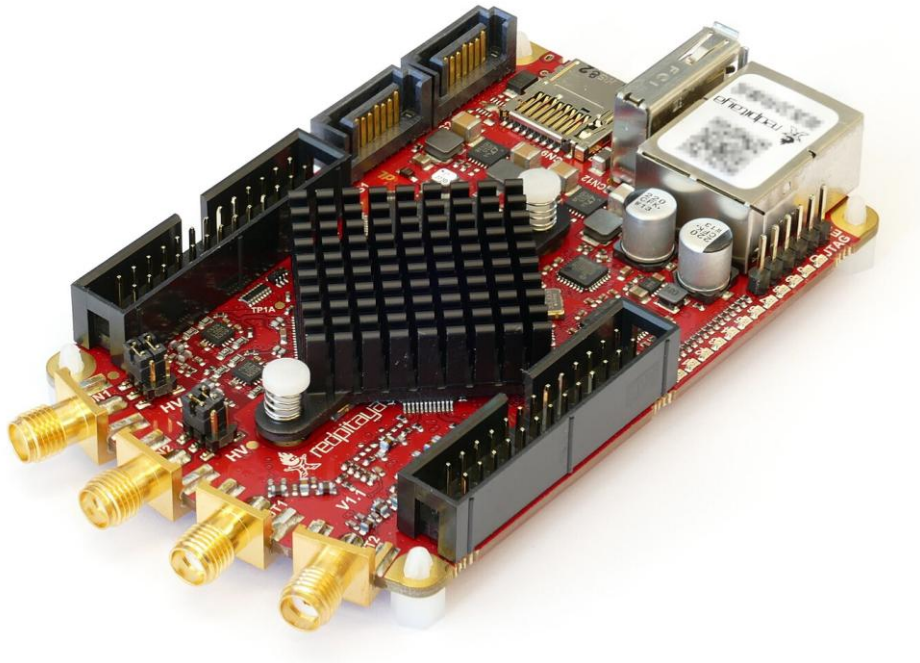


The Phasemeters

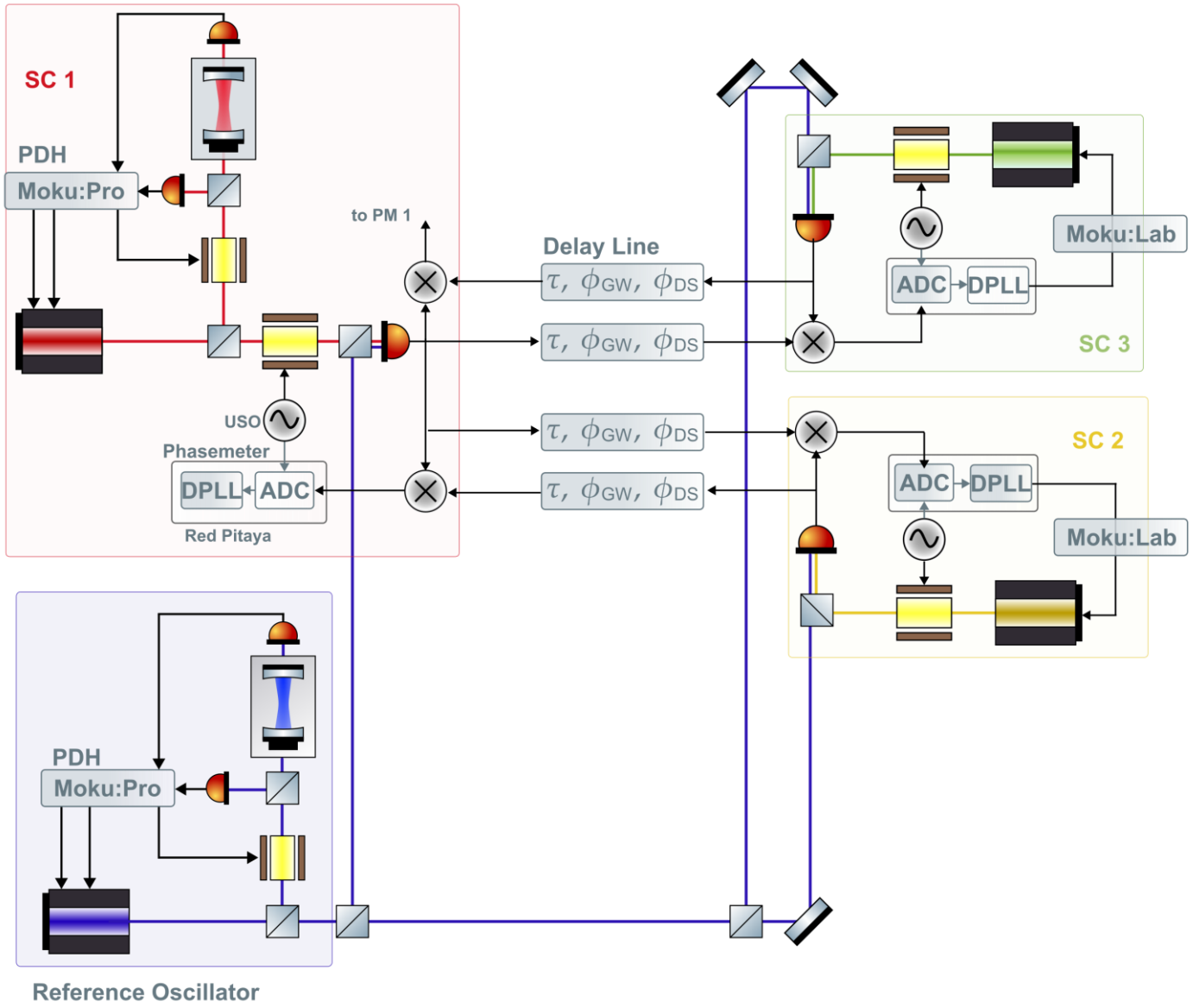
Red Pitaya running LISA gateware

Not space-qualified, but enables MHz phase readout

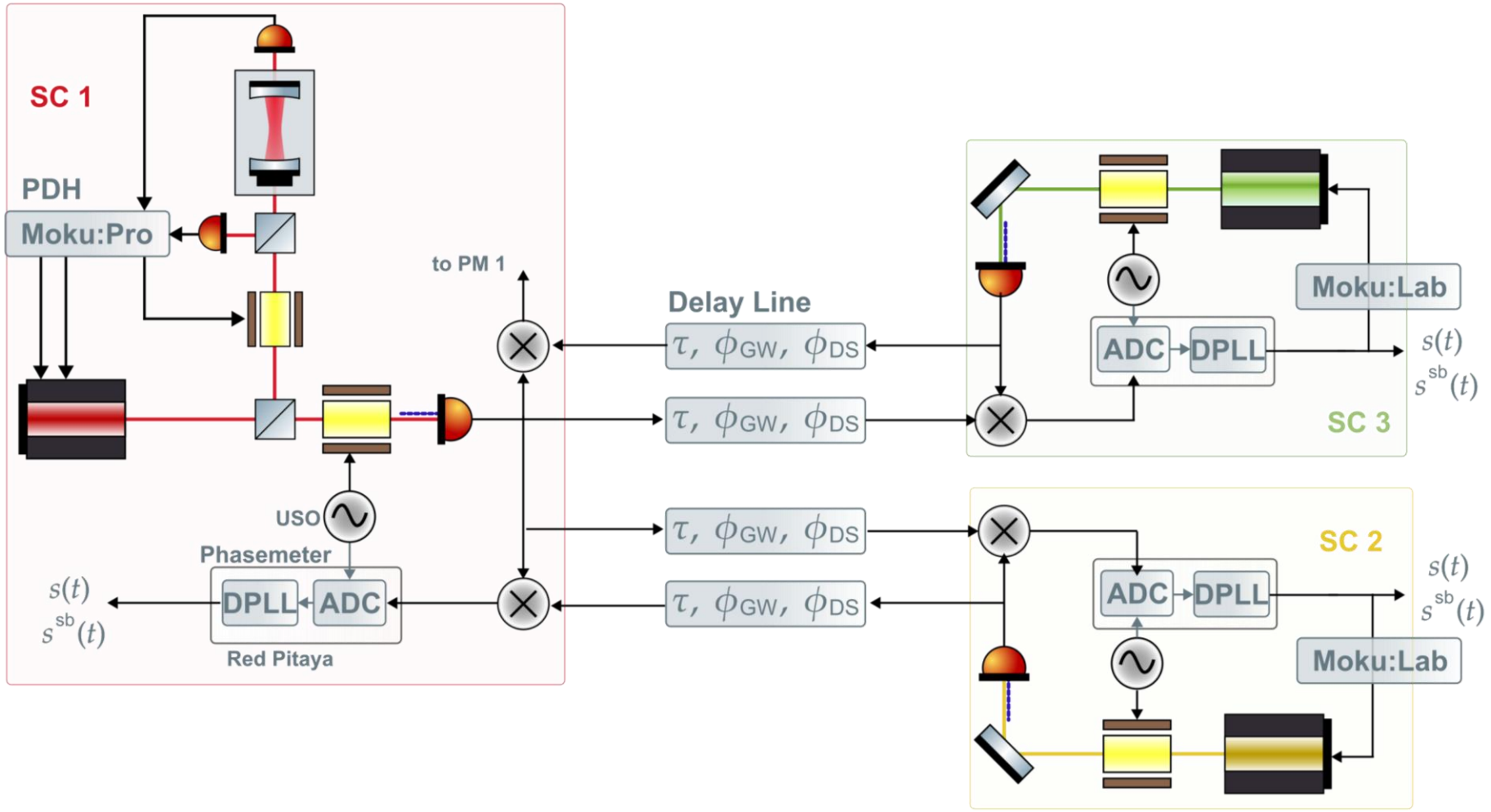
ADC is noisier than LISA's frontend, but pilot tone correction helps
Each board has two inputs and two outputs.



Two-arm Testbed



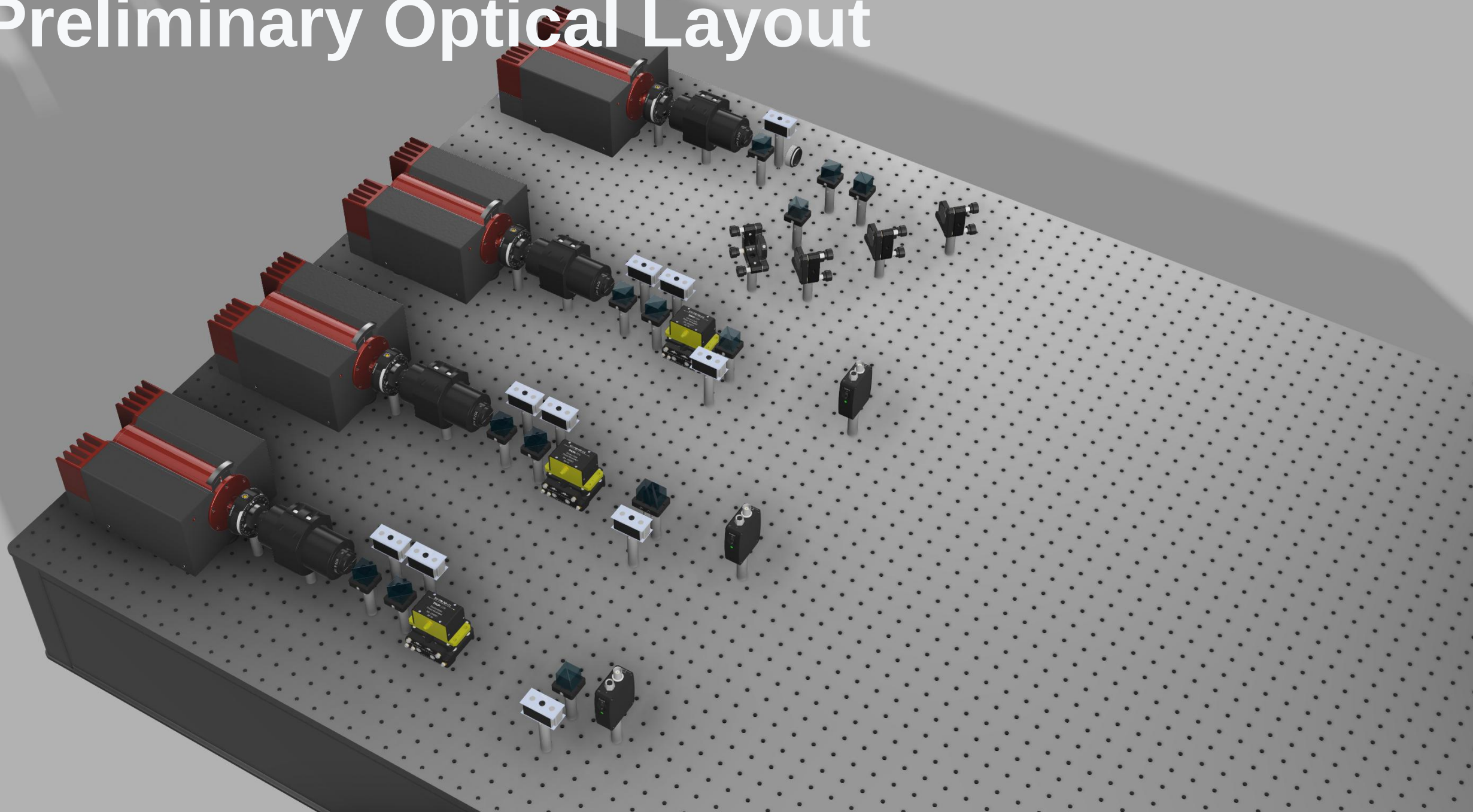
Two-arm Testbed



Possible Additions

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

Preliminary Optical Layout




Thank you for listening!