LISA OPTICAL METROLOGY CHALLENGES

Daniel Penkert[1,2], Oliver Gerberding[1,2], Gerhard Heinzel[1,2] and the AEI LISA Team

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Gravitational-Waves Science & Technology Symposium, March 1-2, 2018

Background image: hydrogen, sulfur, and oxygen in part of the Orion Constellation including Barnard's Loop along with the Orion and Flame Nebulae © David Lindemann

Outline of this talk

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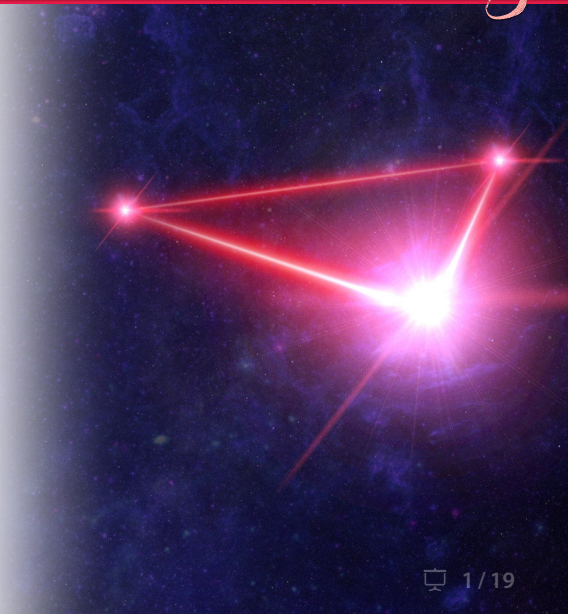

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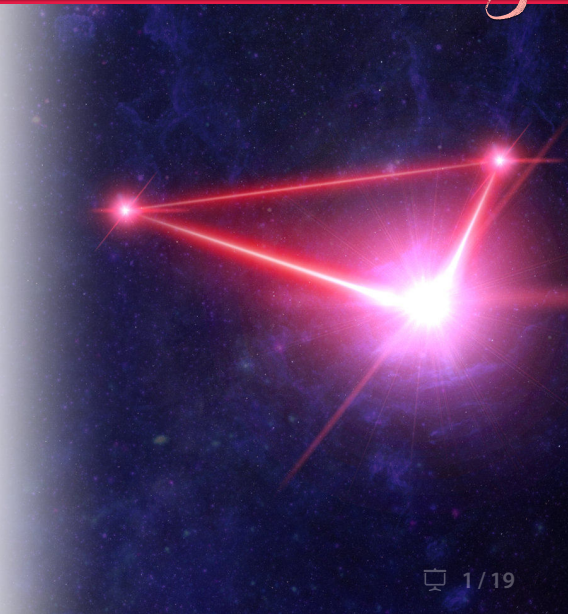
2. The Hexagon Interferometer



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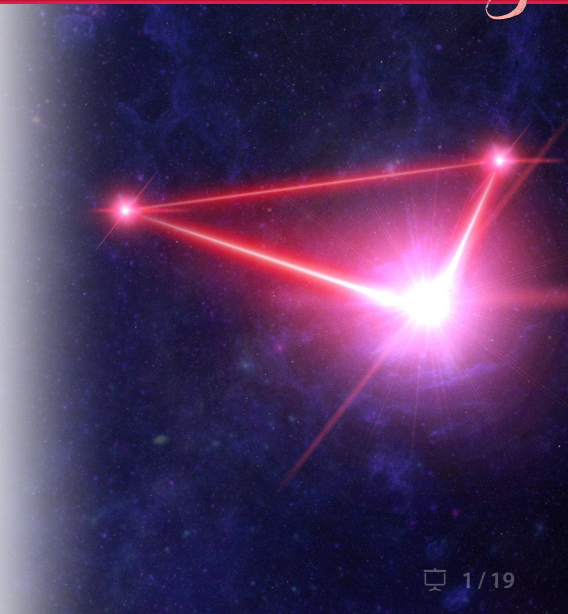

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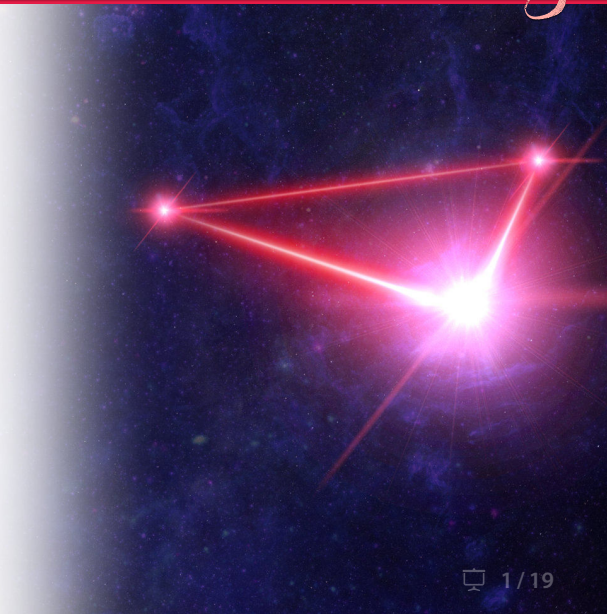

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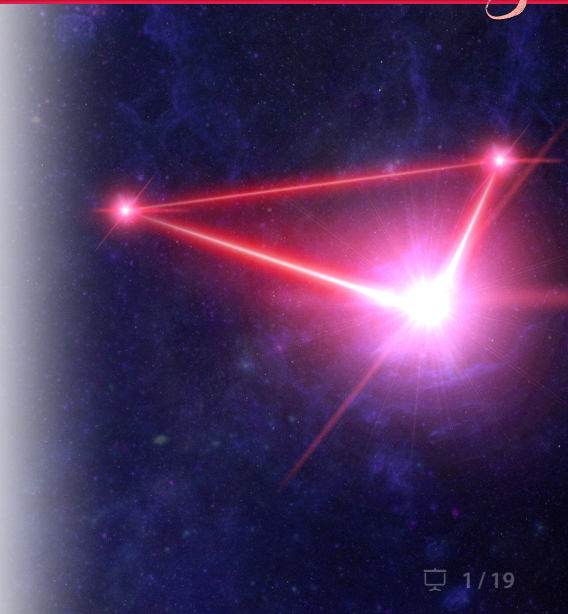
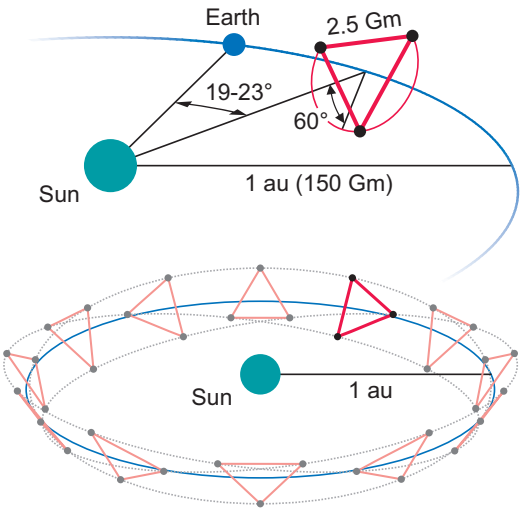
5. Summery

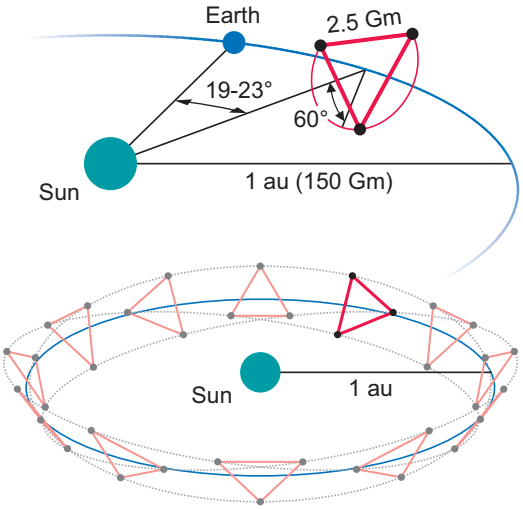


Laser Interferometer Space Antenna



Laser Interferometer Space Antenna

- space-borne gravitational wave observatory



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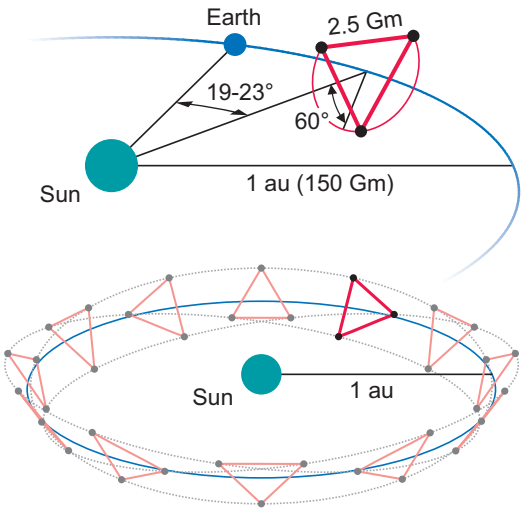

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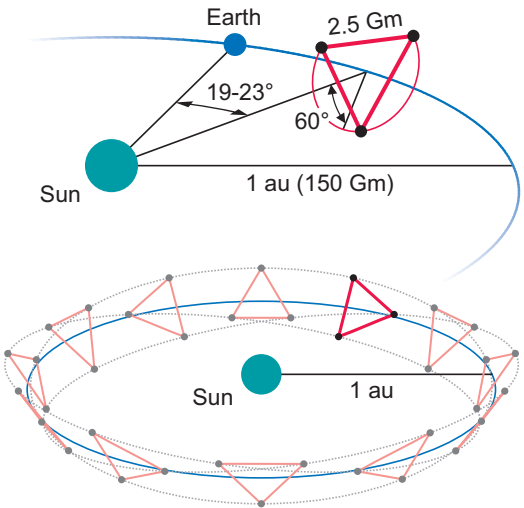

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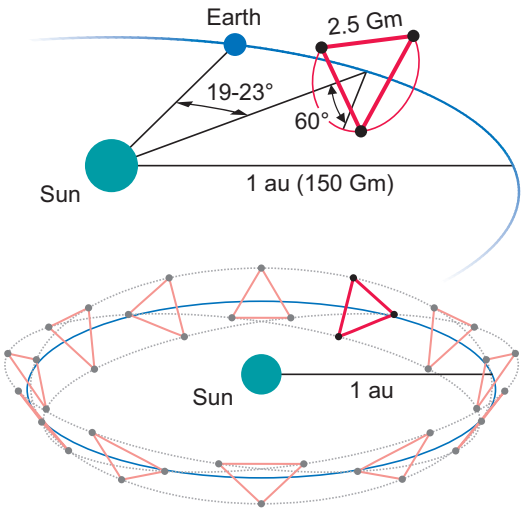

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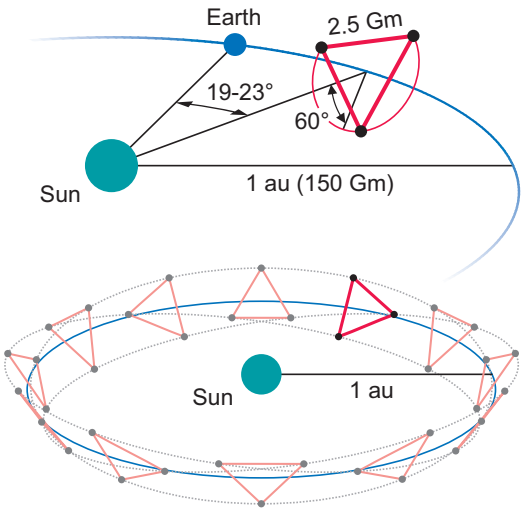

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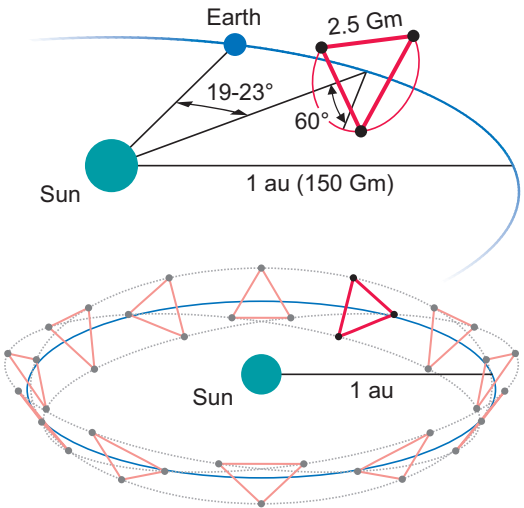

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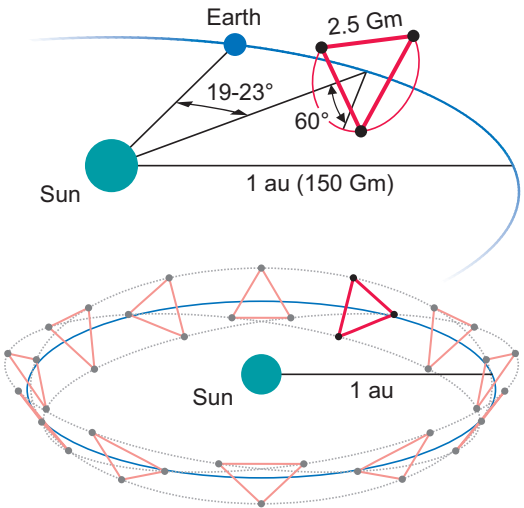

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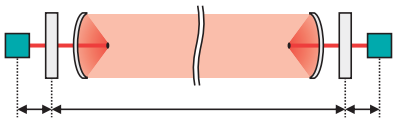

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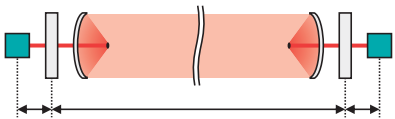

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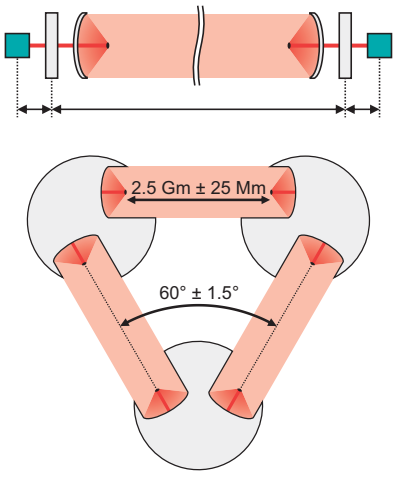

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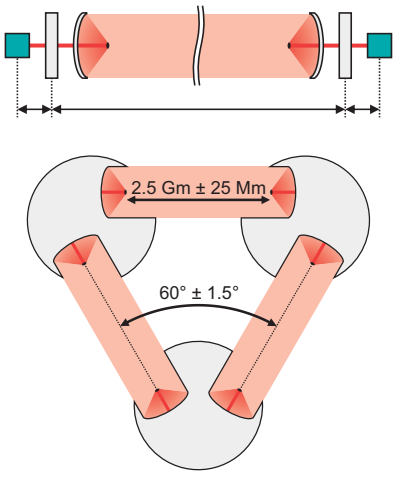

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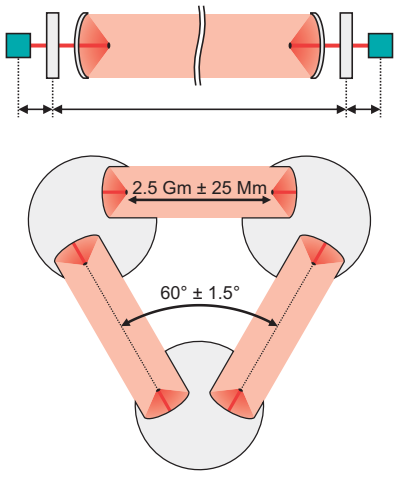
- many aspects of inter-S/C interferometry will be tested within the GRACE-FO mission (scheduled for launch on April 27, 2018)



Primary beat-note readout and phase extraction

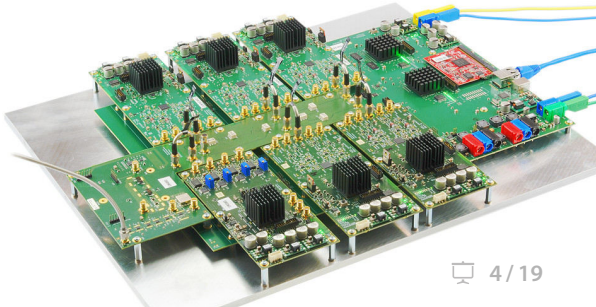


Image: FPGA-based LISA phasemeter prototype (co-developed in the scope of an ESA technology development program by AEI Hannover, Technical University of Denmark and Axcon ApS)

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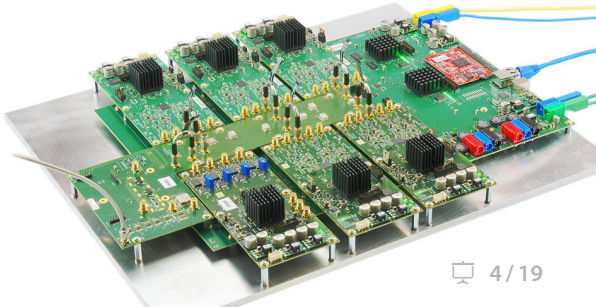

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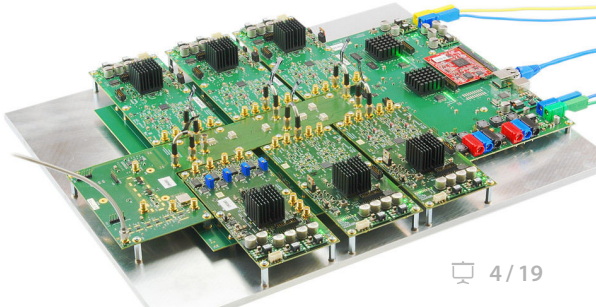

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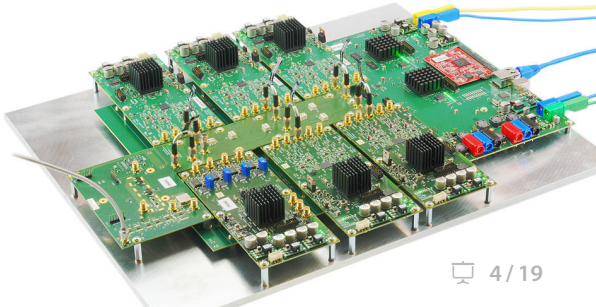

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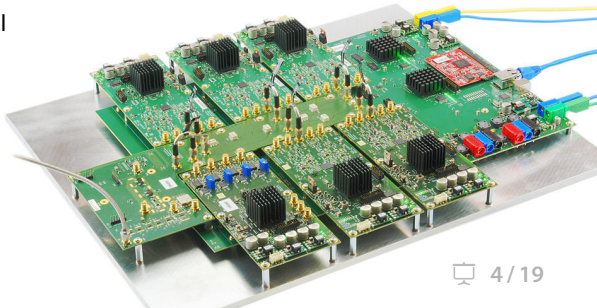
- cascaded arm interferometry approach $\Rightarrow$ no optical cancellation of laser frequency noise in the sectional measurements $\Rightarrow$ phase readout with high dynamic range (up to 10 orders of magnitude)



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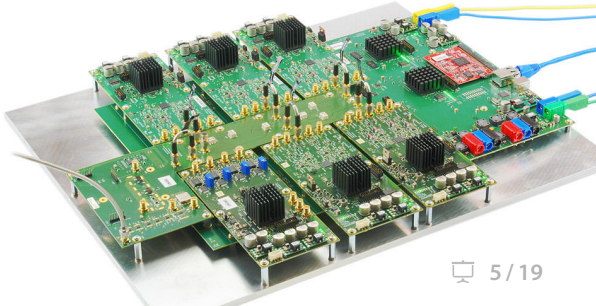
Hexagon – Testing the Phase Readout System

Problem: How can we test a phase readout system for this unusually high level of precision?



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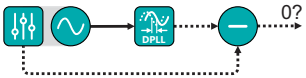
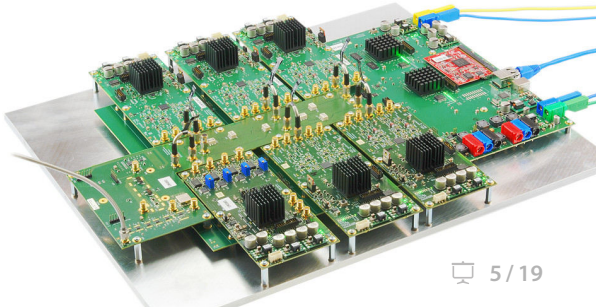


Absolute signal test: requires a signal generator with an extremely high phase fidelity (not readily available)



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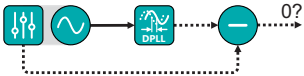

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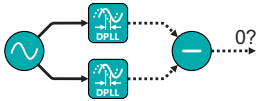
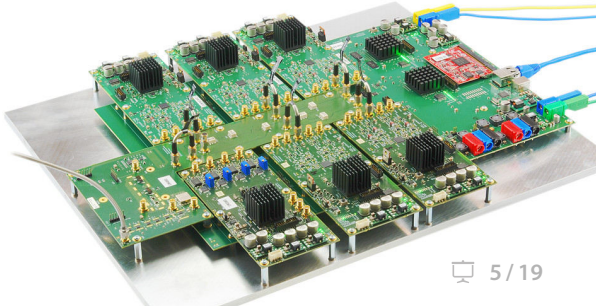


Split signal test: oblivious to common-mode effects like phase nonlinearity or signal-triggered cycle slips



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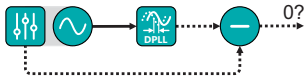

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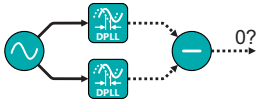

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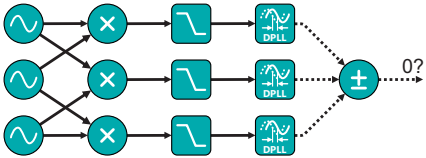
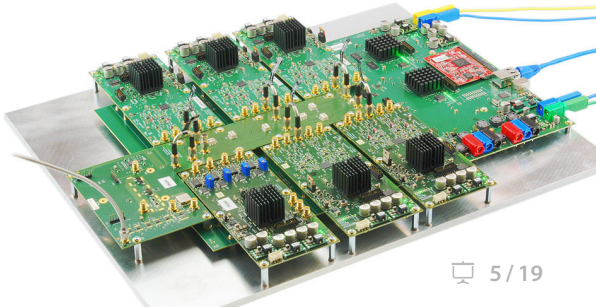


Three-signal test: generates three signals, the sum of which should vanish if measured correctly ⇒ Hexagon



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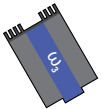

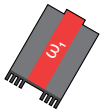

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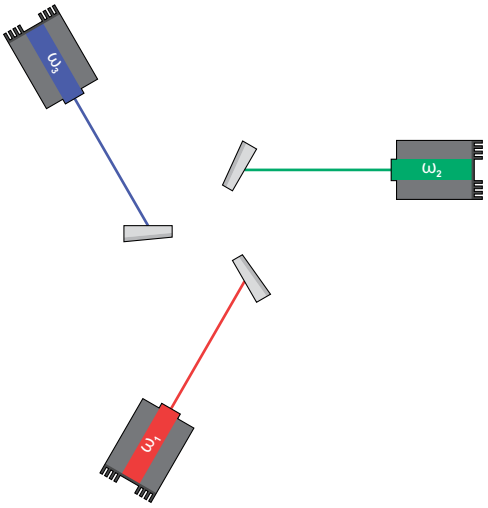

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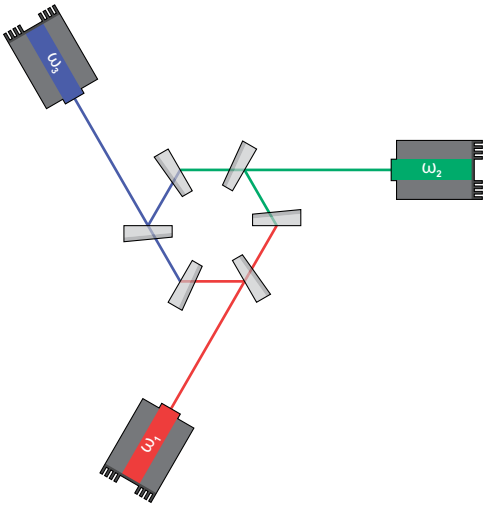

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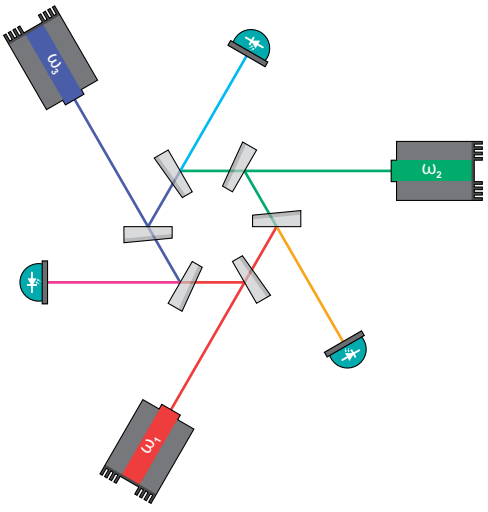

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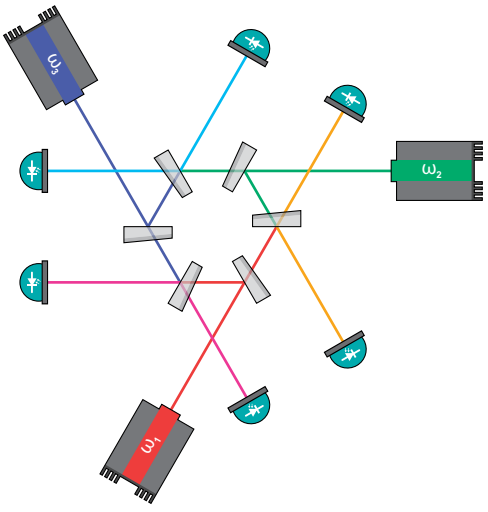

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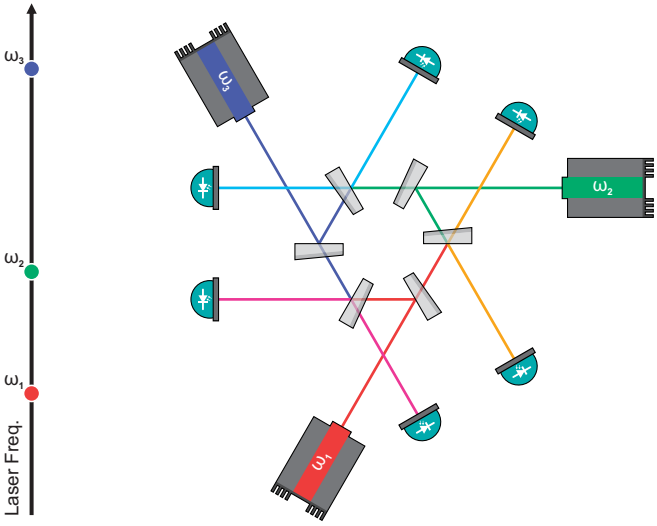

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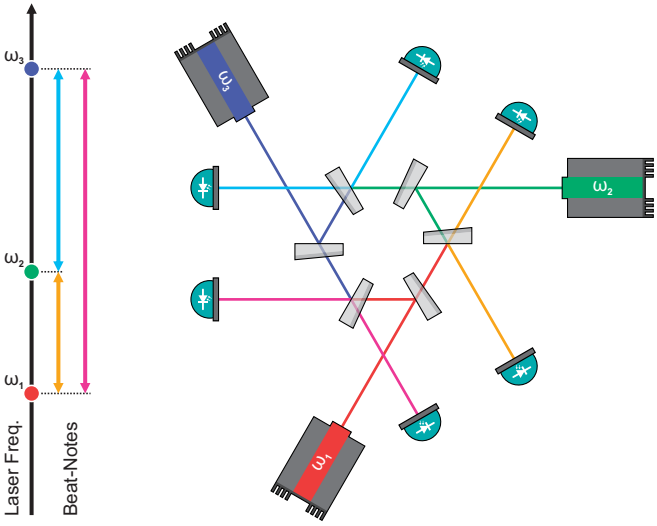

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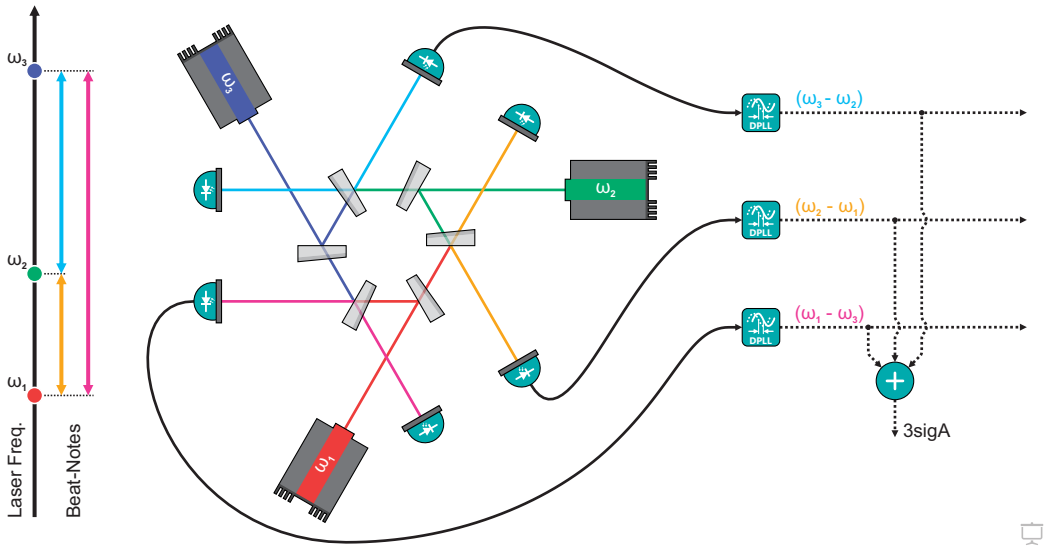

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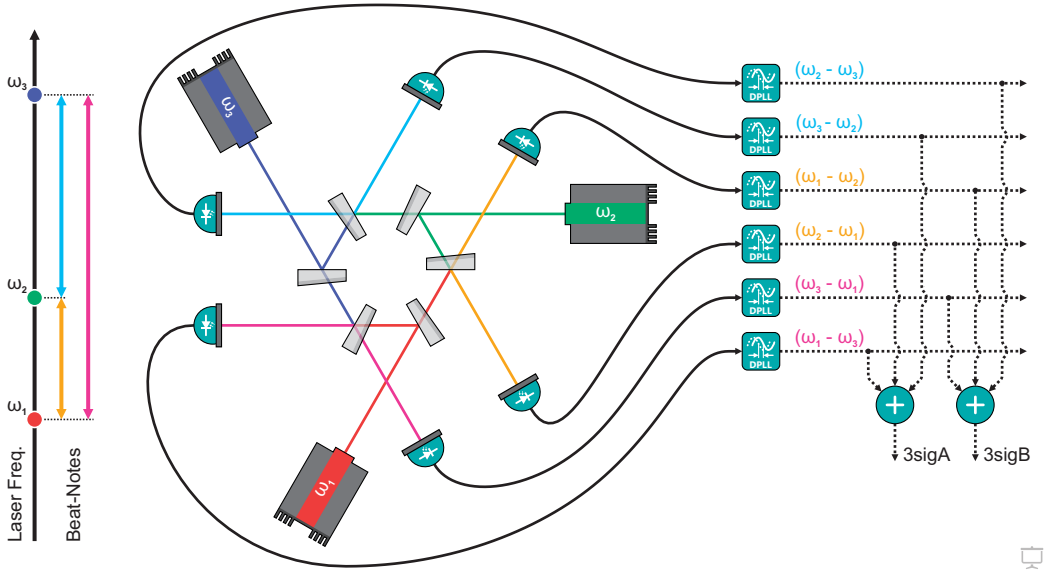

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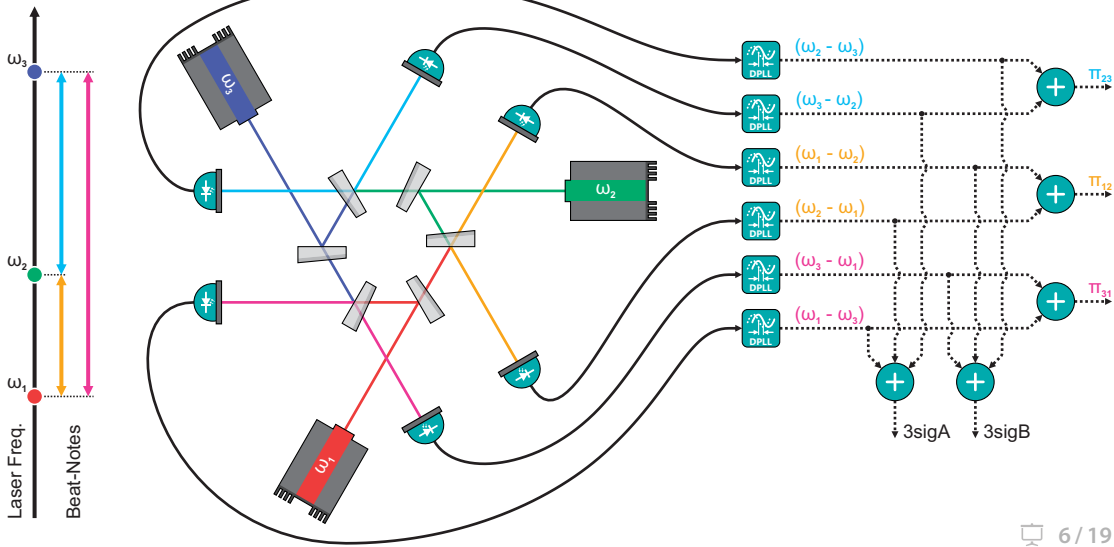
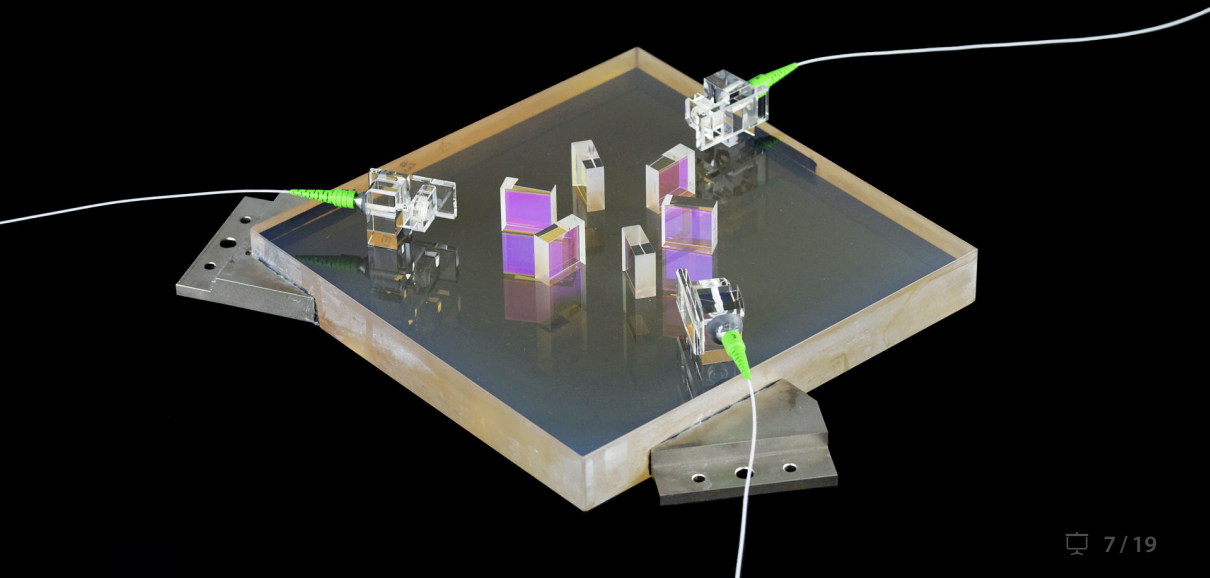
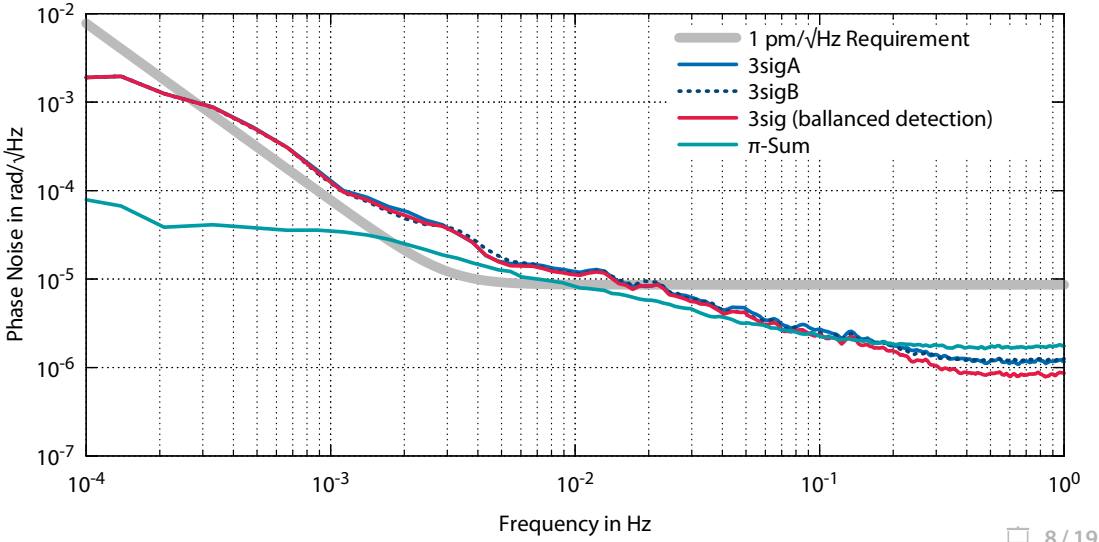


Hexagon – Ultra-stable Implementation



Hexagon – Performance Results



List of Metrology Challenges – Part 2

Post-processing & Auxiliary Functionality

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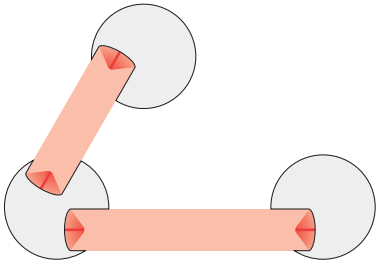
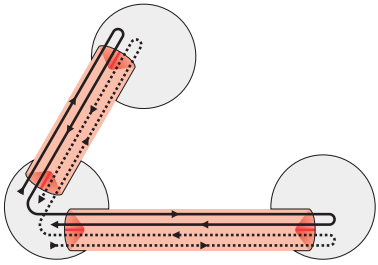
- direct signal combinations are equivalent to an unequal arm length Michelson ⇒ laser frequency noise does not cancel



Post-processing & Auxiliary Functionality

- direct signal combinations are equivalent to an unequal arm length Michelson $\Rightarrow$ laser frequency noise does not cancel $\Rightarrow$ time-delay interferometry (TDI), uses sums of delayed signals to synthesize an equal arm length interferometer



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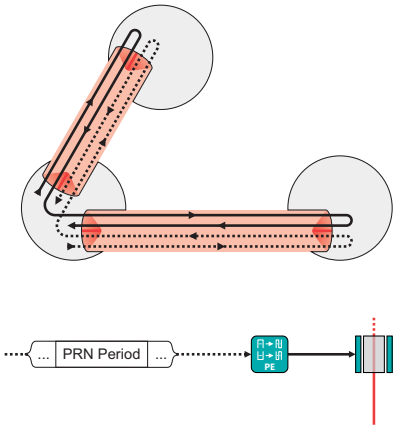

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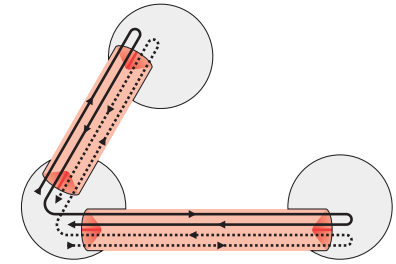

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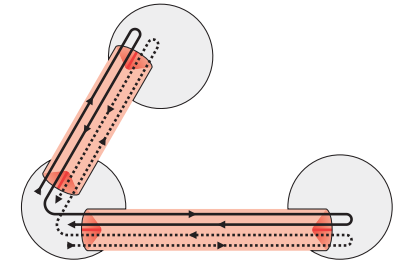
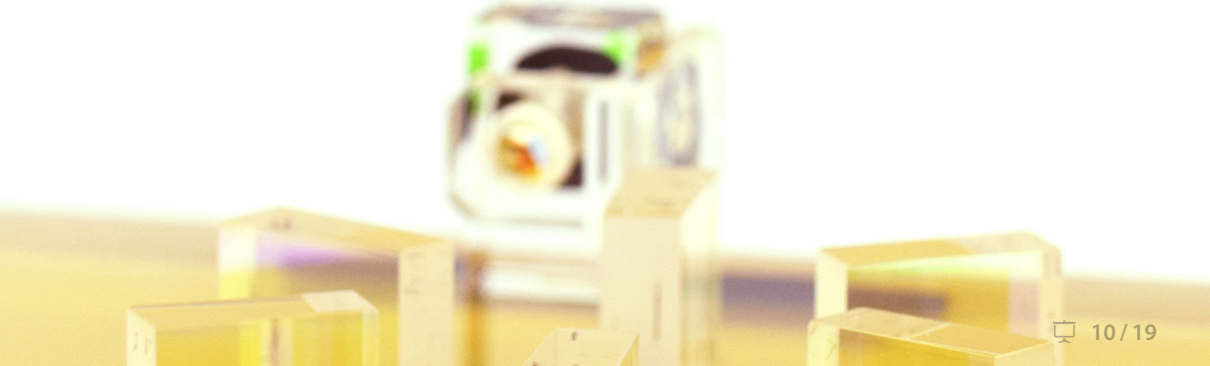
- each S/C running on its own separate clock ⇒ clock-tone transfer via GHz sidebands on the laser links ⇒ dynamic re-sampling in post-processing (often considered part of TDI)



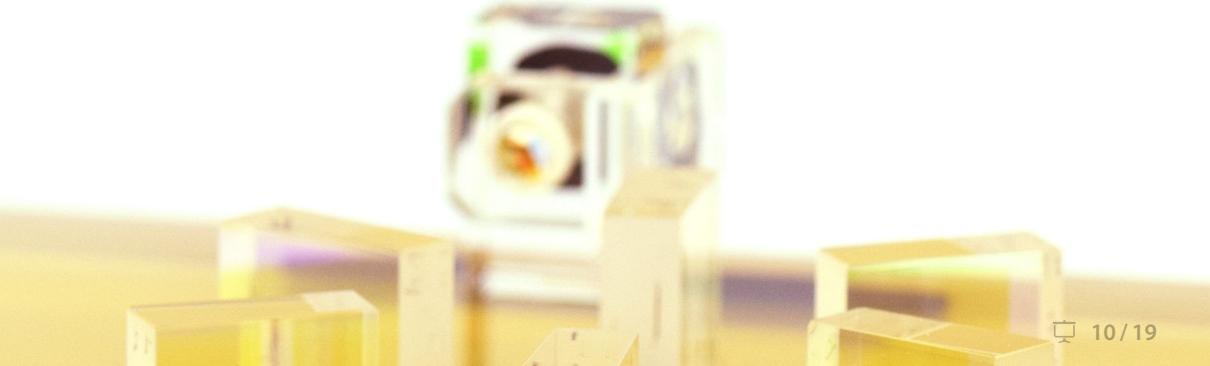
Step-by-step simplification of LISA



Hexagon – Simplified LISA Constellation

Step-by-step simplification of LISA

- no external forces acting upon the three LISA S/C



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Step-by-step simplification of LISA

- no external forces acting upon the three LISA S/C
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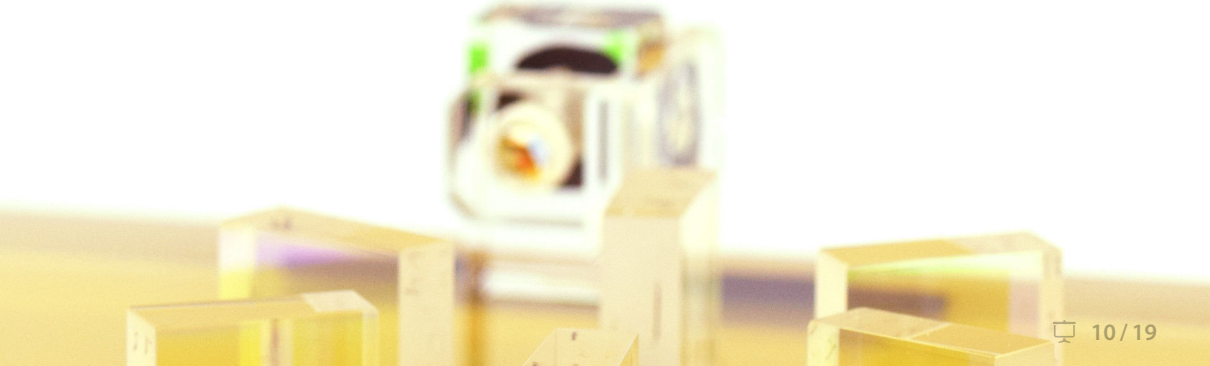

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Step-by-step simplification of LISA

- no external forces acting upon the three LISA S/C
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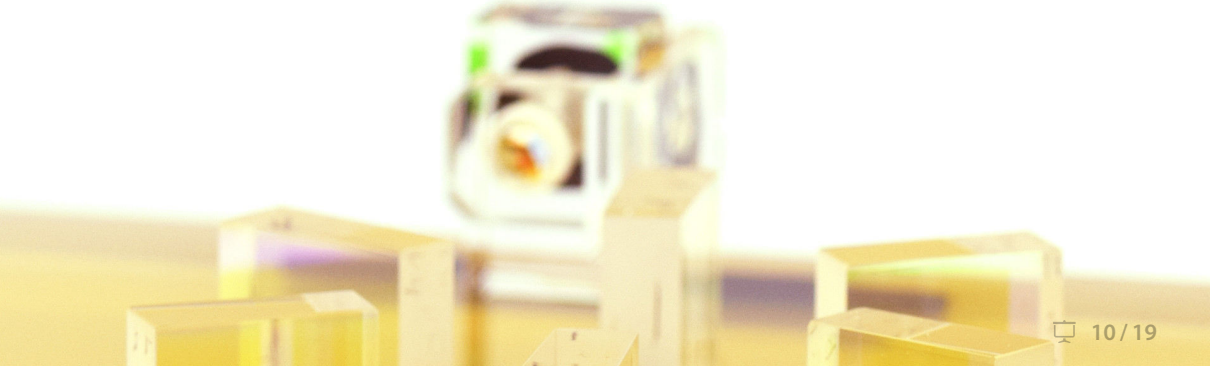

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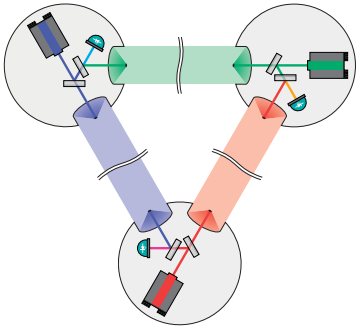
- remove all clockwise laser links



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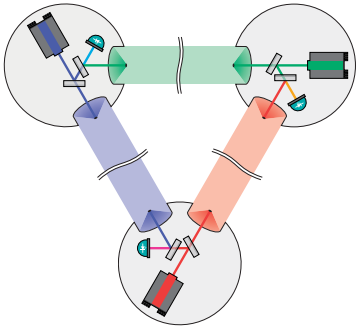

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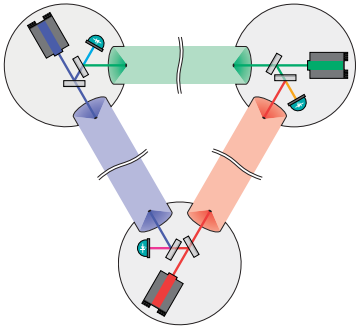
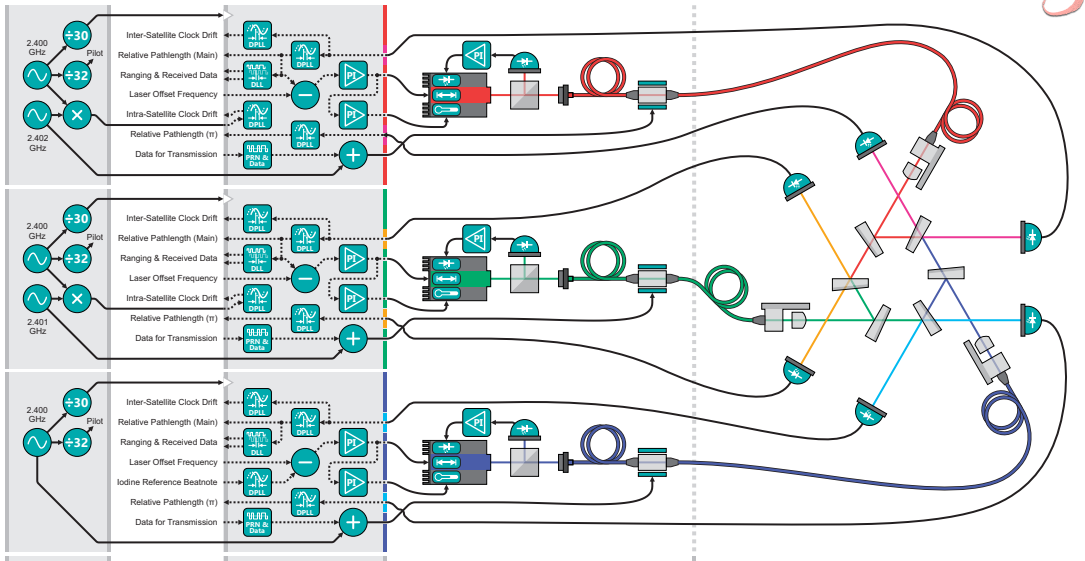
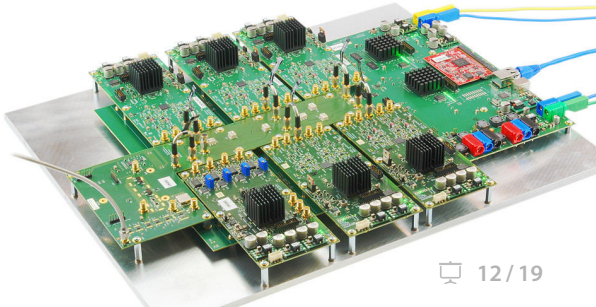


Hexagon – Testing the Full LISA Arm Metrology Chain



Supplemental and Auxiliary Phasemeter Functionality

- **automatic beat-note acquisition**
  FFT-based search for spectral peaks and initialization of digital phase-locked loops (DPLLs)



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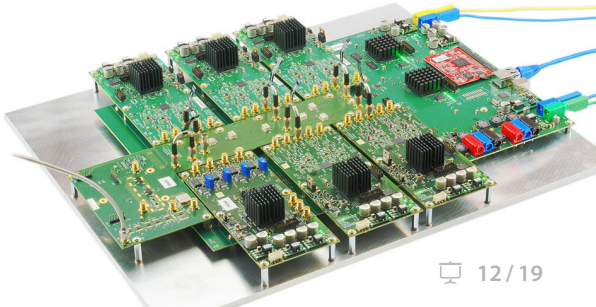

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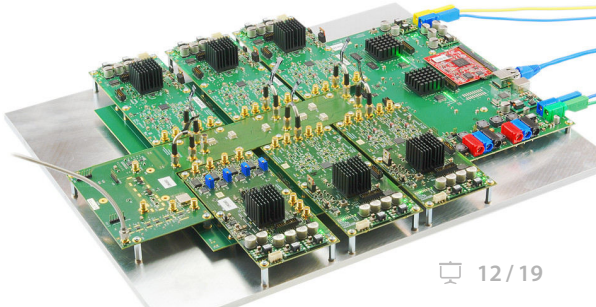

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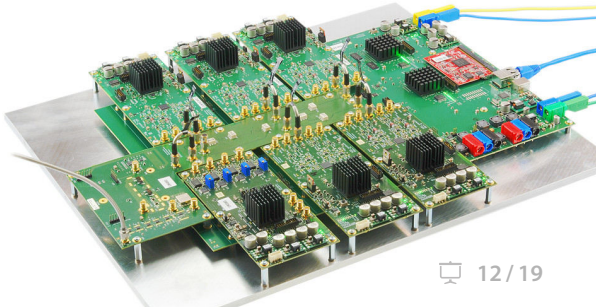

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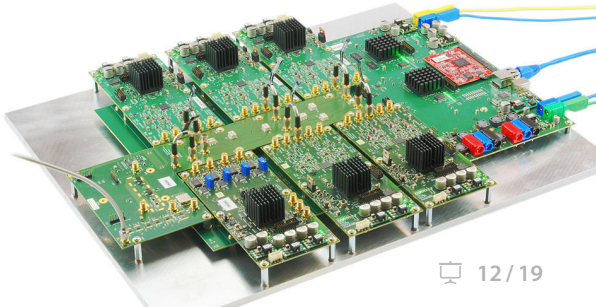

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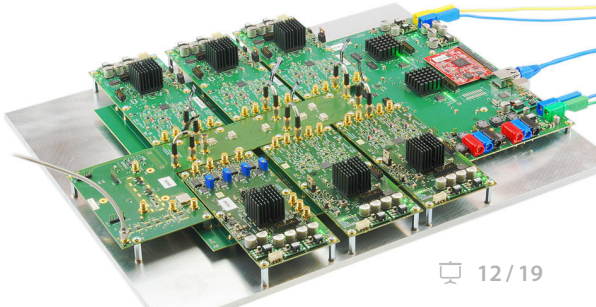

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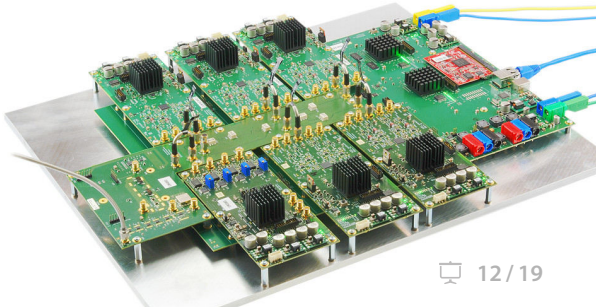
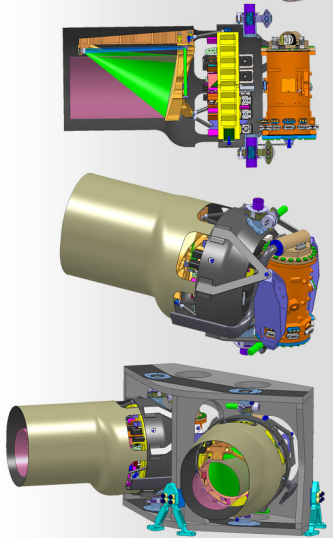
- **low bandwidth data communication**
  switching sign of chunks of PRN chips



List of Metrology Challenges – Part 3

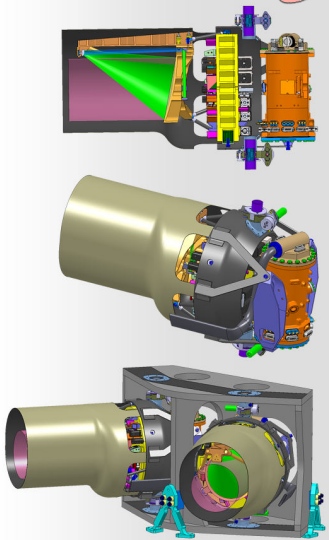
Intra-Spacecraft Motion and Spurious Light



Images: LISA moving optical subassemblies (MOSAs), each comprising telescope, optical bench and test mass chamber; courtesy of Airbus D&S

Intra-Spacecraft Motion and Spurious Light

- angular breathing $\Rightarrow$ variable pointing of telescopes and their rigidly attached dedicated optical benches $\Rightarrow$ inter-bench phase reference distribution system (PRDS a.k.a. "backlink") to subtract laser frequency noise in post-processing (requirement: $2\,\mathrm{pm}/\sqrt{\mathrm{Hz}}$ reciprocal phase noise)



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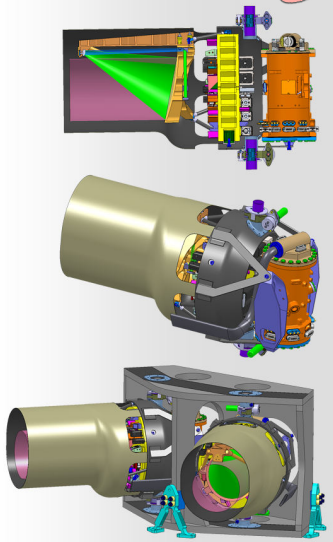

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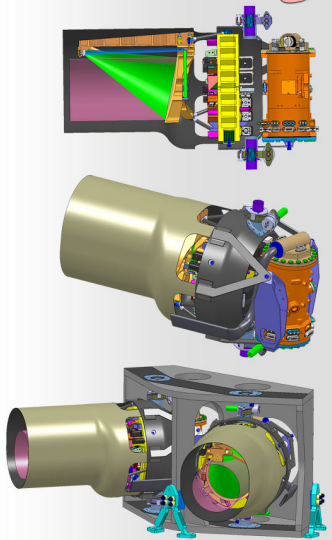
- fiber back scatter within PM fibers has previously been measured to be $\approx 4\,^{\mathrm{ppm}}/_{\mathrm{m}}$, but what are the effects of cosmic/solar radiation? ⇒ separate experiment using gamma and neutron radiation [AEI & Fraunhofer INT]



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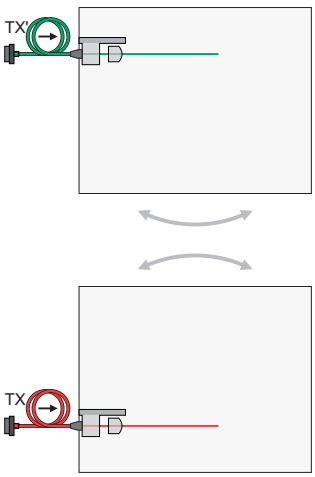
Classic Attenuated Fiber Backlink – Setup

Classic Attenuated Fiber BL



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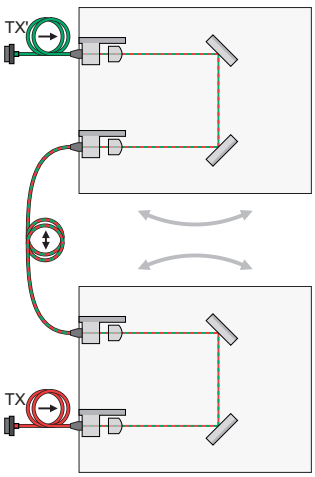

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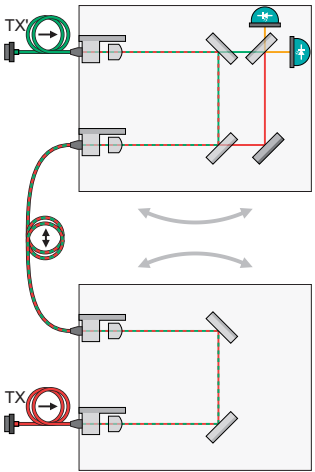

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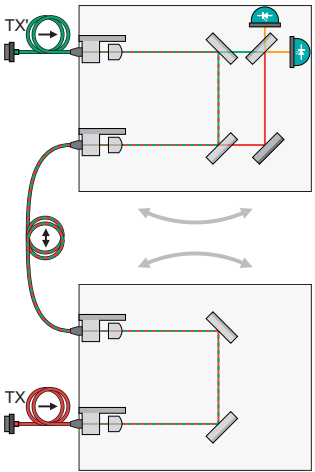

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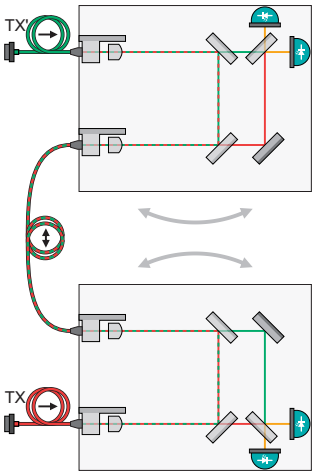

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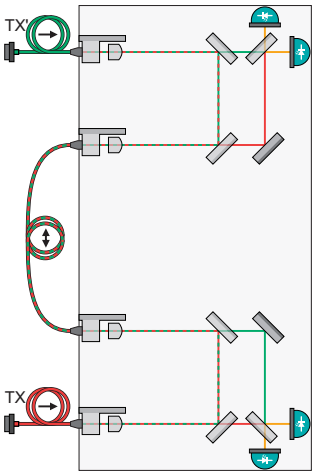

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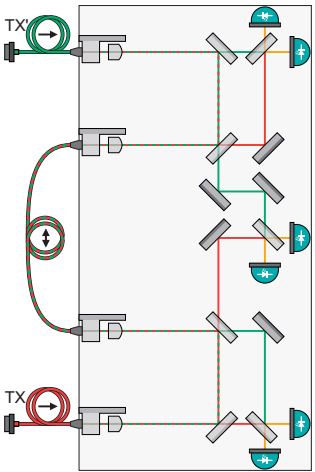

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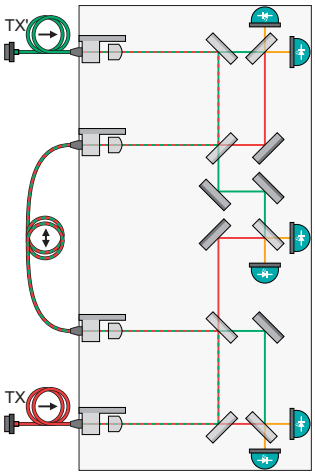
Classic Attenuated Fiber BL



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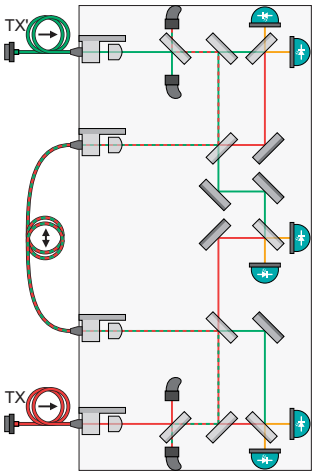
- not sufficient: back-reflected beams wherever light was coupled into a fiber coupler ⇒ spurious beat-notes in our interferometers

Classic Attenuated Fiber Backlink – Setup

Classic Attenuated Fiber BL



- objective: each spacecraft houses two TX laser sources (one for each arm, indicated in red and green) which need to be interconnected by a flexible optical backlink ⇒ easiest solution: PM fiber
- lock the green laser to the red one, using the upper interferometer
- fiber has a very poor path length stability ⇒ use the lower interferometer to measure the phase drift between the two lasers for subtraction in post-processing ⇒ this only works if the backlink behaves reciprocally (same optical pathlength in both directions)
- lab test: place setup on a common optical bench and add reference interferometer (middle) ⇒ classic fiber backlink experiment
- not sufficient: back-reflected beams wherever light was coupled into a fiber coupler ⇒ spurious beat-notes in our interferometers
- attenuation stages after TX fiber couplers ⇒ back-reflected beams attenuated twice as much as TX beams

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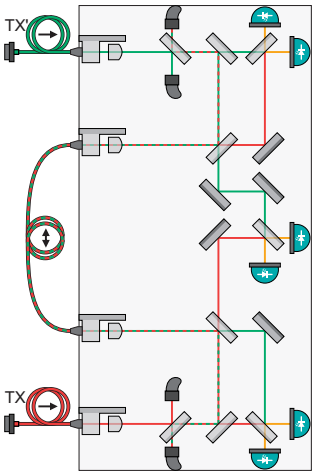

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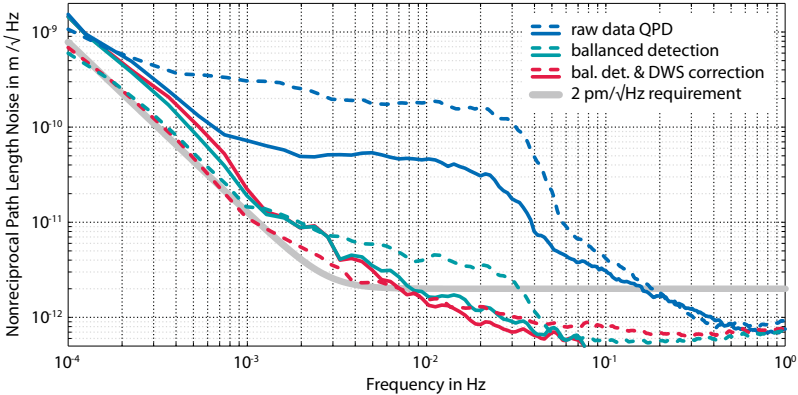
- attenuation stages after TX fiber couplers ⇒ back-reflected beams attenuated twice as much as TX beams
- no such solution exists for the backlink fiber couplers (backlink light and spurious beams would see the same attenuation)

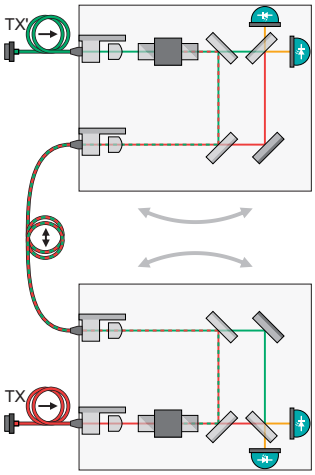
Classic Attenuated Fiber Backlink – Results



- attenuation stages (solid lines) and balanced detection sufficient for required fiber phase reciprocity
- balanced detection requires more photoreceivers and phasemeter channels
- DWS correction (classic backlink used commercial fiber couplers instead of monolythic ones)

More Backlink Candidates

Classic Fiber Equivalent BL



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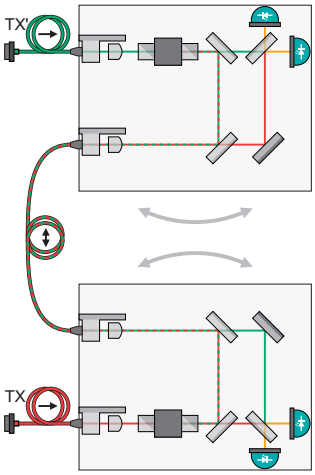
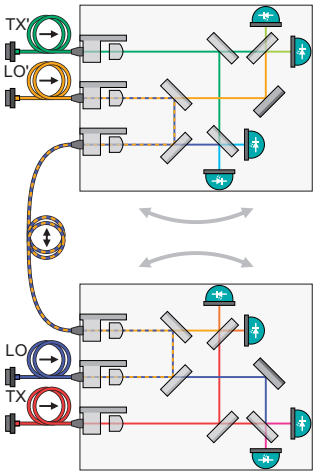


Frequency-shifted Fiber BL



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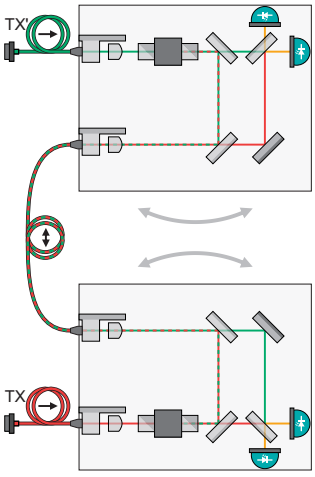

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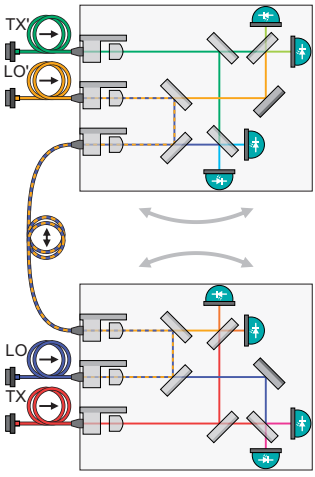
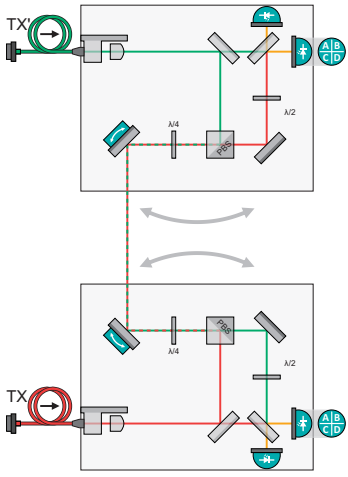
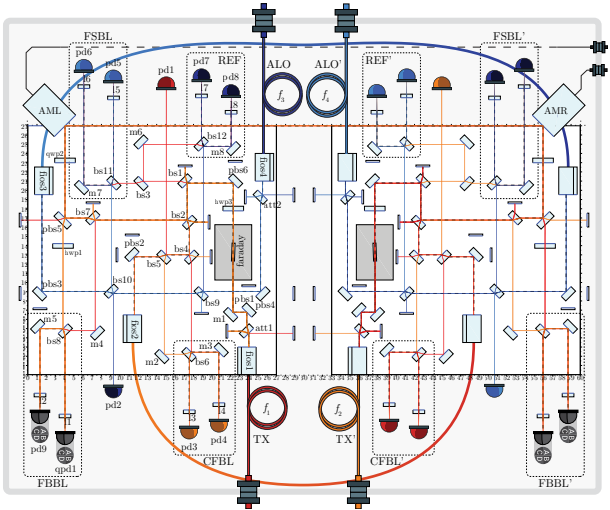
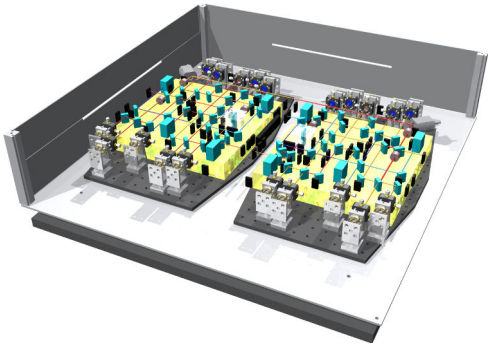


Pol-encoded Free Beam BL



Three-Backlink Experiment





Paper: KS Isleif et al., Towards the LISA Backlink, CQG 2018

Other Activities

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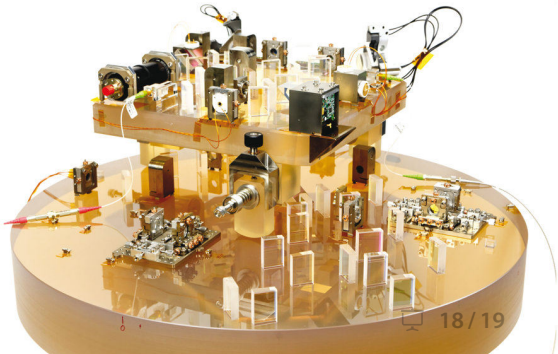

List of Metrology Challenges – Part 4

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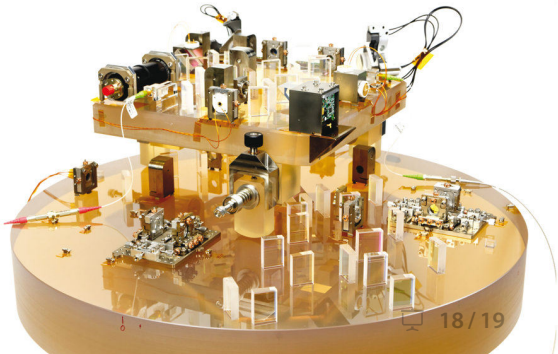

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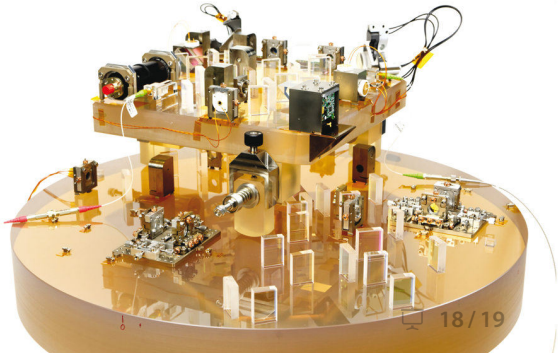

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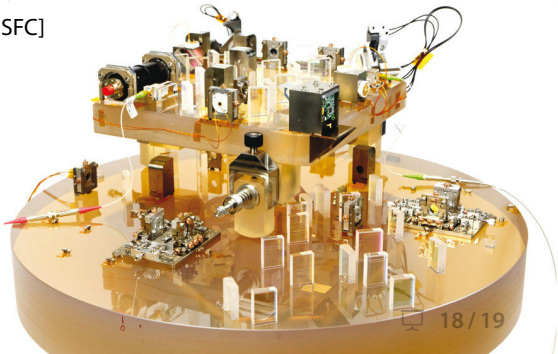

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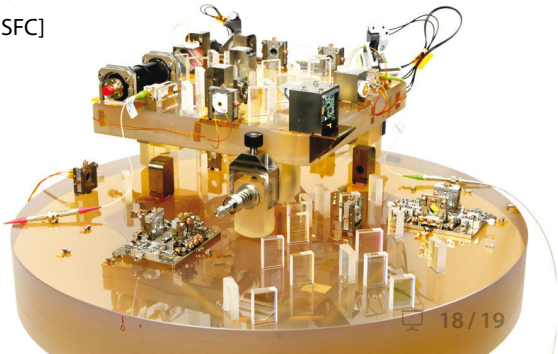

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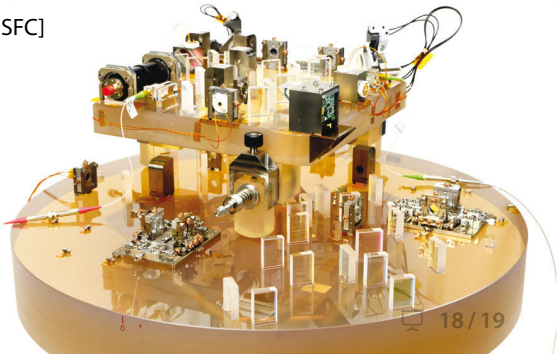
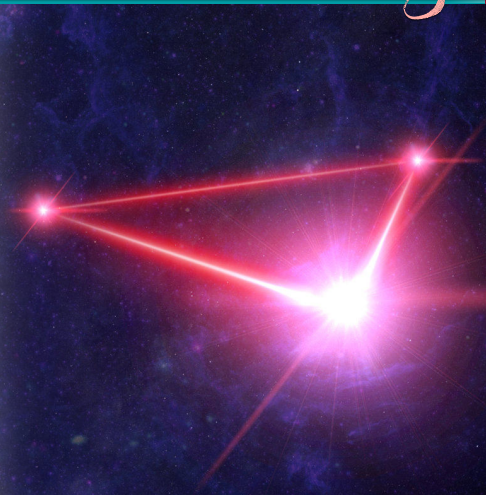
- and much more: laser development, frequency pre-stabilisation, laser link acquisition, signal pre-processing, TDI, LISA simulator, ...



Summary

- **Laser Interferometer Space Antenna**
  space-borne gravitational wave observatory for sources inaccessible to ground-based detectors
- **The Hexagon Interferometer**
  an optical three-signal testbed for LISA's phase readout system but capable of testing the full LISA arm metrology chain in the future
- **The Three-Backlink Experiment**
  direct comparison between several alternative implementations of a LISA backlink, providing an optical phase reference between the two moving optical benches within one S/C



Thank you very much!