The Hexagon interferometer: a dedicated testbed for the LISA phasemeter

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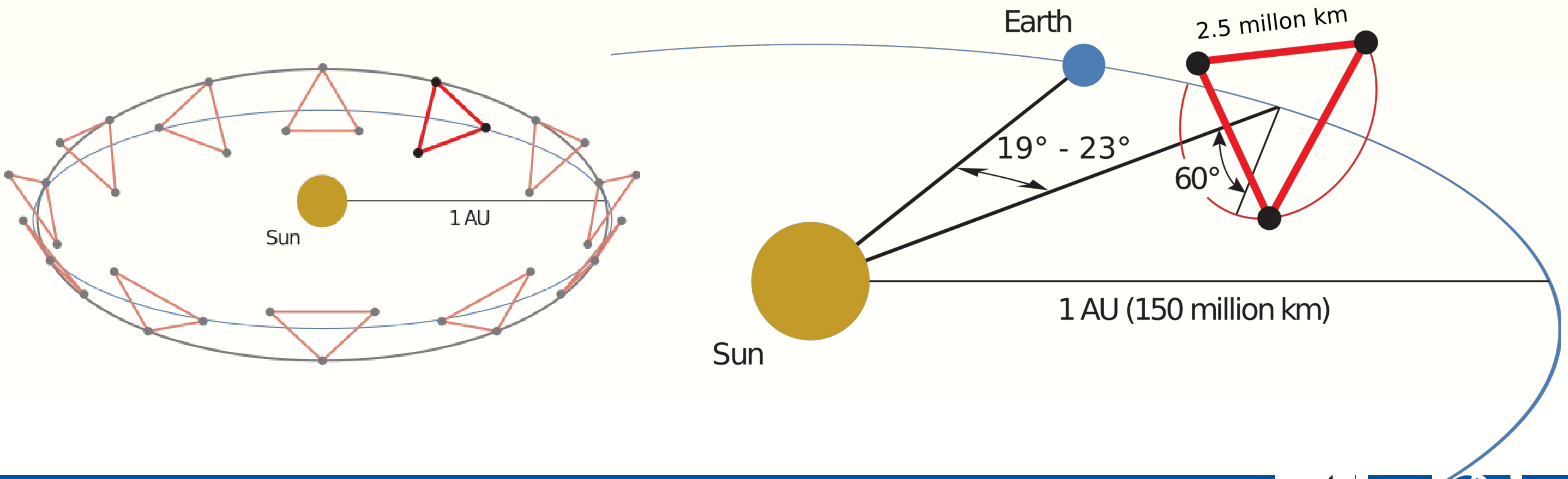
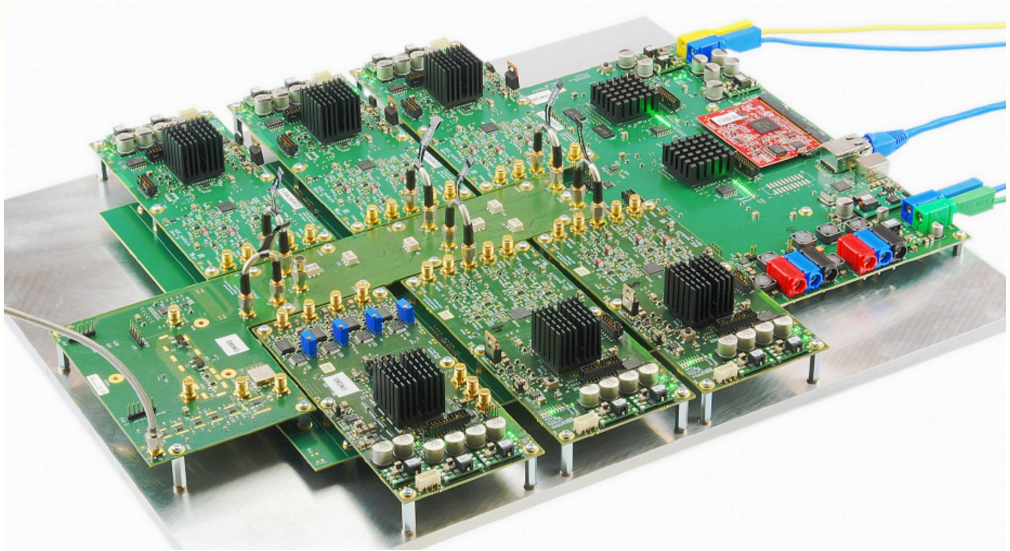
LISA

- ESA L mission to measure low-frequency gravitational waves
- Heterodyne Laser interferometry over 2.5 million km
- Received light power with 30 cm telescope : ~ 1nW
- Doppler shifts of ±10 MHz
- GW are encoded in the phase of received light
- Need ~10pm noise at mHz frequencies



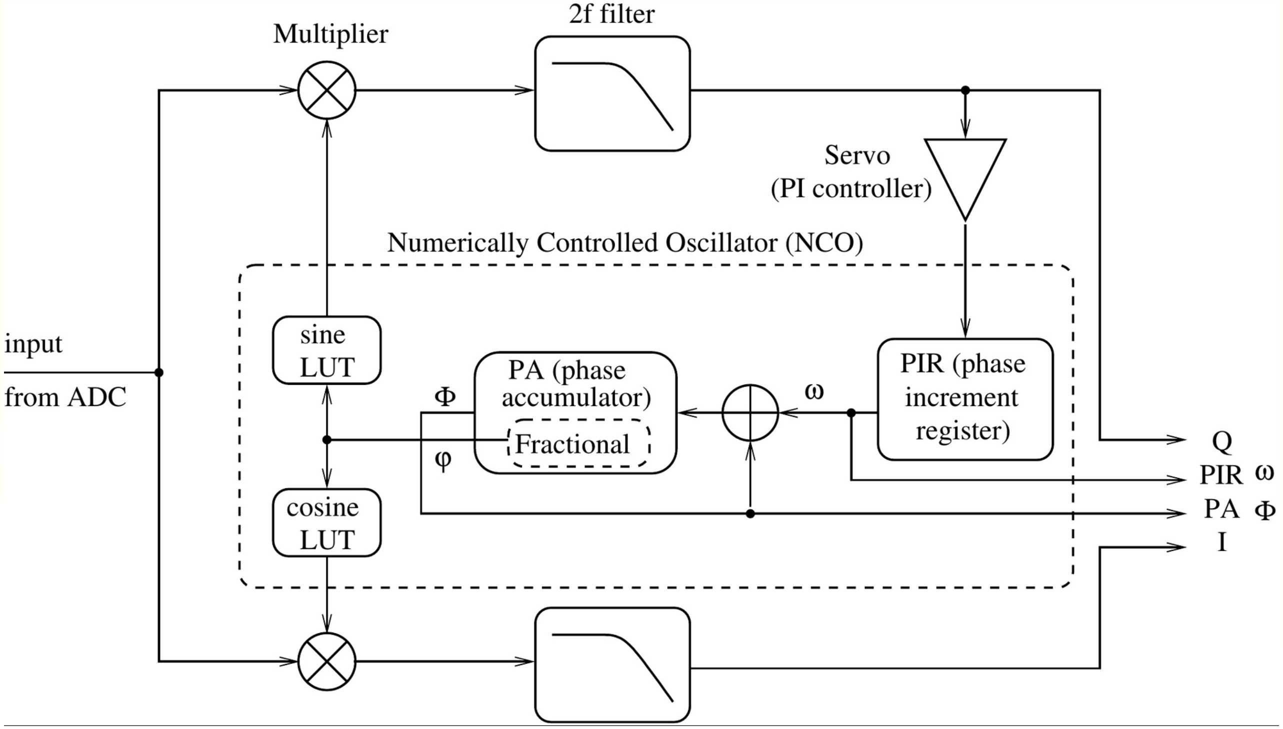
LISA phasemeter

- At the core of the LISA metrology
- Primary function: measure phase of multiple beat notes at 5...30 MHz, varying at few Hz/s, with poor SNR
- Phase must be continuously tracked to μcycle accuracy, output rate 16 Hz
- Auxiliary functions include extra beatnotes for clock noise transfer, and pseudo-random noise modulation for absolute ranging and data transfer
- German(+DK) contribution to LISA



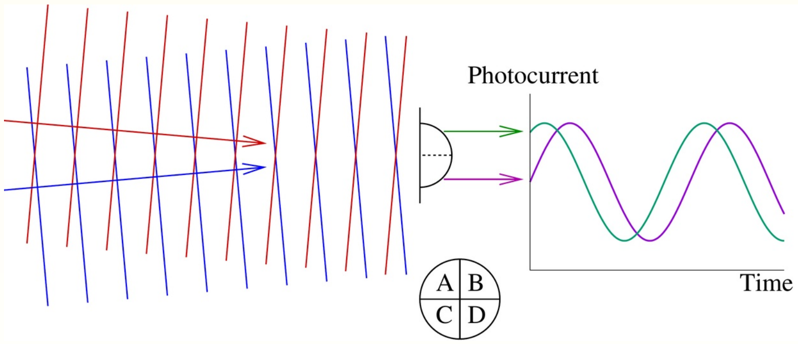
LISA phasemeter

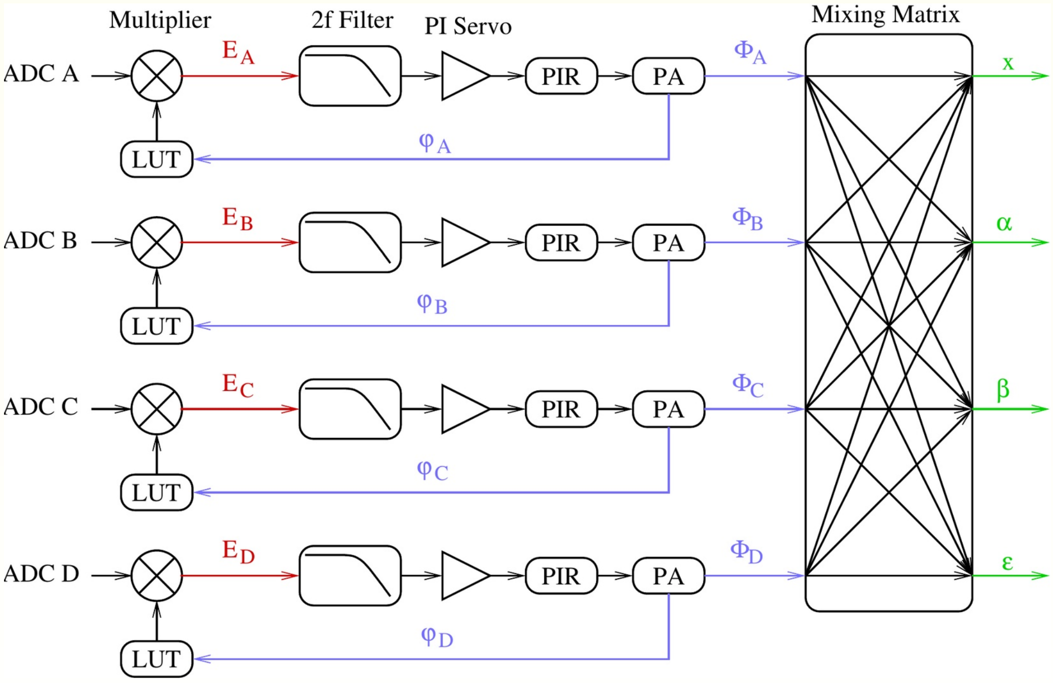
- Based on digital phase locked loop (DPLL)
- A replica of the analog input signal is created and tracked in a digital Numerically controlled oscillator (NCO)
- Phase and frequency then exist in digital registers from where they can be directly read out



Differential Wavefront Sensing (DWS)

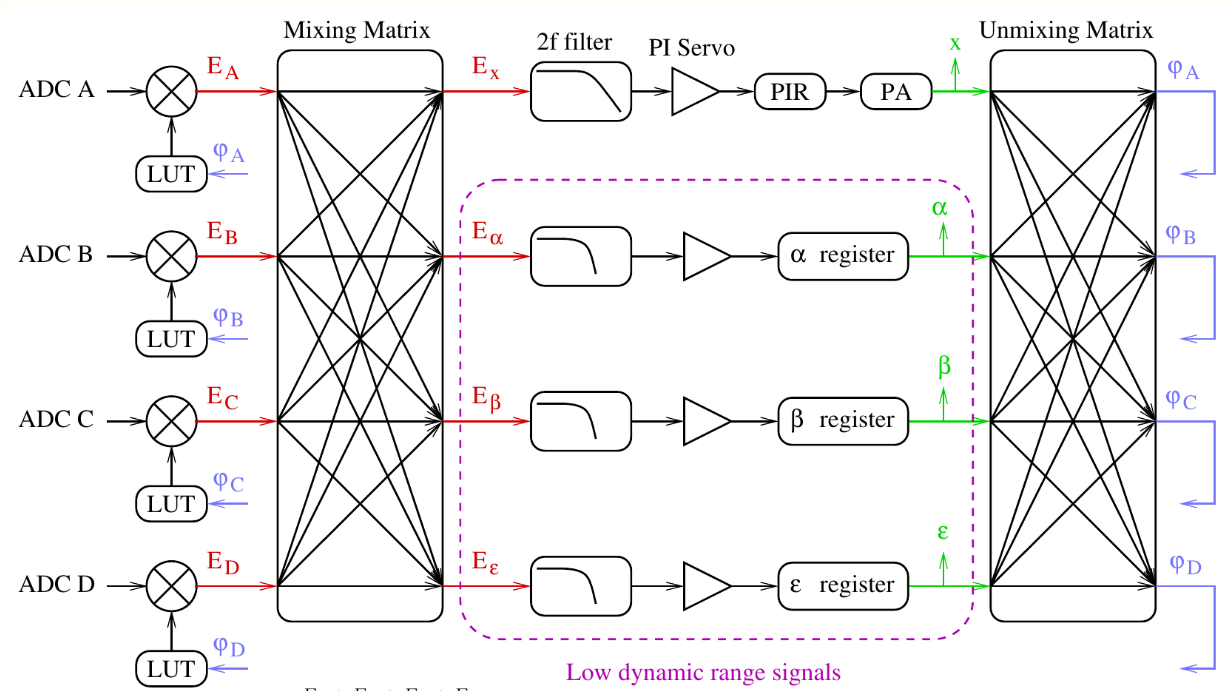
- Standard technique to sense relative misalignments of interfering beams
- Essential for LISA to control spacecraft pointing
- Usual method uses four separate DPLLs and then combines the output





New DWS approach

- Separate tracking loops for length (high dynamic range) and angles (slow)
- Can be separately optimized
- Increases robustness against cycle slips



$$\varphi_A = x + \frac{\alpha+\beta+\varepsilon}{2},$$
$$\varphi_B = x + \frac{-\alpha+\beta-\varepsilon}{2},$$
$$\varphi_C = x + \frac{\alpha-\beta-\varepsilon}{2},$$
$$\varphi_D = x + \frac{-\alpha-\beta+\varepsilon}{2},$$

$$E_x = \frac{E_A+E_B+E_C+E_D}{4},$$
$$E_\alpha = \frac{E_A-E_B+E_C-E_D}{2},$$
$$E_\beta = \frac{E_A+E_B-E_C-E_D}{2},$$
$$E_\varepsilon = \frac{E_A-E_B-E_C+E_D}{2}.$$

PHYSICAL REVIEW APPLIED **14,** 054013 (2020)

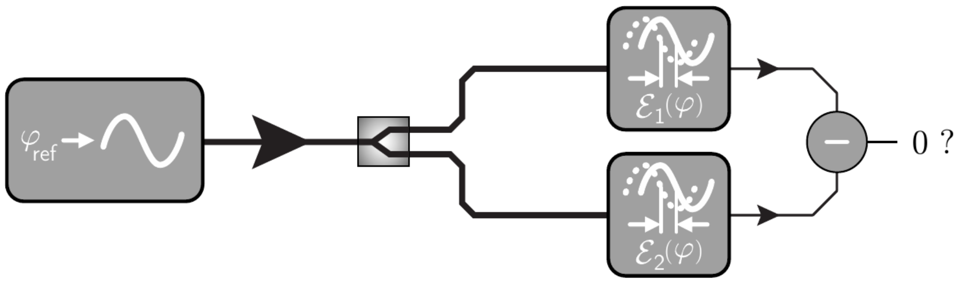
Tracking Length and Differential-Wavefront-Sensing Signals from Quadrant Photodiodes in Heterodyne Interferometers with Digital Phase-Locked-Loop Readout

Gerhard Heinzel,[*] Miguel Dovale Álvarez,[†] Alvise Pizzella, Nils Brause, and Juan José Esteban Delgado

The testing question

- There is no reference phasemeter of sufficient quality
- Only choice: test phasemeter against itself
- Splitting the zero: $0 = a - a$

➡ Only lower noise limit, common mode errors are not detected



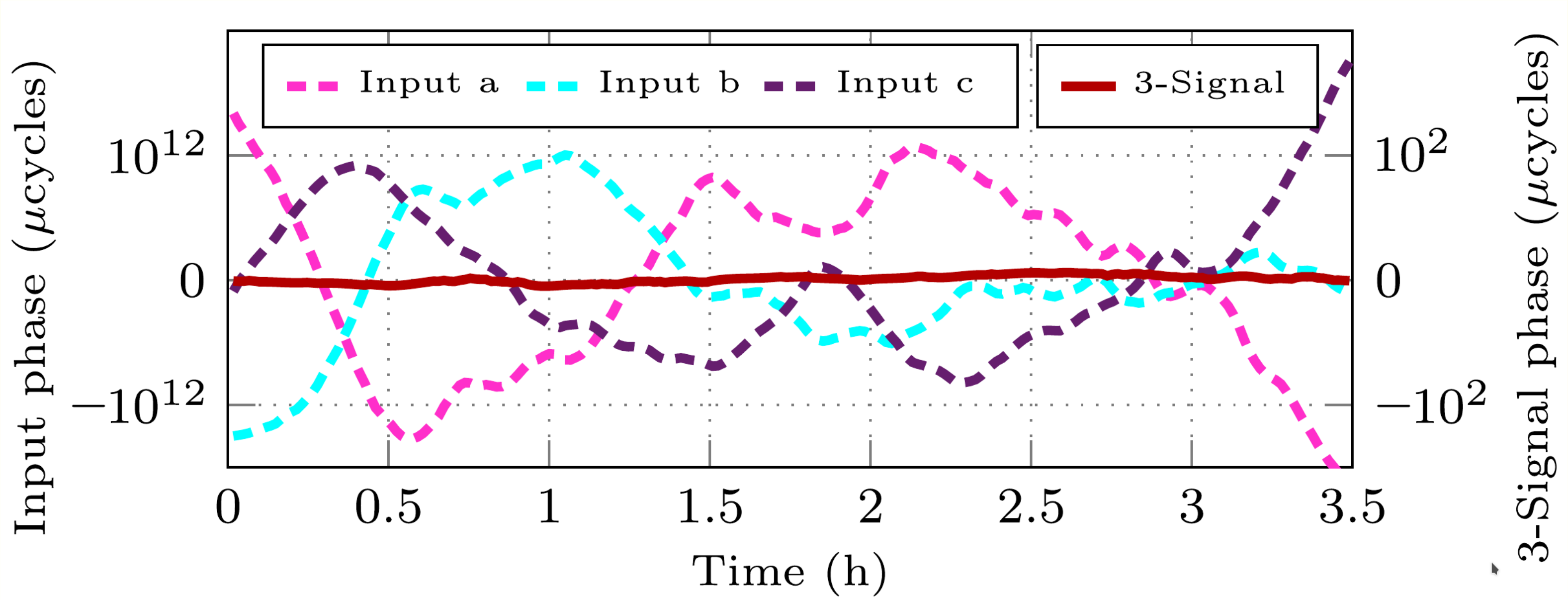
$$\mathcal{E}_1\left(\varphi_{\mathrm{ref}}\right) - \mathcal{E}_2\left(\varphi_{\mathrm{ref}}\right) \stackrel{!}{=} 0$$

3-signal test

Split three different signals: $0 = a + b + c$

Generate 3 independent signals that fulfil a+b+c=0,
pass them through 3 separate phasemeters / channels,
test the output for a+b+c=0

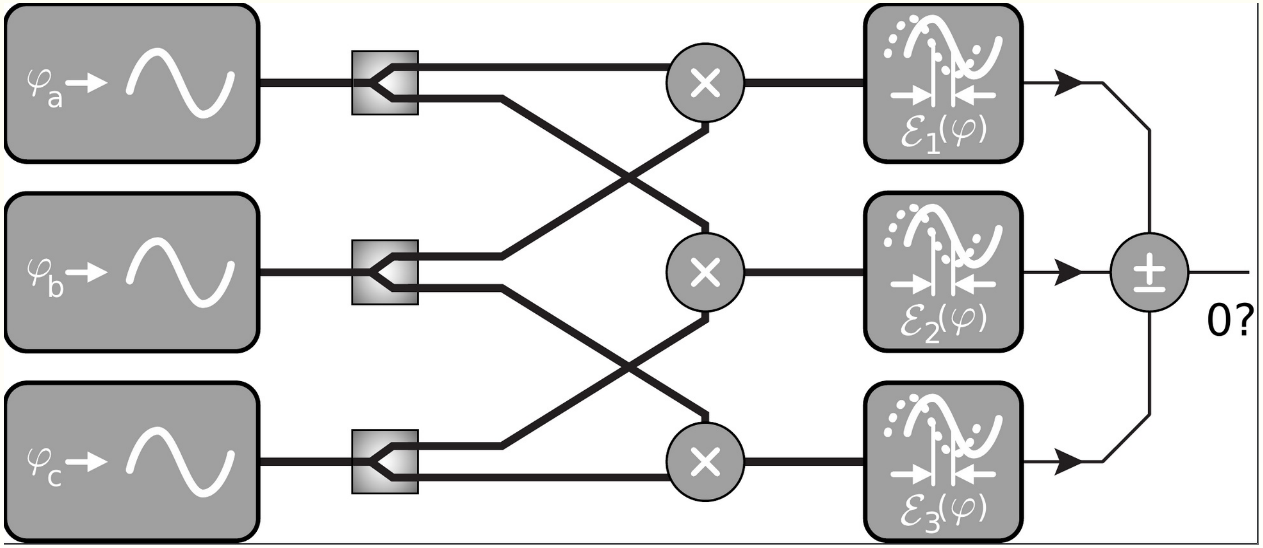
Allows arbitrary dynamics and probing of nonlinearities



3-signal test

Test $0 = a + b + c$:

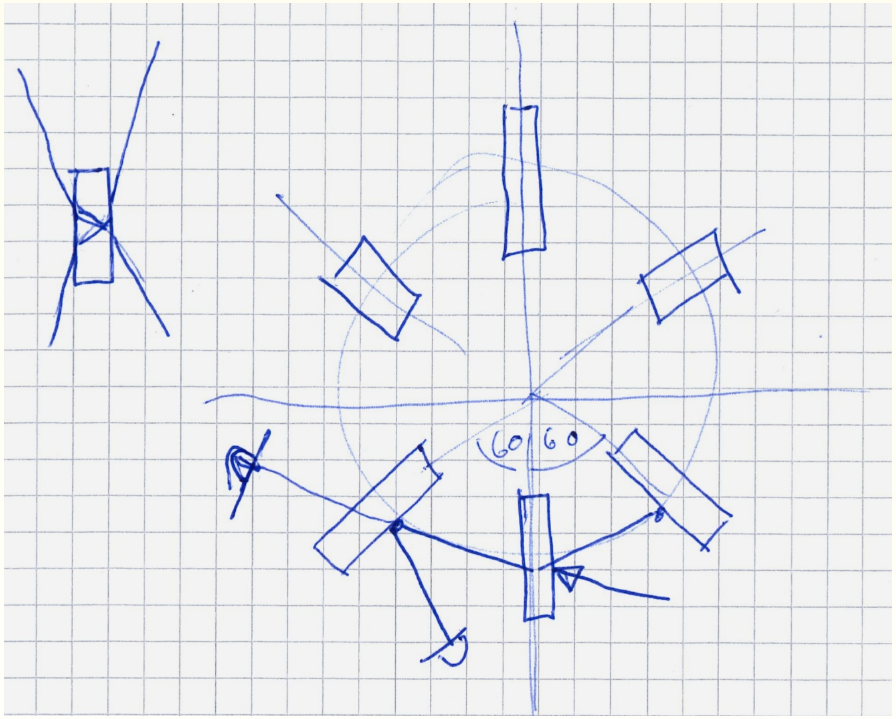
- Three methods
  - Digital only: possible but incomplete
  - Analog electrical
  - **Optical**



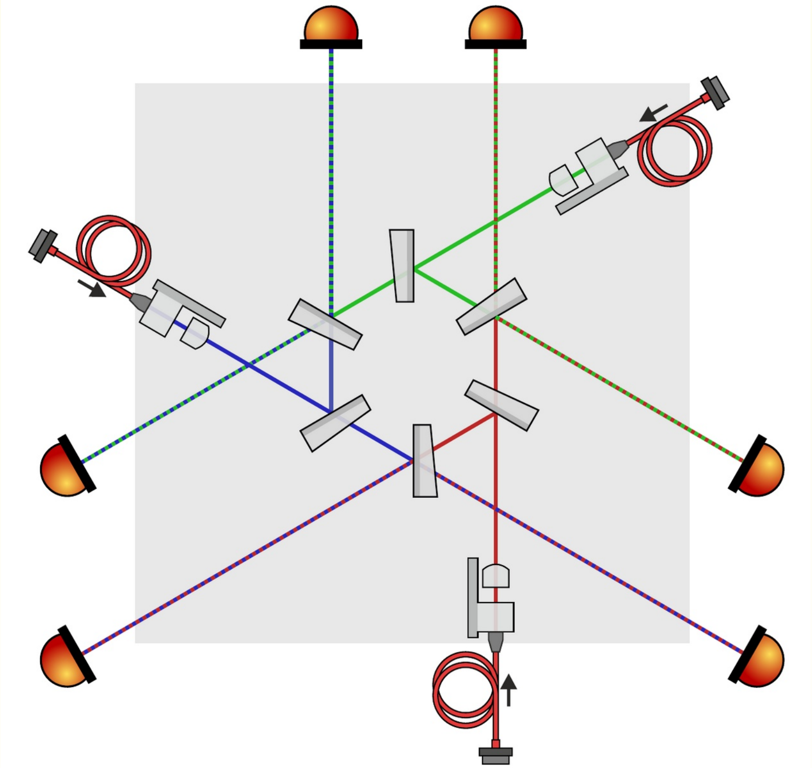
Electrical test with analog MHz signals is possible but limited by performance of analog mixers

Optical 3-signal test

Includes photoreceivers, more complete test of signal chain



Lab notebook 2009

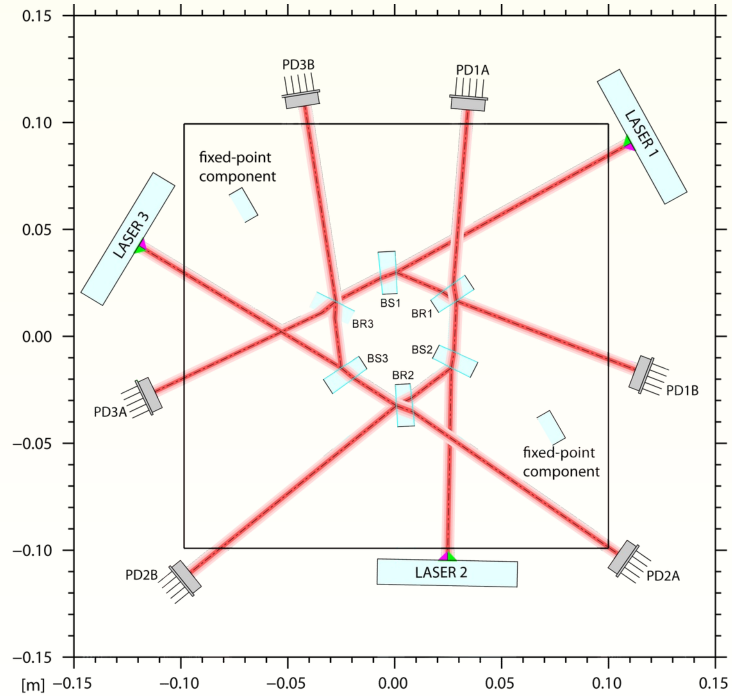


3 different lasers are mixed, producing beatnotes a-b, a-c, b-c
- By construction, they can be combined to zero, after separately passing through optics, photoreceiver, phasemeter

Optical simulation

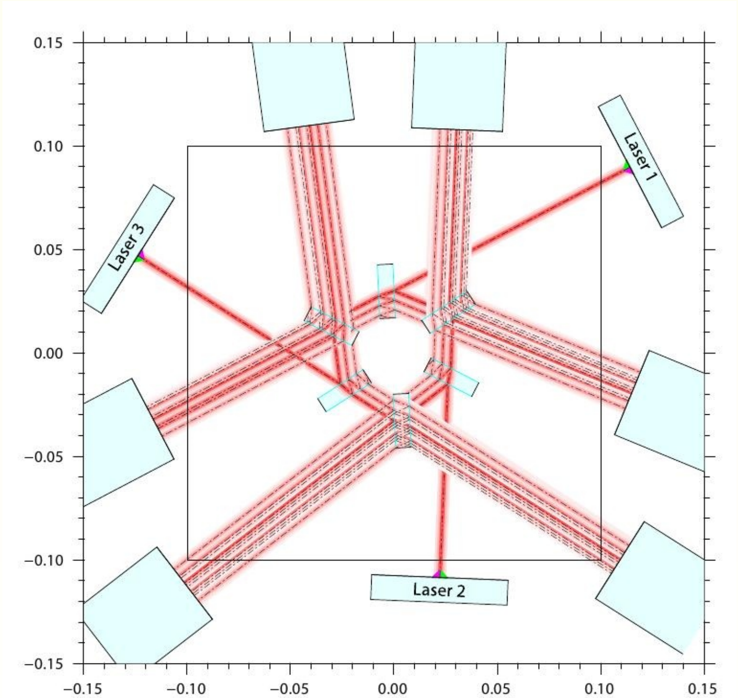
No suitable software was available: Development of IFOCAD

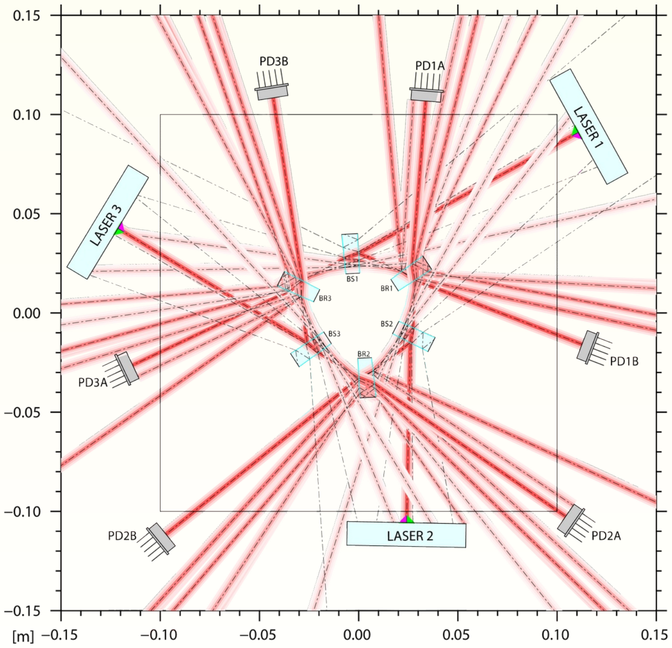
- 3D raytracing
- Parametrized layout
- Includes optimization functions (zero-finding, minimizing FOM)
- Started as a C program in 2009



Ghost beams

Ghost beams were expected to create extra noise, thus the components are designed with a wedge angle to deflect them

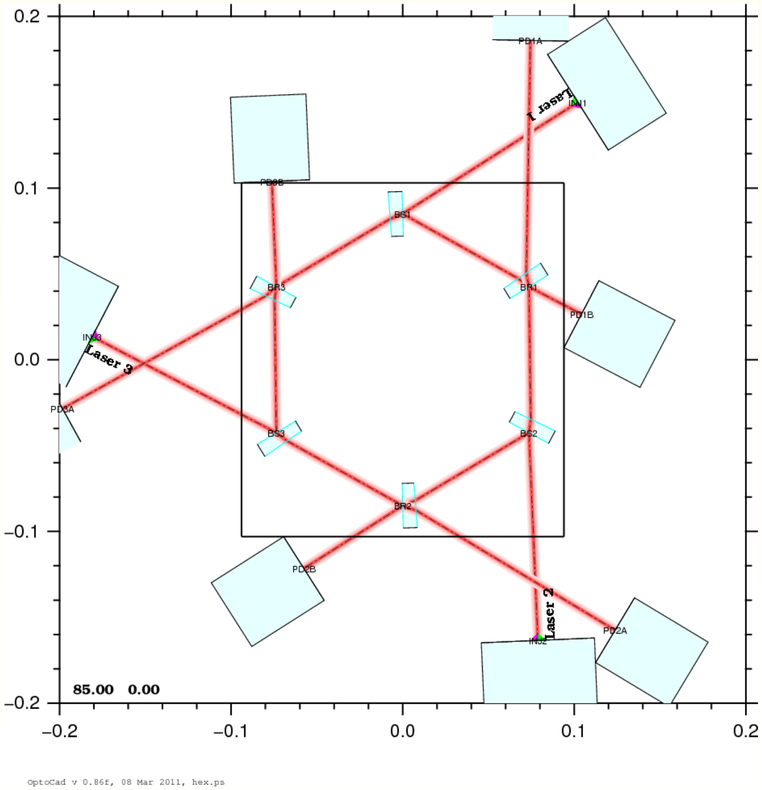




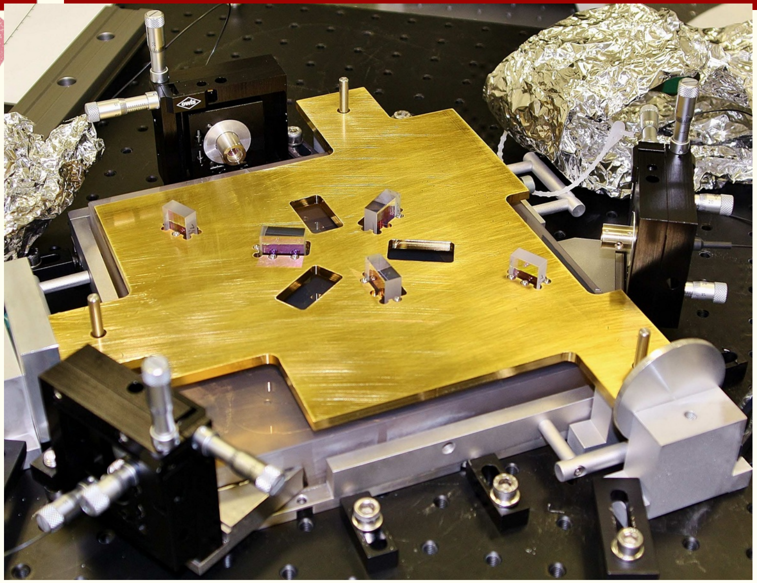
Optical simulation

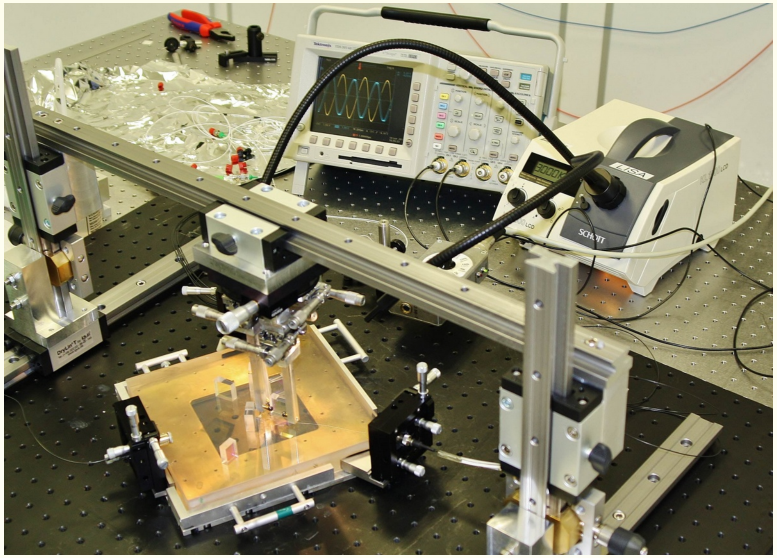
IFOCAD is now a much larger software, taken over by others

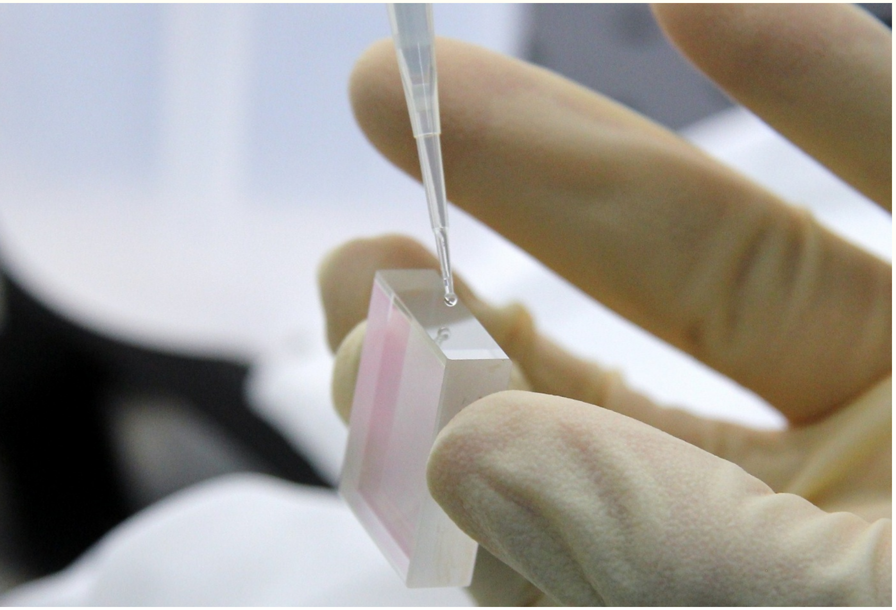
- Converted to C++
- Includes many new features, i.e. non-Gaussian beams...

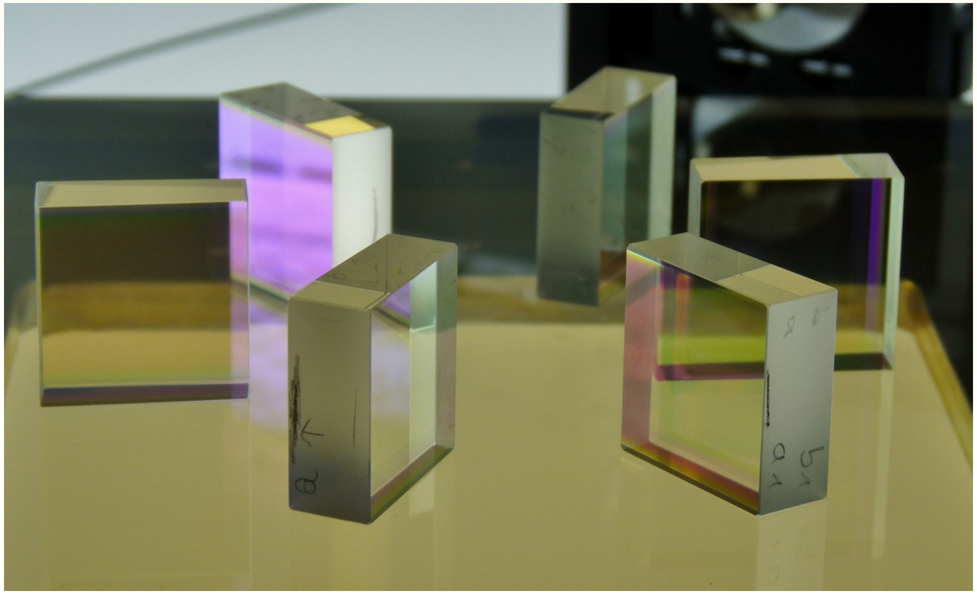


Building the Hexagon: Marina Kaufer (born Dehne)

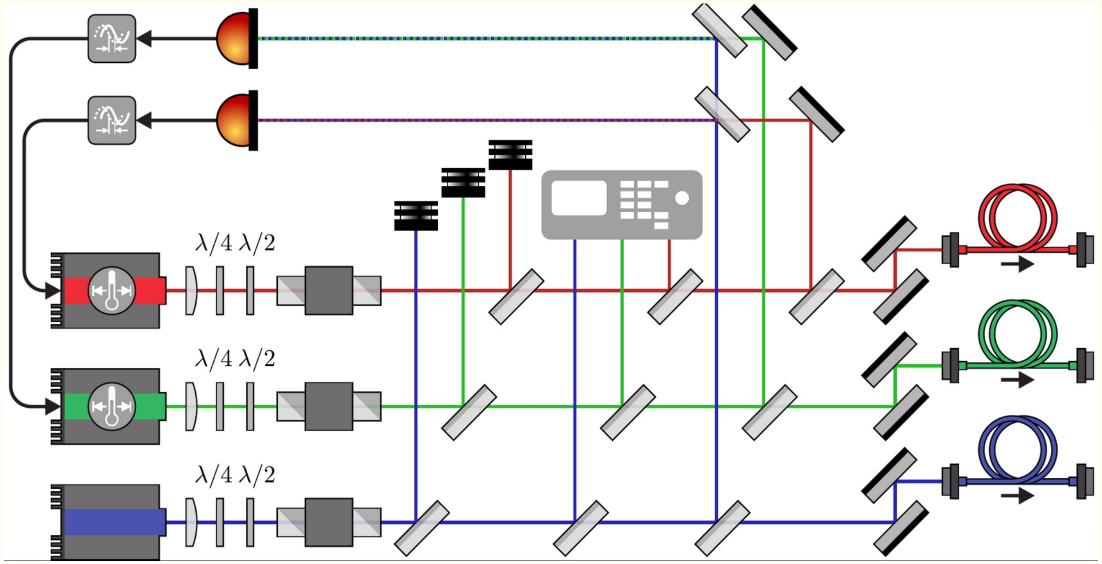








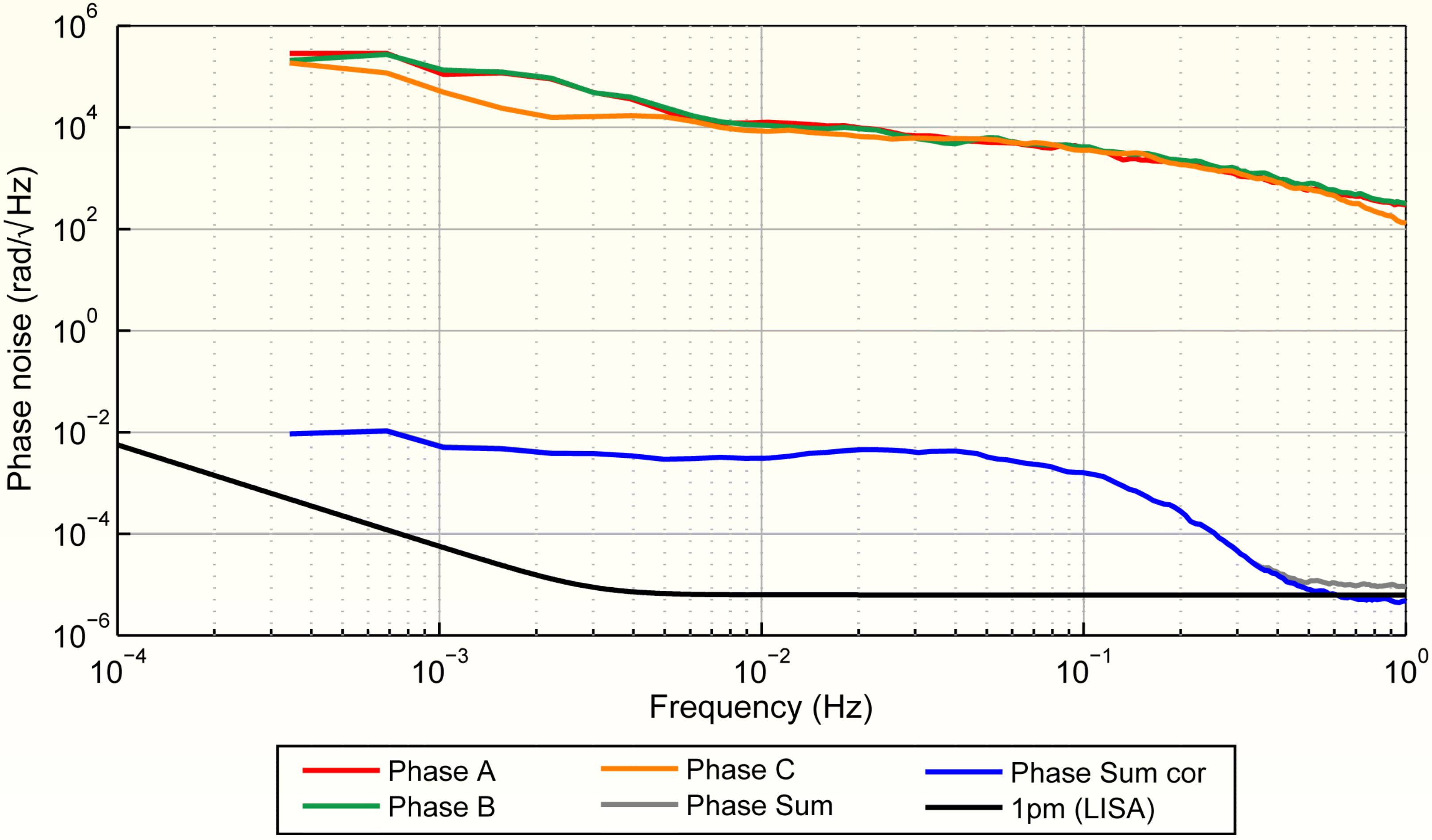
Beam preparation



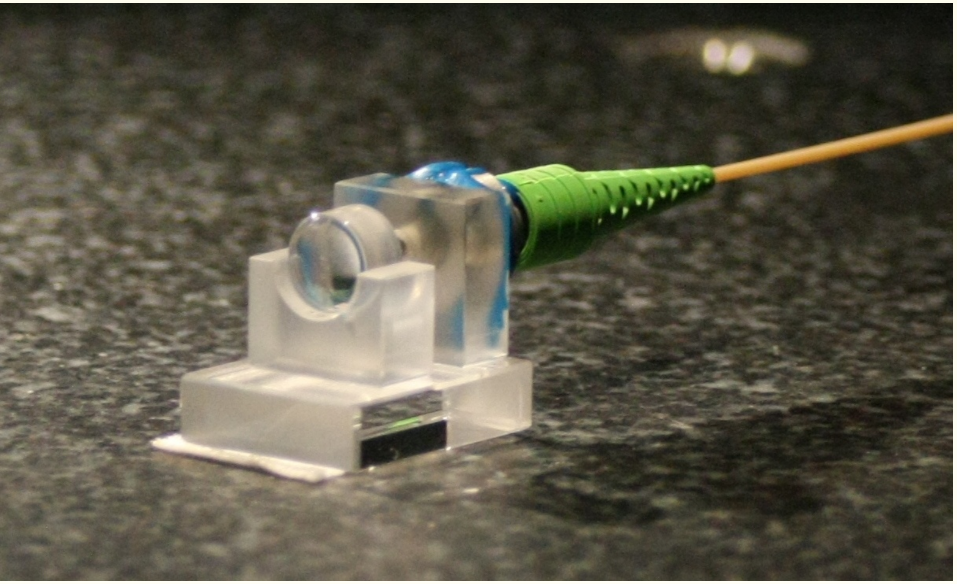
The frequency differences (=phasemeter signals) can be chosen arbitrary, including high dynamics.

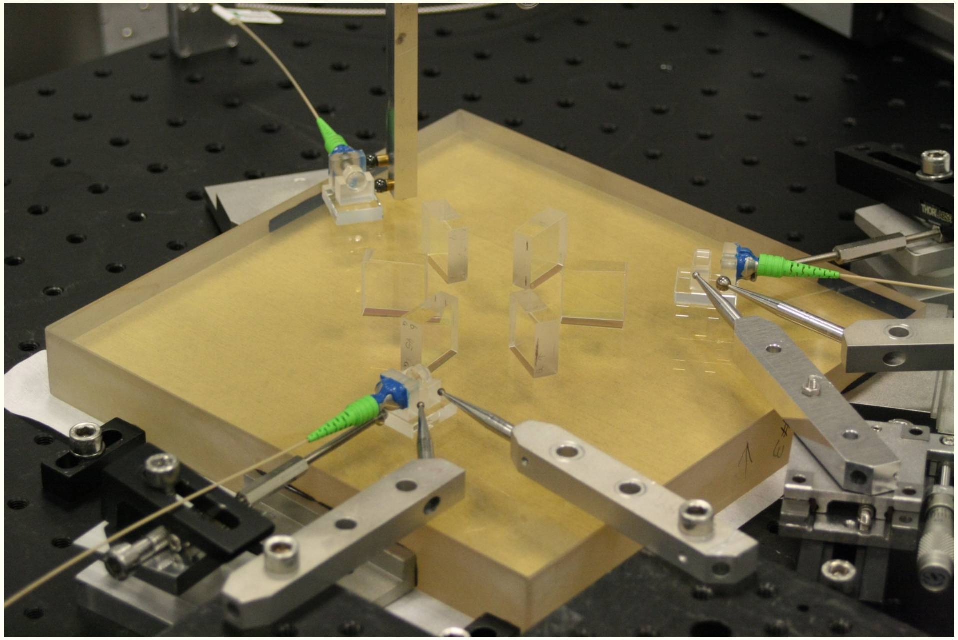
- Only restriction: <25MHz
- a+b+c = 0 automatically achieved by optics

Initial results in air



New monolithic fiber couplers: Daniel Penkert

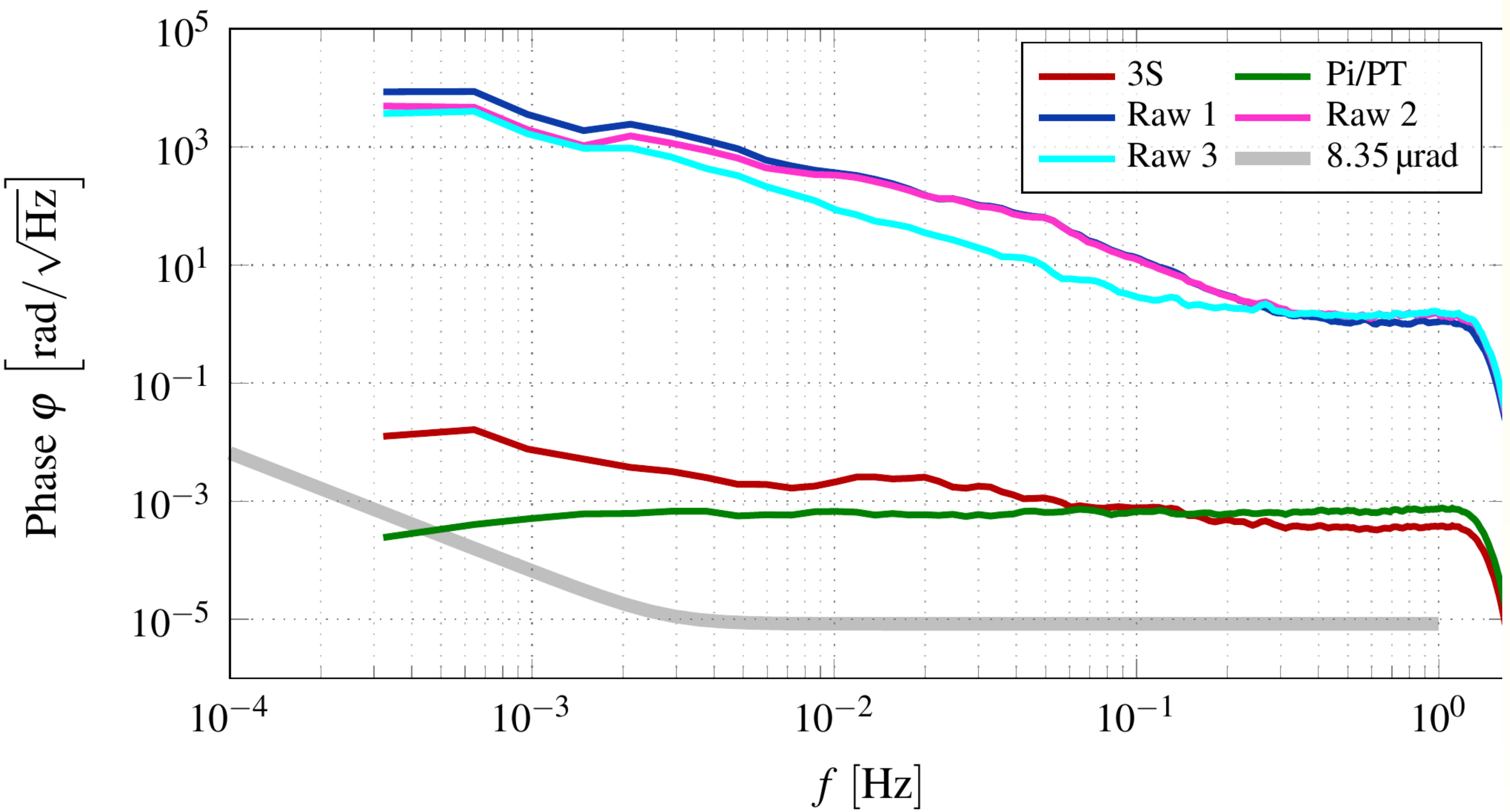




The wedged components cause a huge tilit-to-length coupling; and the commercial metal fiber couplers were not stable enough.

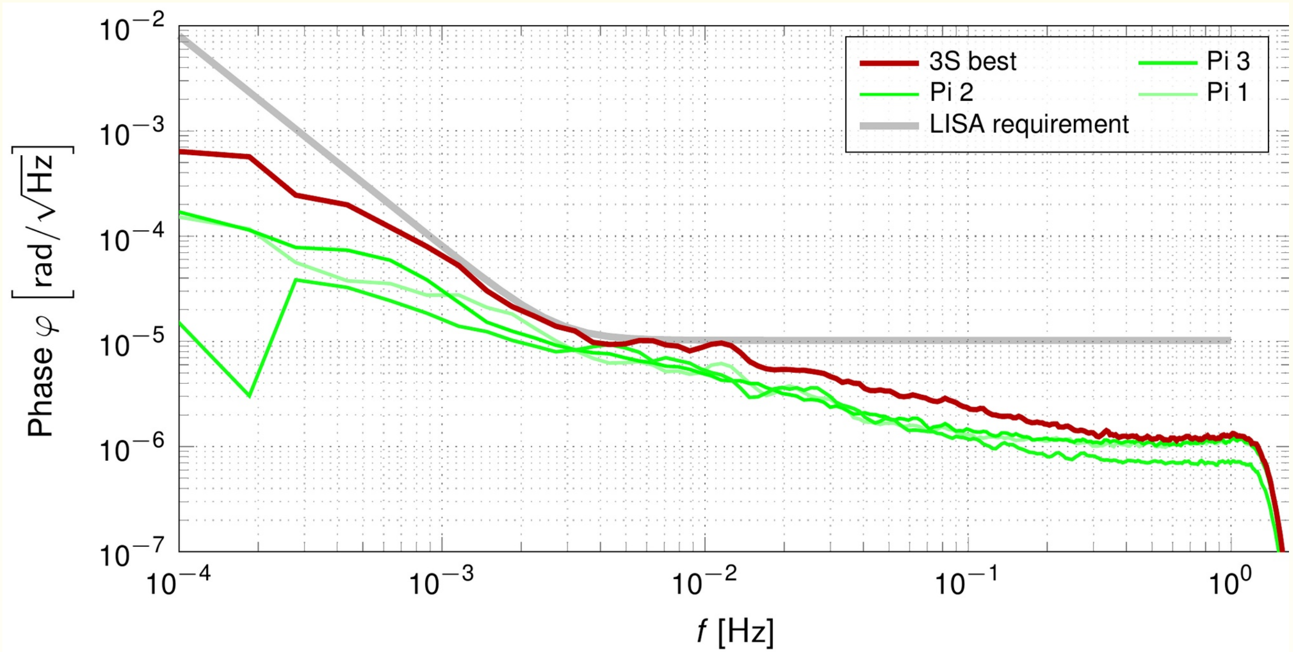
- Therefore a monolithic design was developed; now also used in other projects

Commissioning and noise hunting: Thomas Schwarze



Starting point: noise subtraction by many orders of magnitude, but not yet quite there

Commissioning and noise hunting: Thomas Schwarze



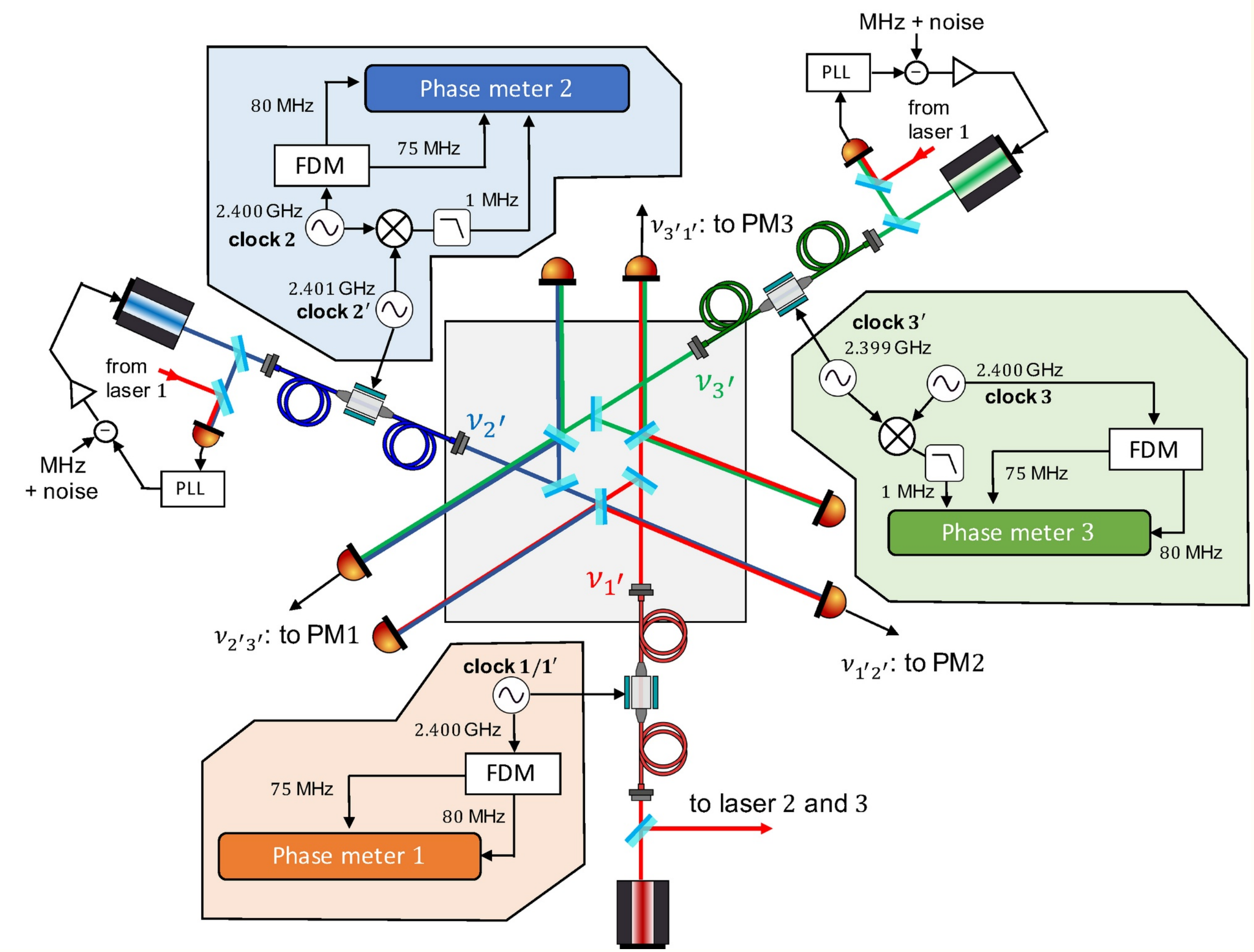
PHYSICAL REVIEW LETTERS **122,** 081104 (2019)

Picometer-Stable Hexagonal Optical Bench to Verify LISA Phase Extraction Linearity and Precision

Thomas S. Schwarze,[*] Germán Fernández Barranco, Daniel Penkert,
Marina Kaufer,[†] Oliver Gerberding, and Gerhard Heinzel
Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Callinstrasse 38, 30167 Hannover, Germany and Leibniz Universität Hannover, Institut für Gravitationsphysik, Callinstrasse 38, 30167 Hannover, Germany

Long and careful noise hunting: polarization, amplitude,…,…
in parallel development of phasemeter

Extending the scope: Kohei Yamamoto

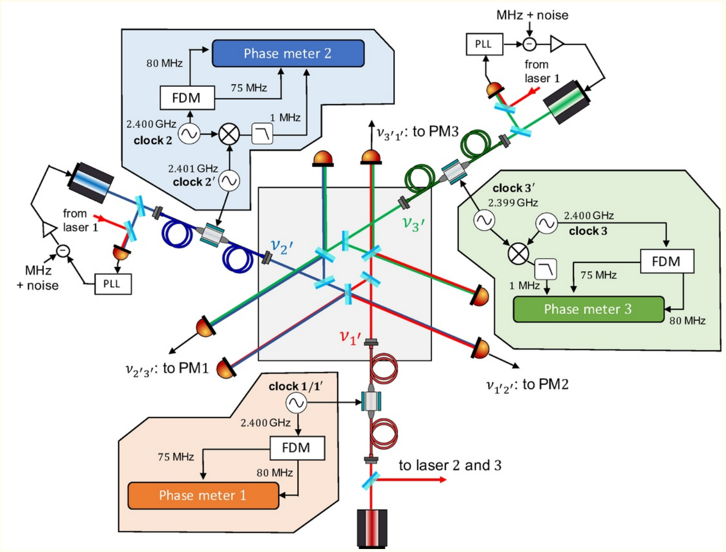


3 independent phasemeters and all modulations

Extending the scope: Kohei Yamamoto

3 independent phasemeters and all modulations:

- Test of key TDI ingredients:
  - Clock sync, PRN ranging, TDI ranging
  - Clock noise removal
  - Shift and interpolate time series to nsec
- Test of PRN data transfer
- Test of Phasemeter behaviour at low SNR



PHYSICAL REVIEW D **105,** 042009 (2022)

Experimental verification of intersatellite clock synchronization at LISA performance levels

Kohei Yamamoto,[1,*] Christoph Vorndamme,[1] Olaf Hartwig,[1,2] Martin Staab,[1] Thomas S. Schwarze,[1,†] and Gerhard Heinzel[1]

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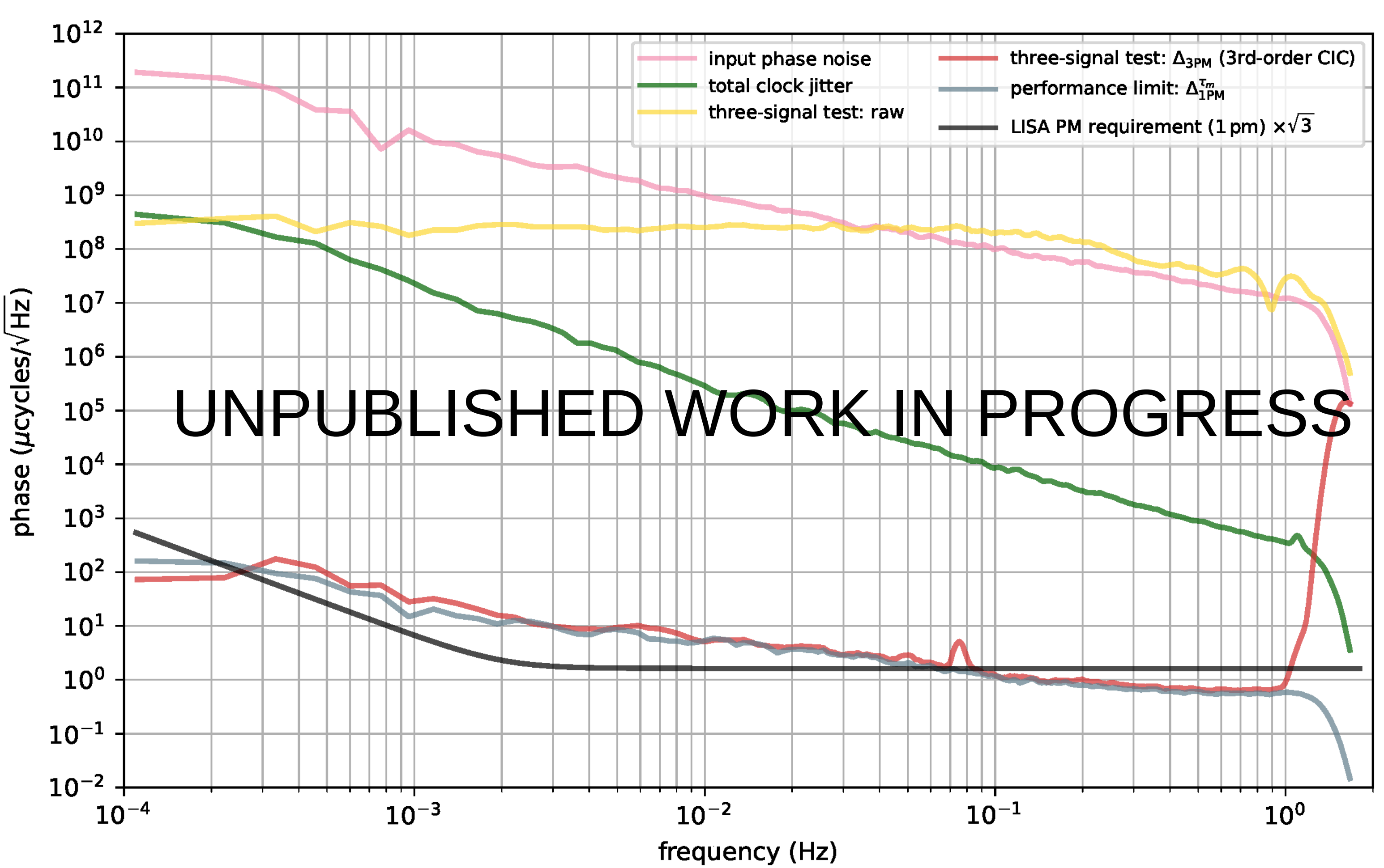
Extending the scope: Kohei Yamamoto



Test of clock noise removal, filtering, interpolation…..

Next steps

Continue clock-noise, ranging experiments: Kohei Yamamoto

Testbed for phasemeter development (new algorithms, data rates...)

Inject Hexagon data with all its artefacts into processing steps of LISA data analysis (instead of stationary white noise): Narjiss Messied

Build second Hexagon with minor modifications from lessons learnt (non-wedged components, polarization cleaning): Daniel Penkert, Reid Ferguson