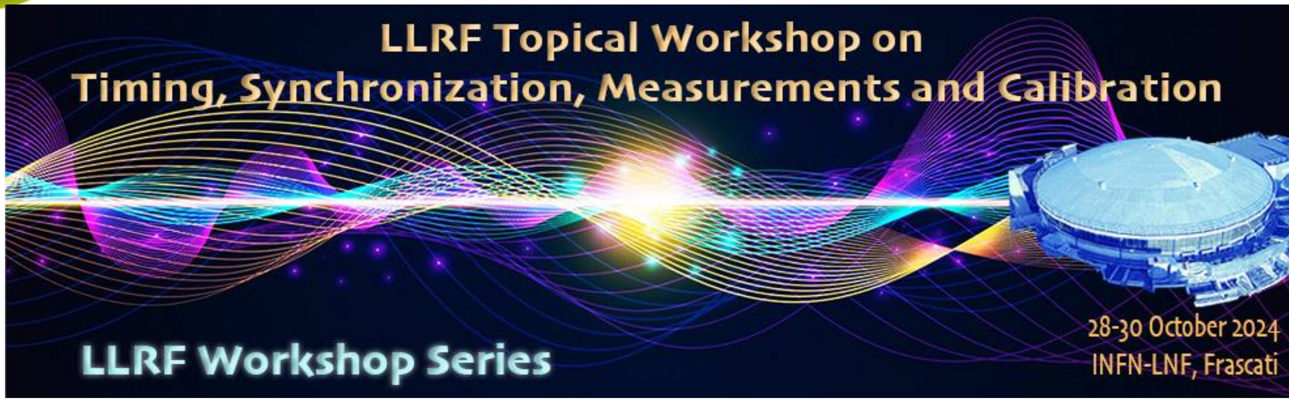
Optical technologies for generating microwaves, time and frequency distribution and synchronization

Ronald Holzwarth

Menlo Systems GmbH
Martinsried, Germany

And

Max-Planck-Institute for Quantum Optics
Garching, Germany



Menlo Systems

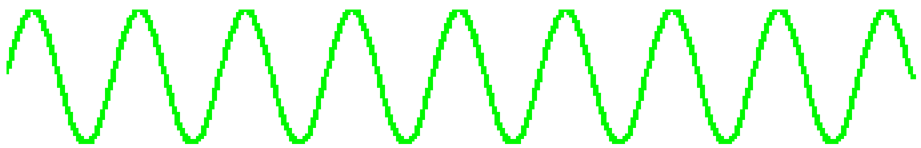
MenloSystems GmbH

- Spin off from Max-Planck-Institut of Quantum Optics (Garching (near Munich), Germany)
- Founded in 2001 by T.W. Hänsch, M. Mei, and R. Holzwarth
- Known for its Nobel Prize winning optical frequency comb technology (T.W. Hänsch 2005)
- For 20 years leading developer and global supplier for precision metrology instrumentation
- International customers from science and industry
- 230 employees (headcount, world wide)
- Headquarter in Martinsried, Germany, subsidiaries in US, Japan and China

Co-Founder
Theodor W. Hänsch

Precision in photonics. Together we shape light.

Optical frequencies



532 nm or 560 THz

$f = c/\lambda$

560 000 000 000 000 oscillations per second

Period: 1.8 fs

RF vs. Optical

Radio Frequencies

Local oscillator:
Quartz: 10E-13 at 1 sec
Cryogenic sapphire: 10E-15 at 1 sec

Clock transitions:
Hyperfine in Rb, Cs, H

Frequency:
9.2 GHz (Cs)

10E-15 at 1 sec is equivalent to:
10 µH
or 1/100 000 of one cycle

Optical Frequencies

Local oscillator:
Optical cavity: 10E-15 at 1 sec

Clock transitions:
forbidden optical in
neutral atoms: Yb, Sr, Hg, Ca…
or ions: Hg, Yb, In, …

Frequency
430 THz (Sr neutral)

10E-15 at 1 sec is equivalent to:
0.5 Hz
½ cycle

Clocks

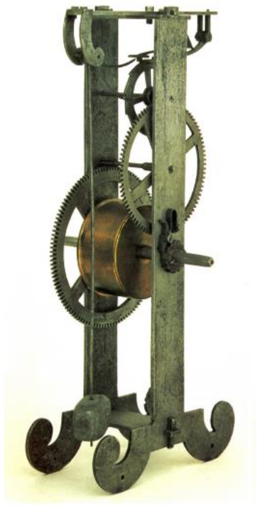
A clock consists of an oscillator,
and a counter that counts these uniform oscillations.

The finer the partition of time, the more accurate the clock can be

From 3500 BC

Sun dial:
One oscillation
per day

1656

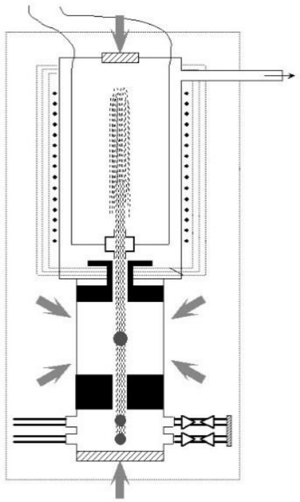


Pendulum clock:
One oscillation
per second

1918

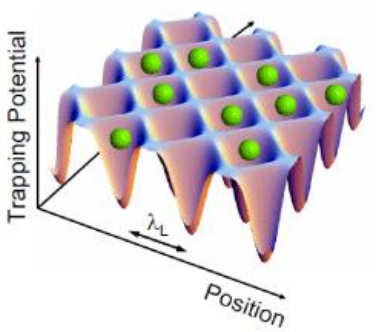
Quartzuhr:
32 768 oscillations
Per second

1955



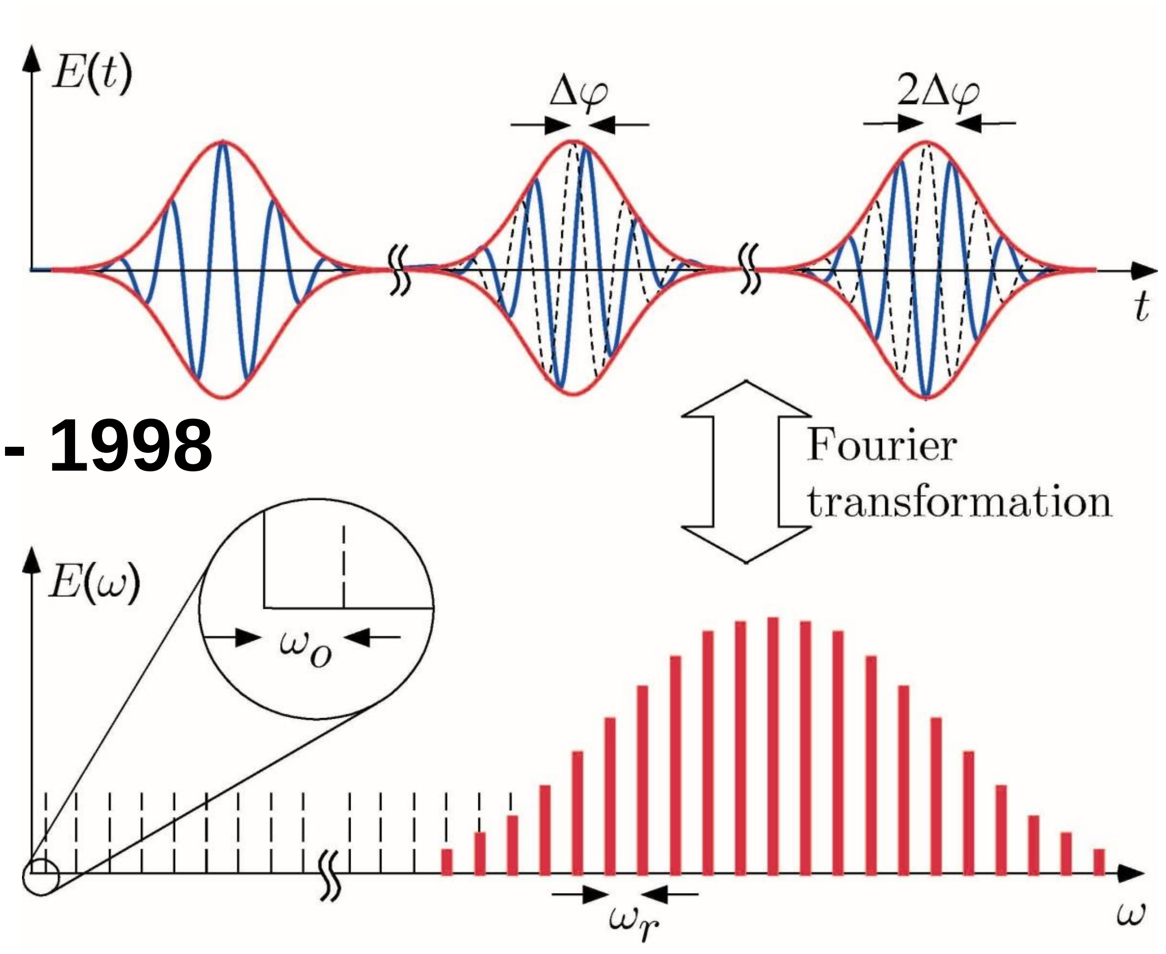
Cesium atomic clock:
9 192 631770 Hz
Now in the low 10^{-16}

2017



Optical atomic clock:
429 228 066 418 008 Hz
Now at the 10^{-18} level!

Tools of the trade: the Frequency Comb



Nobel Prize for Physics 2005

Ted Hänsch 1978 - 1998

$\omega_{opt} = N\ \omega_{rep} + \omega_0$

Paradigm shift!

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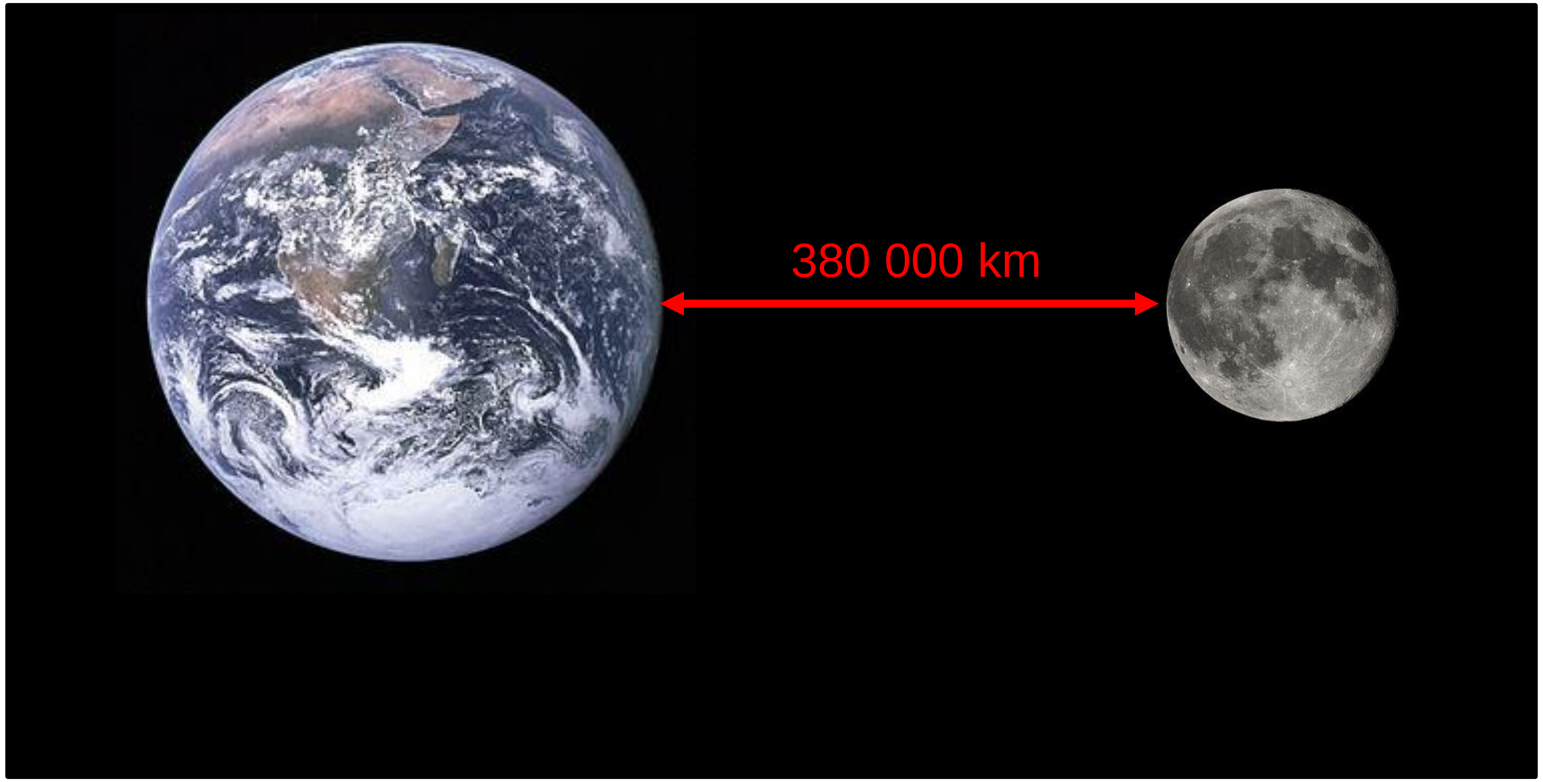
What does 10^{-xx} mean?



1×10^{-12}: 380 µm
1×10^{-15}: 380 nm
1×10^{-18}: 380 pm

(human hair: 50 µm)

In 1 fs light travels 300nm

Jun Ye: 10^{-19} clocks

nature photonics

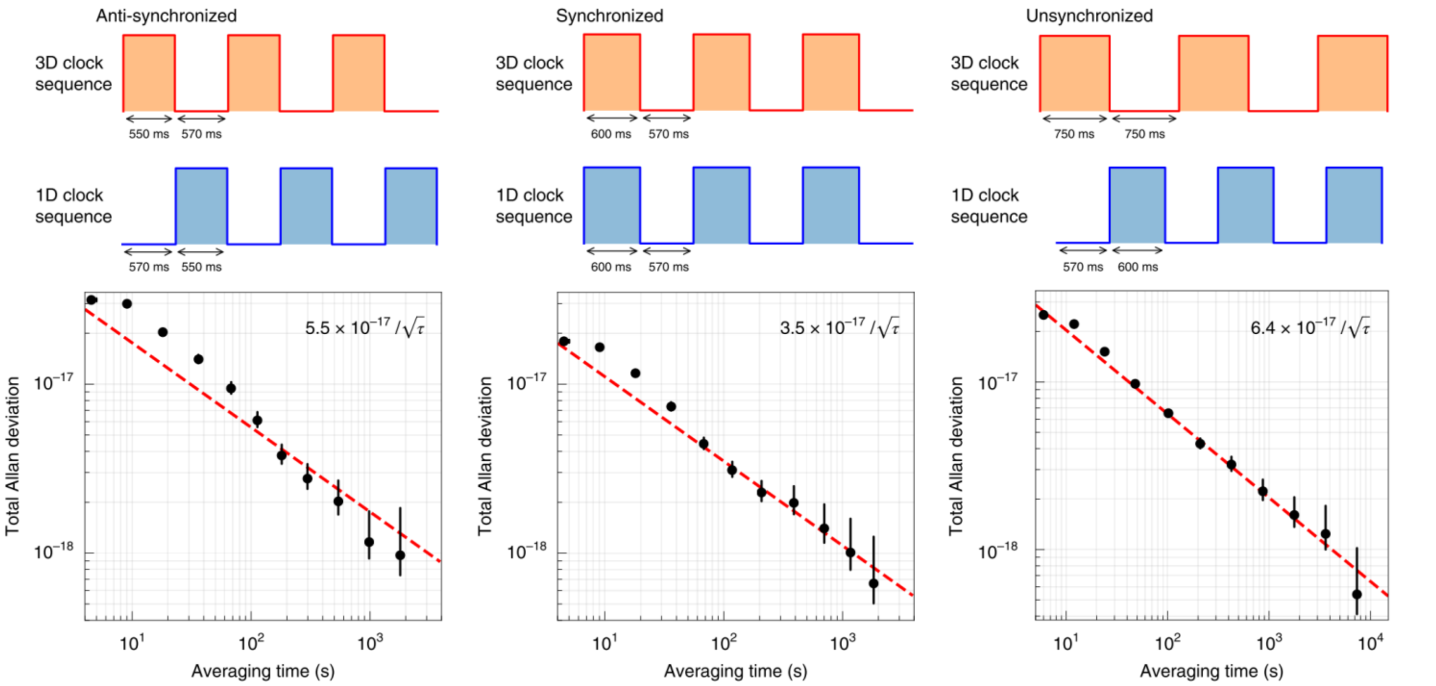
ARTICLES

https://doi.org/10.1038/s41566-019-0493-4

Demonstration of 4.8×10^{-17} stability at 1 s for two independent optical clocks

E. Oelker[1]*, R. B. Hutson[1], C. J. Kennedy[1], L. Sonderhouse[1], T. Bothwell[1], A. Goban[1], D. Kedar[1], C. Sanner[1], J. M. Robinson[1], G. E. Marti[1,5], D. G. Matei[2,6], T. Legero[2], M. Giunta[3,4], R. Holzwarth[3,4], F. Riehle[2], U. Sterr[2] and J. Ye[1]*

6×10^{-19} in 1h



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Hero Experiment in Japan

Hidetoshi Katori @ RIKEN (Japan)

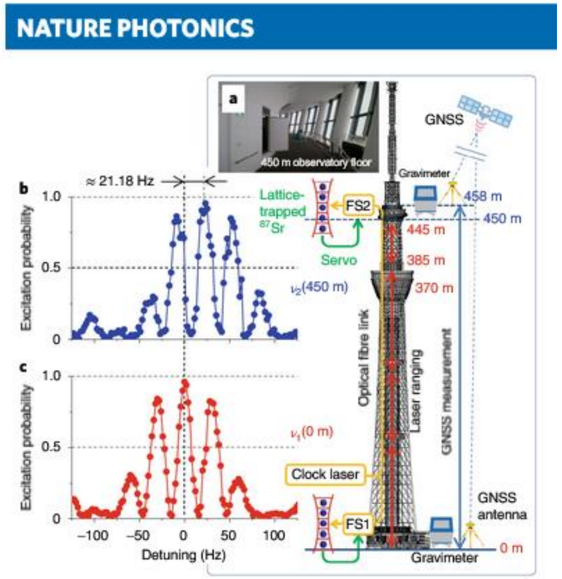
Skytree tower Tokyo
(wikipedia)

Height measurement by clock comparison

Difference 21 Hz (@430THz)
Height difference: 450m

Sr Clock 2

Sr Clock 1



Nature Photonics, VOL 14, July 2020, p 411–415

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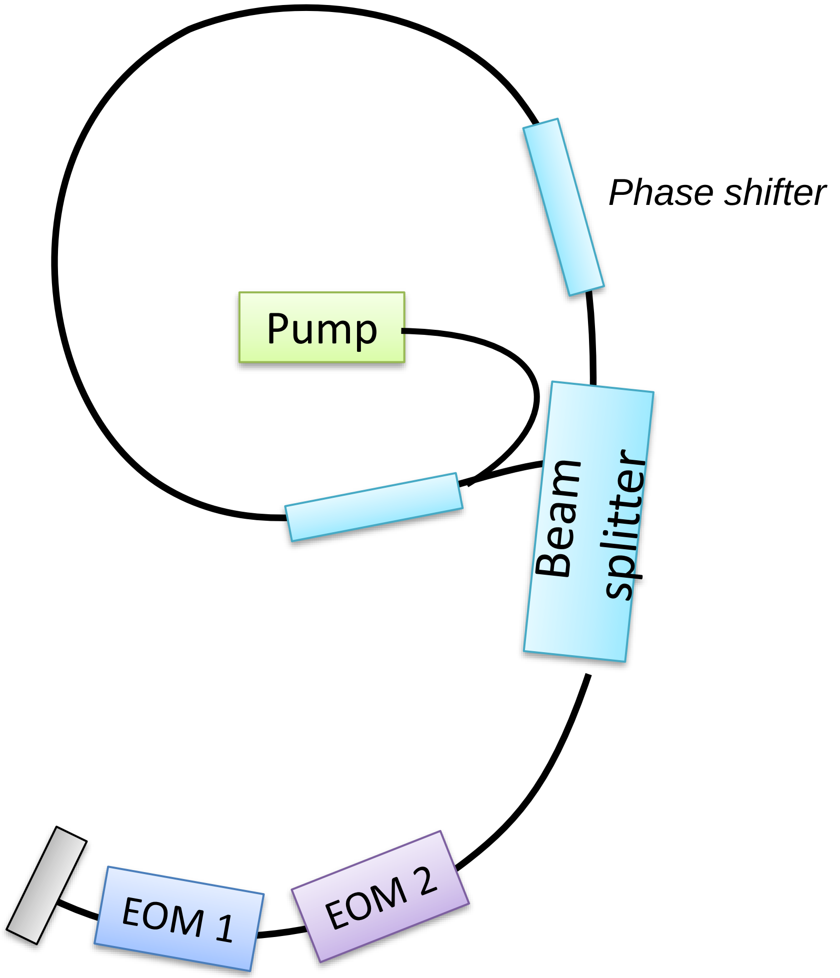
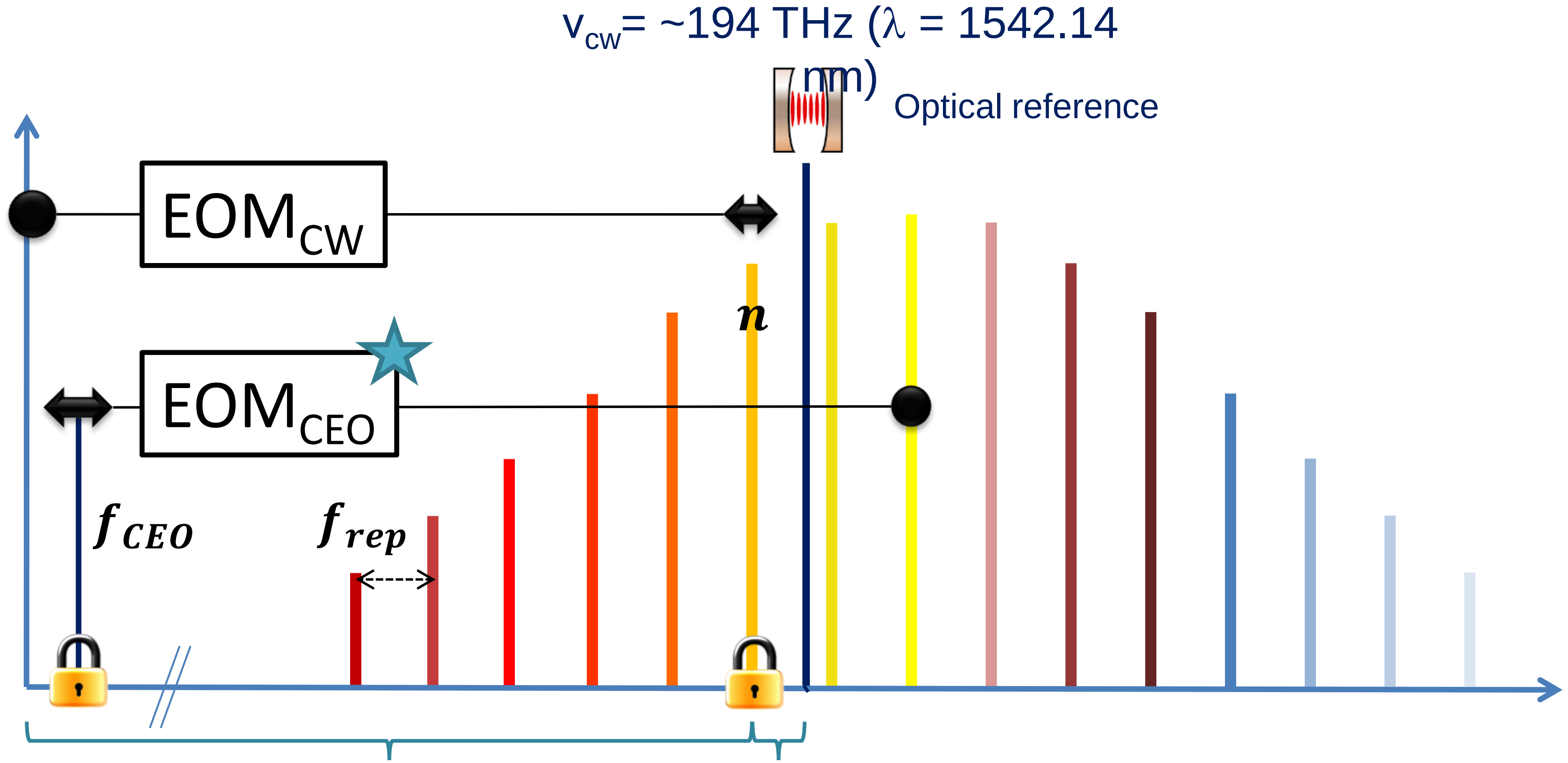
Fiber laser technology „Figure 9“



Appl. Phys. B 123, 41 (2017);
Space-borne frequency comb metrology. *Optica* 3, 1381 (2016)

Frequency Comb: Actuators

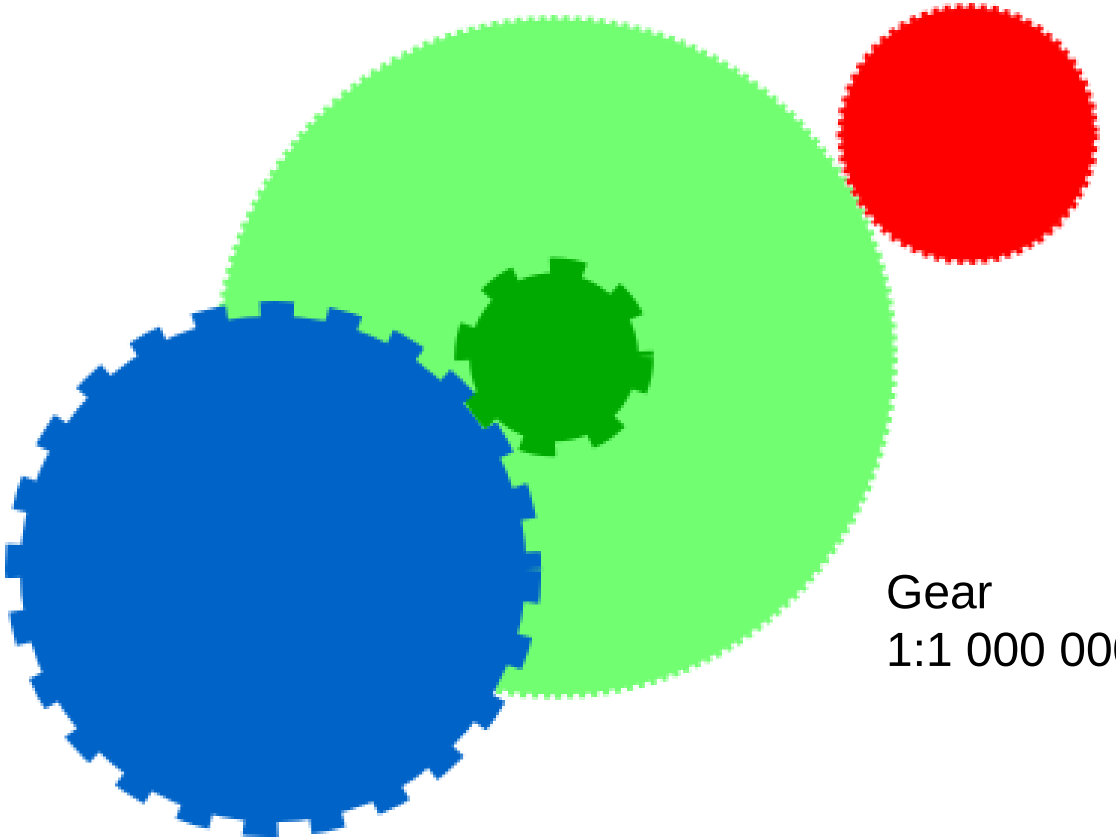


$$\left(f_{CEO} + n \cdot f_{rep}\right) \quad + \quad f_{beat} \quad = \upsilon_{cw}$$

Hansel, W., Giunta, M., Fischer, M., Lezius, M., & Holzwarth, R. (2017).
Rapid electro-optic control of the carrier-envelope-offset frequency for ultra-low noise frequency combs. In *2017 (EFTF/IFCS).*

Comb acts as gear box

RF
MHz to GHz



Optical
Several 100 THz

Gear
1:1 000 000

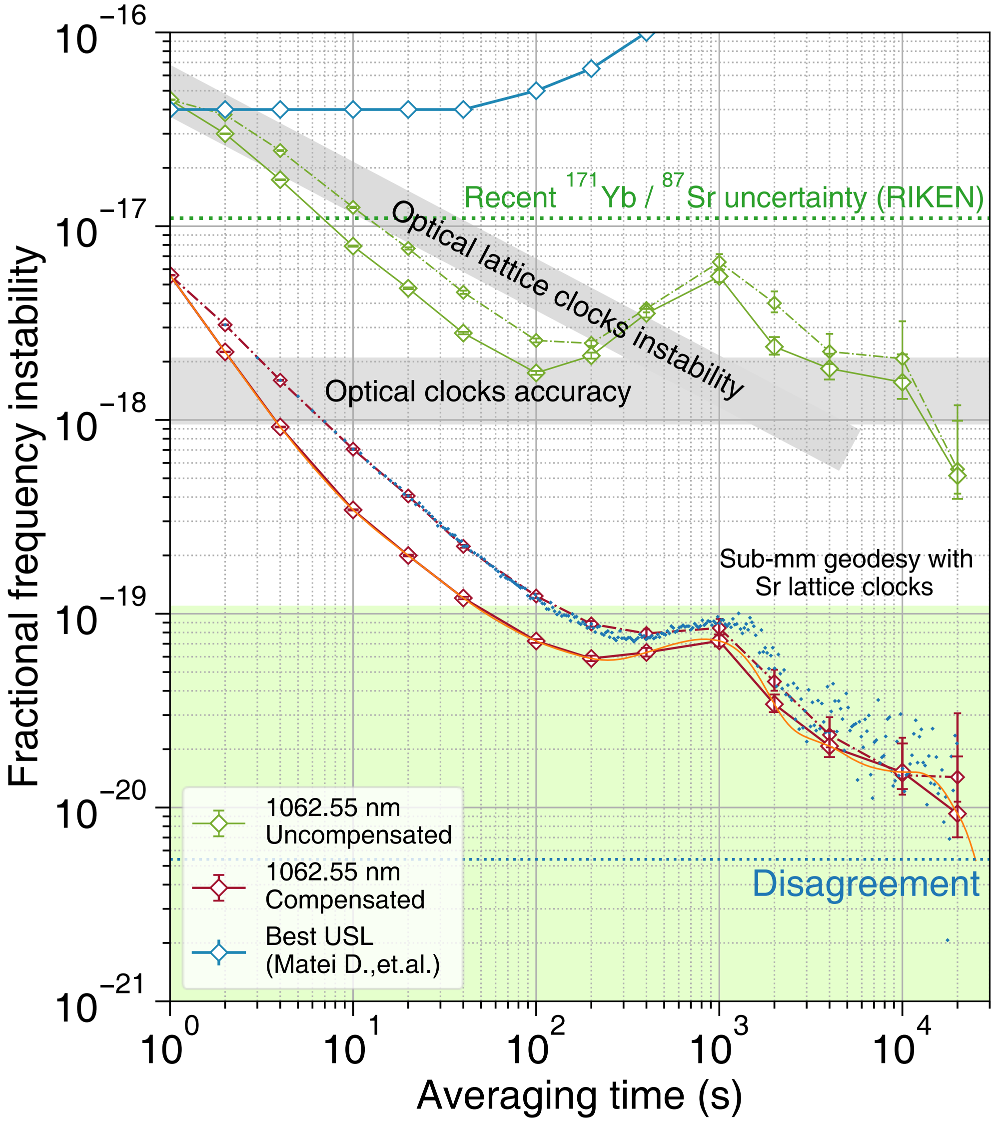
How good are the combs?

ARTICLES
https://doi.org/10.1038/s41566-019-0520-5
nature photonics

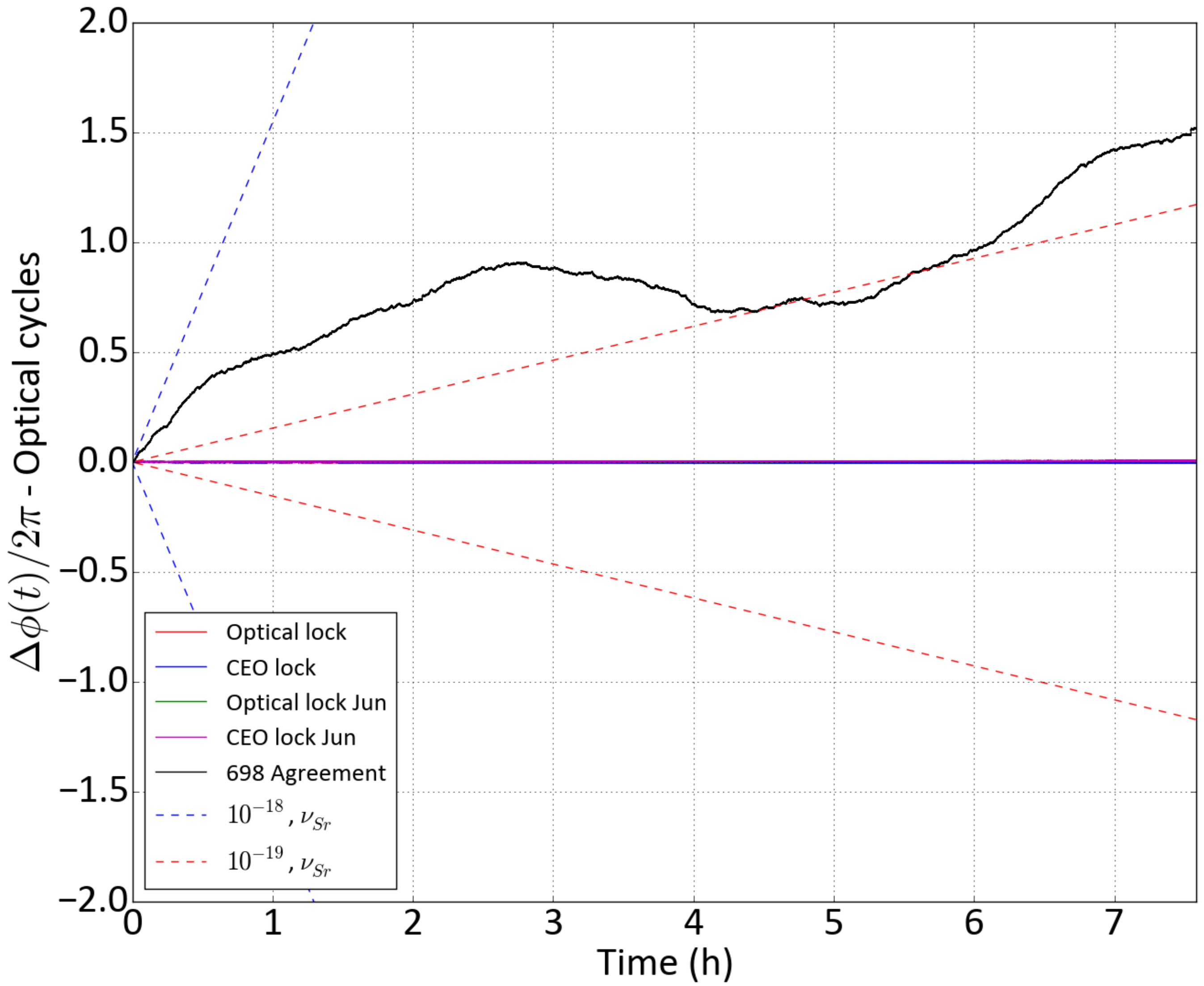
Real-time phase tracking for wide-band optical frequency measurements at the 20th decimal place

Michele Giunta[1,2*], Wolfgang Hänsel[1], Marc Fischer[1], Matthias Lezius[1], Thomas Udem[2] and Ronald Holzwarth[1,2]

Nature Photonics **volume 14**, pages 44–49 (2020)



Optical phase drift at 428 THz (698 nm)



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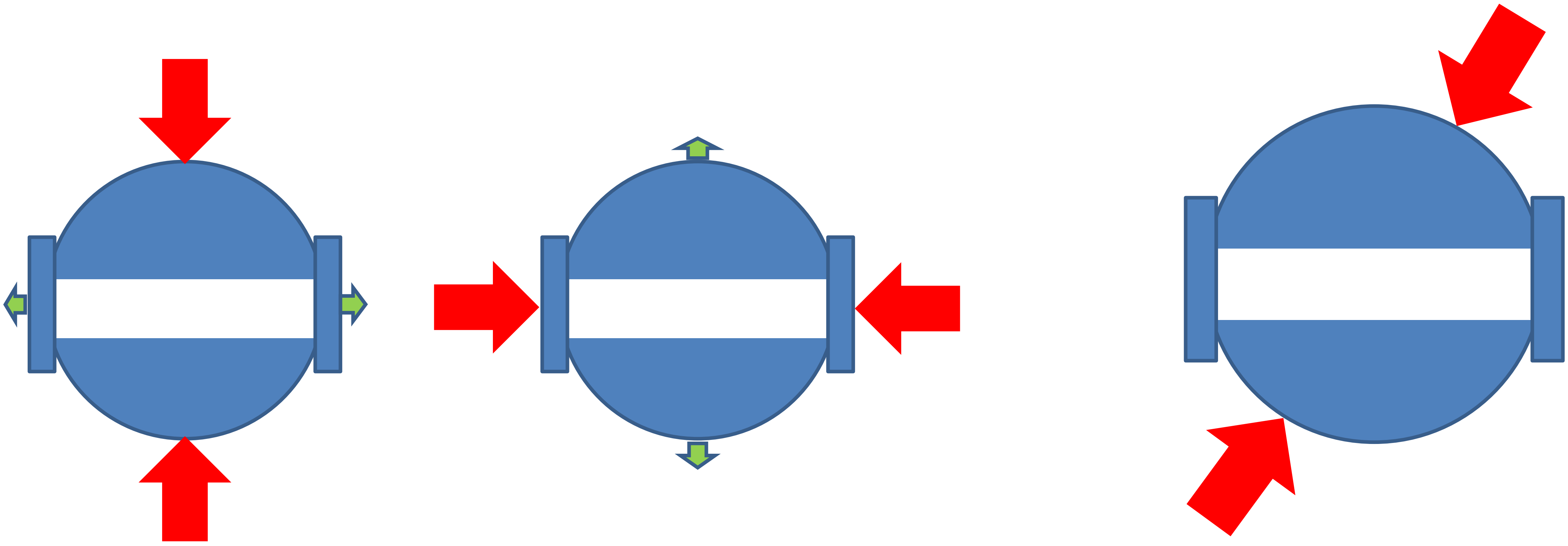
Tools of the trade: optical resonator



Finesse: > 200 000

Magic Angle: 41 °

Stability: Hz level laser

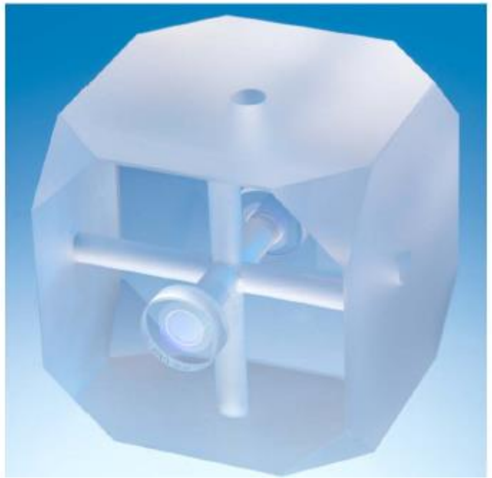
3572 OPTICS LETTERS / Vol. 36, No. 18 / September 15, 2011

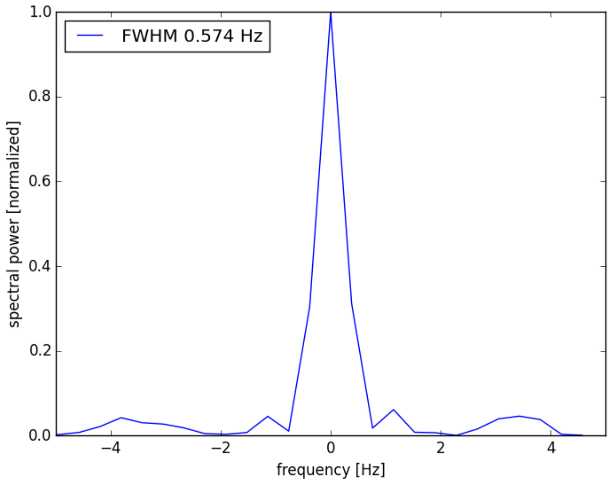
Force-insensitive optical cavity

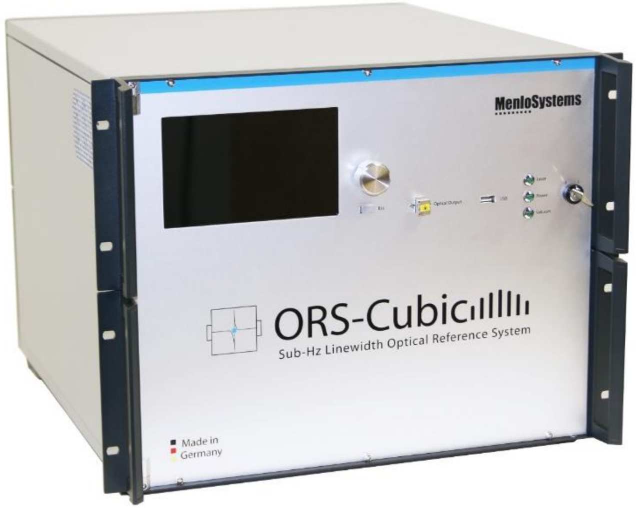
Stephen Webster* and Patrick Gill
National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, UK

Linewidth: **< 1 Hz @ 200 THz**

Allan Deviation: **$< 2 \times 10^{-15}$ at 1 s**







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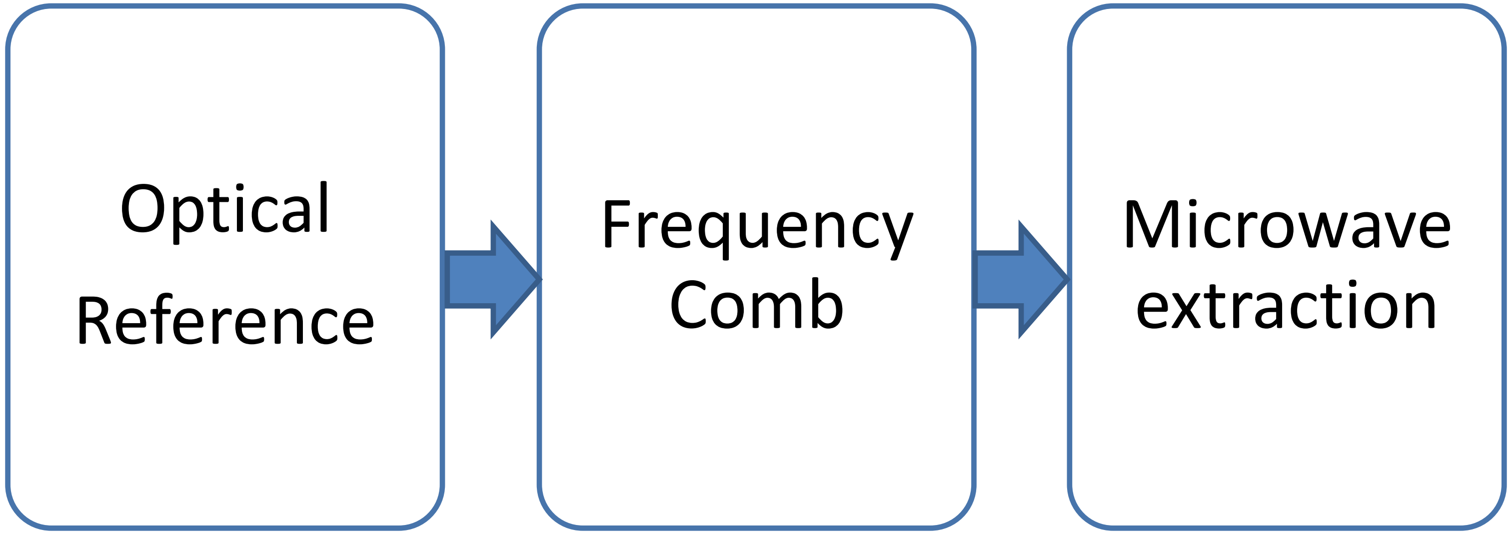
Photonic μ-wave generation (PMWG)



Funded by

DARPA

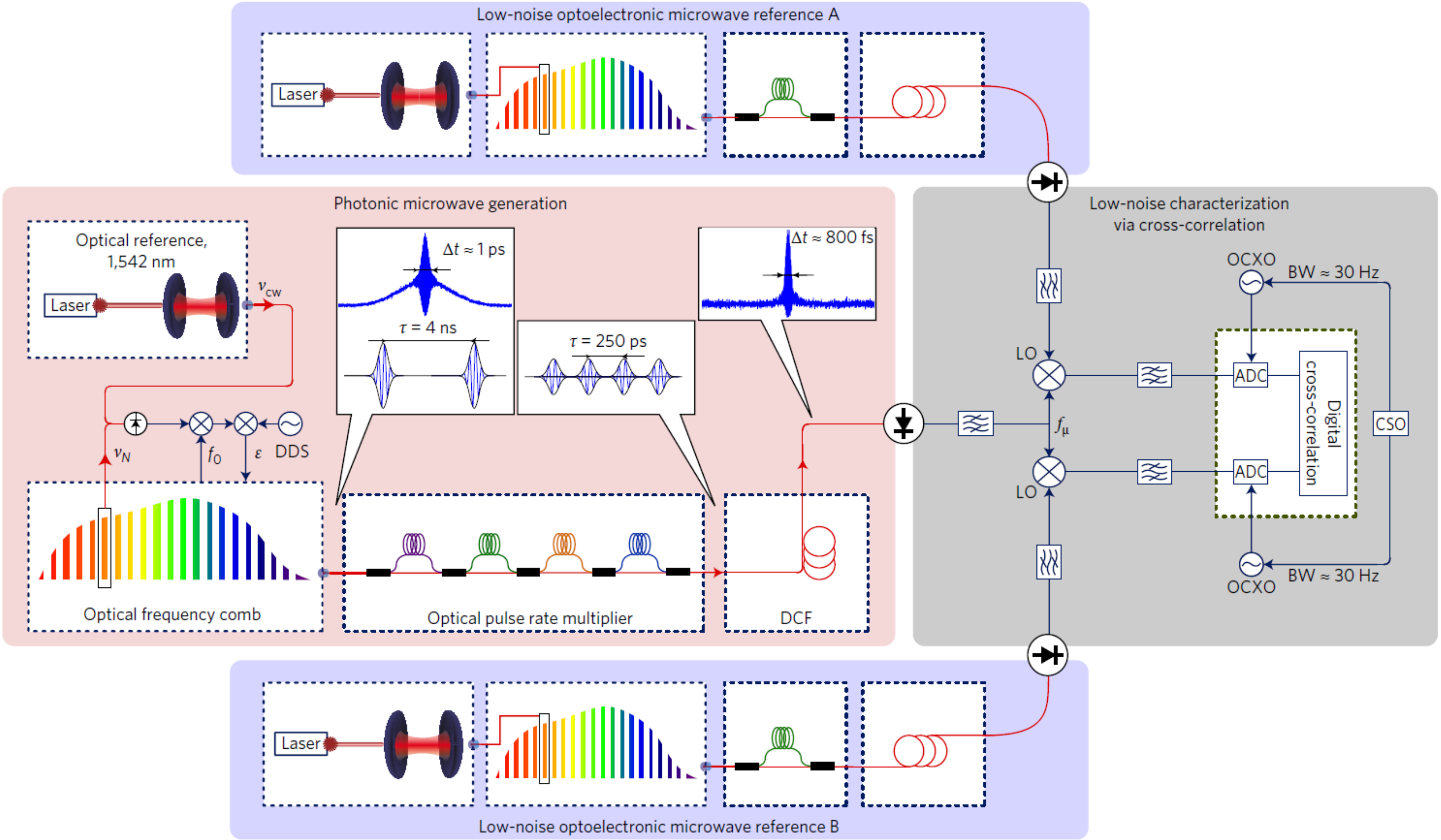
Under the
PULSE program

World record for microwave signal with lowest phase noise

Applications: RADAR, VLBI etc.

Phase noise reduction factor (194 THz vs 12 GHz)
$-20 \log_{10}(194\ \text{THz}/12\ \text{GHz}) = -84\ \text{dB}$

µ-wave measurement setup



Xie, X., Bouchand, R., Nicolodi, D., Giunta, M., Hänsel, W., Lezius, M., … , Holzwarth, R., Le Coq, Y. **(2016).**
Photonic microwave signals with zeptosecond-level absolute timing noise. *Nature Photonics*, *11*(1), 44–47.

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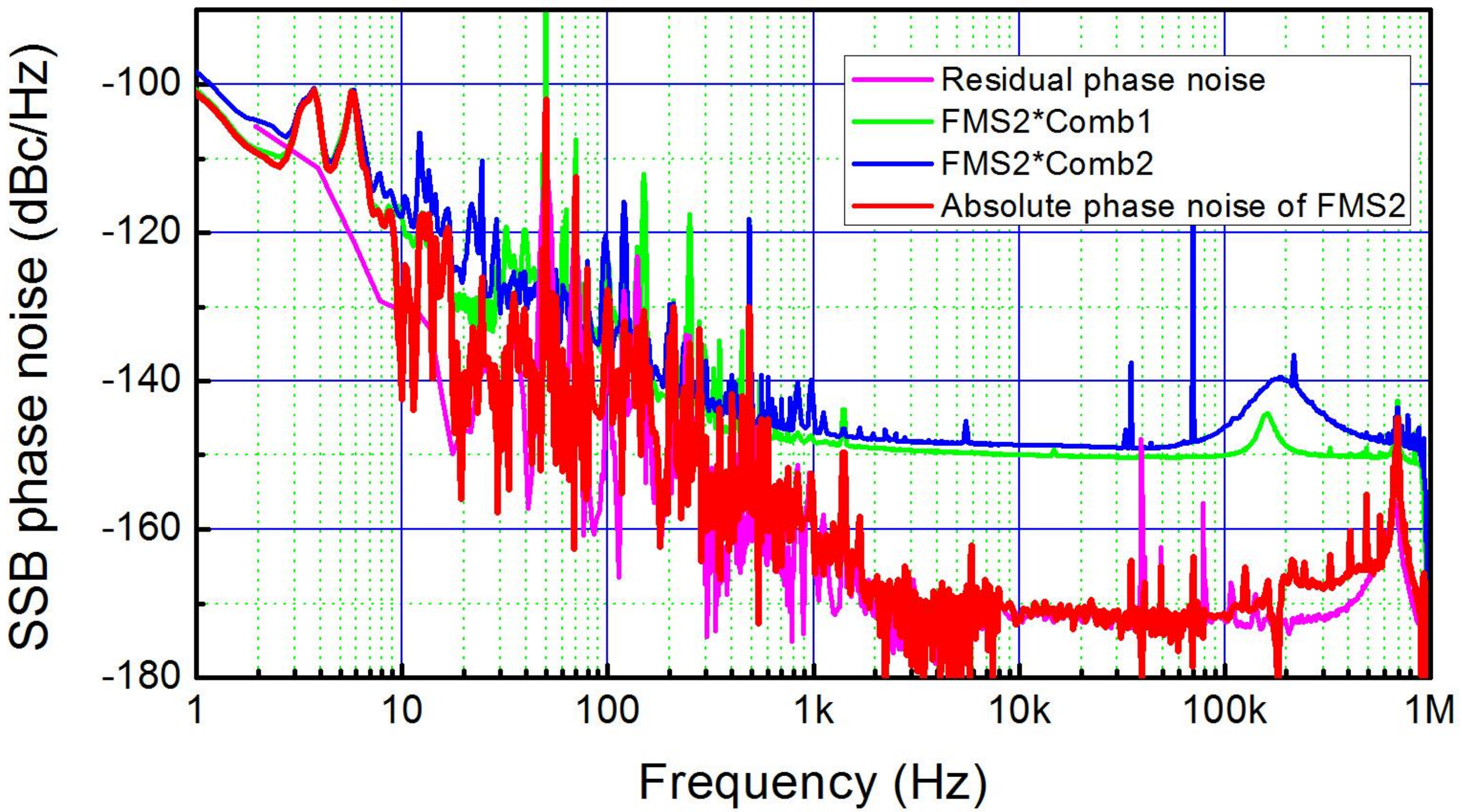
PMWG: world record result

Completely independent systems (including cavity)



In collaboration with G. Santarelli and Y. Le Coq, SYRTE, Paris

Xie, X., Bouchand, R., Nicolodi, D., Giunta, M., Hänsel, W., Lezius, M., … , Holzwarth, R., Le Coq, Y. **(2016). Photonic microwave signals with zeptosecond-level absolute timing noise.** ***Nature Photonics*****,** ***11*****(1), 44–47.**

PWMG published results

nature photonics

LETTERS

PUBLISHED ONLINE: 21 NOVEMBER 2016 | DOI: 10.1038/NPHOTON.2016.215

Photonic microwave signals with zeptosecond-level absolute timing noise

Xiaopeng Xie[1‡], Romain Bouchand[1‡], Daniele Nicolodi[1†], Michele Giunta[2,3], Wolfgang Hänsel[2], Matthias Lezius[2], Abhay Joshi[4], Shubhashish Datta[4], Christophe Alexandre[5], Michel Lours[1], Pierre-Alain Tremblin[6], Giorgio Santarelli[6], Ronald Holzwarth[2,3] and Yann Le Coq[1]*

Photonic synthesis of radiofrequency (RF) waveforms revived the quest for unrivalled microwave purity because of its ability to convey the benefits of optics to the microwave world[1-11]. In this work, we perform a high-fidelity transfer of frequency stability between an optical reference and a microwave signal via a low-noise fibre-based frequency comb and cutting-edge photodetection techniques. We demonstrate the generation of the purest microwave signal with a fractional frequency stability below 6.5×10^{-16} at 1 s and a timing noise floor below 41 zs $Hz^{-1/2}$ (phase noise below −173 dBc Hz^{-1} for a 12 GHz

from the optics to the microwaves: $\delta\nu_{CW}/\nu_{CW} = \delta f_r/f_r = \delta f_\mu/f_\mu$. Thanks to the carrier frequency division, the phase-noise power spectral density (PSD) is intrinsically reduced by M^2, where $M = \nu_{CW}/f_\mu = N/n \sim 10^4$ is the frequency division factor.

The microwave generation system is sketched in Fig. 1: a low-noise erbium-doped fibre-based optical frequency comb (FOFC) that features a 250 MHz repetition rate acts as a frequency divider; an ultrastable CW laser at 1,542 nm, with a fractional frequency stability as low as 5.5×10^{-16} at 1 s (ref. 18), is used as a reference for stabiliz-ing the comb; a specially designed high-linearity photodiode with

World’s lowest phase noise on any microwave signal

PMWG: Commercial Product

UMS-Compact

Ultrastable Microwave System
based on Menlo Systems ORS-Compact and SmartComb
in a robust rack-mount

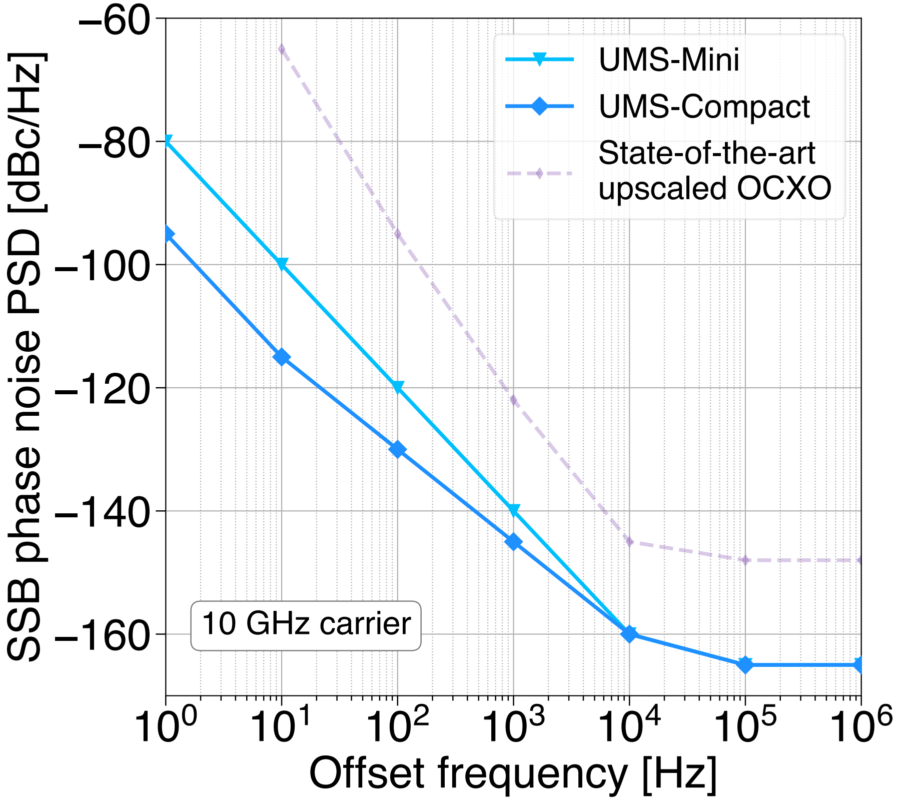
Output frequencies:
Configurable with multiple signal outputs from 100 MHz to 20 GHz.
Phase-coherent optical signals at 1.5 µm from the comb (pulsed) and from the optical reference (cw) are available.
Optical comb outputs from 500 nm to 2 um can also be added.

Phase noise for a 10 GHz carrier:
<-95 dBc Hz^{-1} at 1 Hz
-145 dBc Hz^{-1} at 1 kHz
-160 dBc Hz^{-1} at 10 kHz
-165 dBc Hz^{-1} at >100 kHz

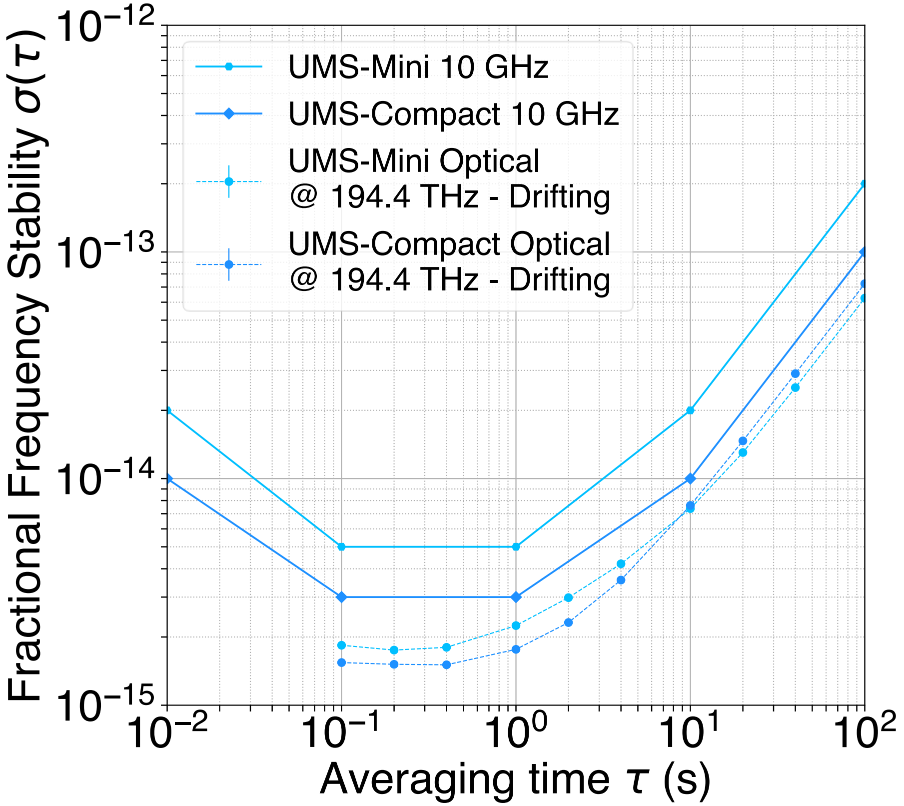
Frequency stability for a 10 GHz carrier:
<3E-15 at 1 s
<1E-13 at 100 s
<50 ppt in one day - GPS/Optical/RF-reference steerable

PMWG: measurement results

Phase Noise



Fractional frequency stability



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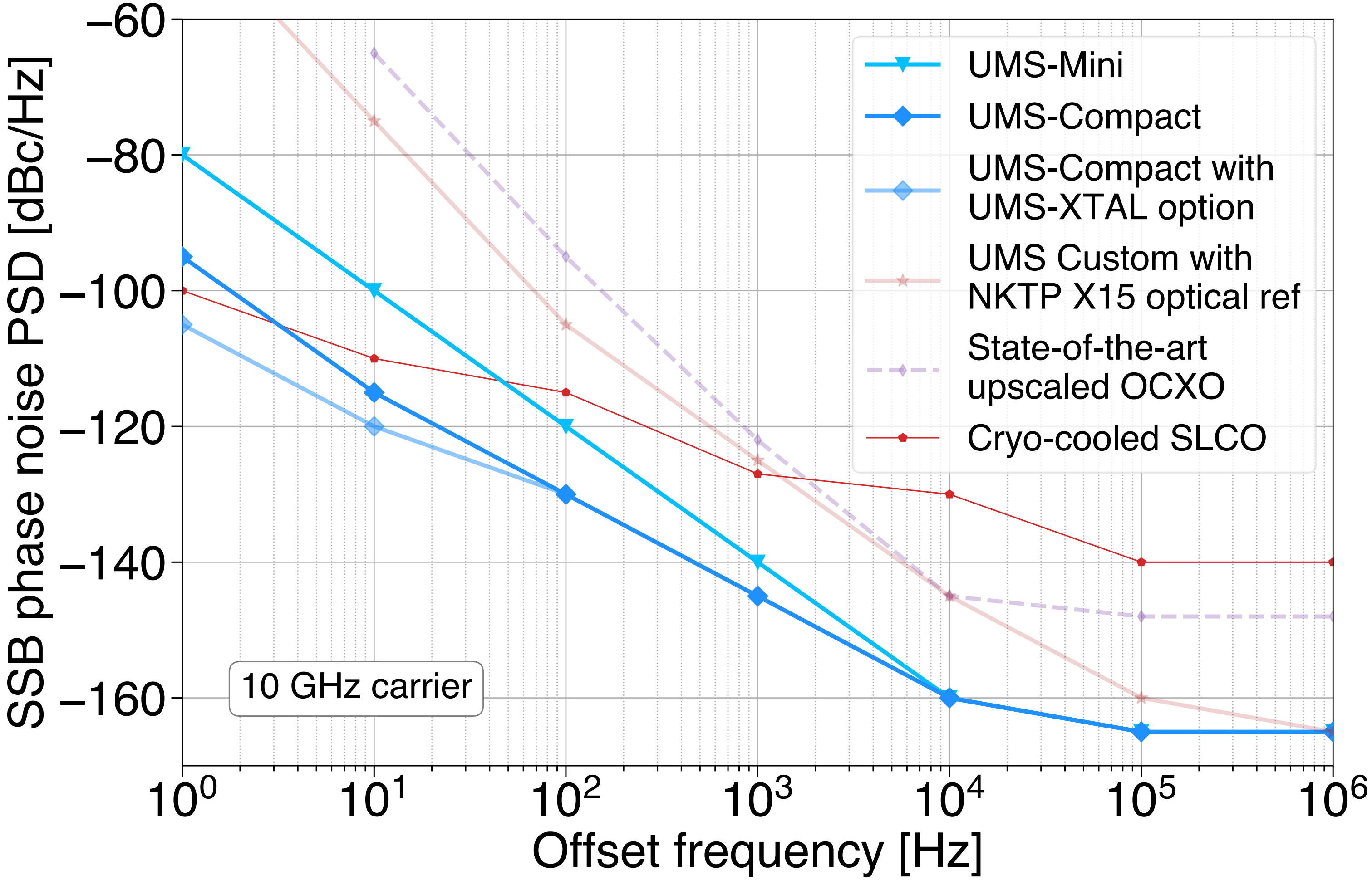
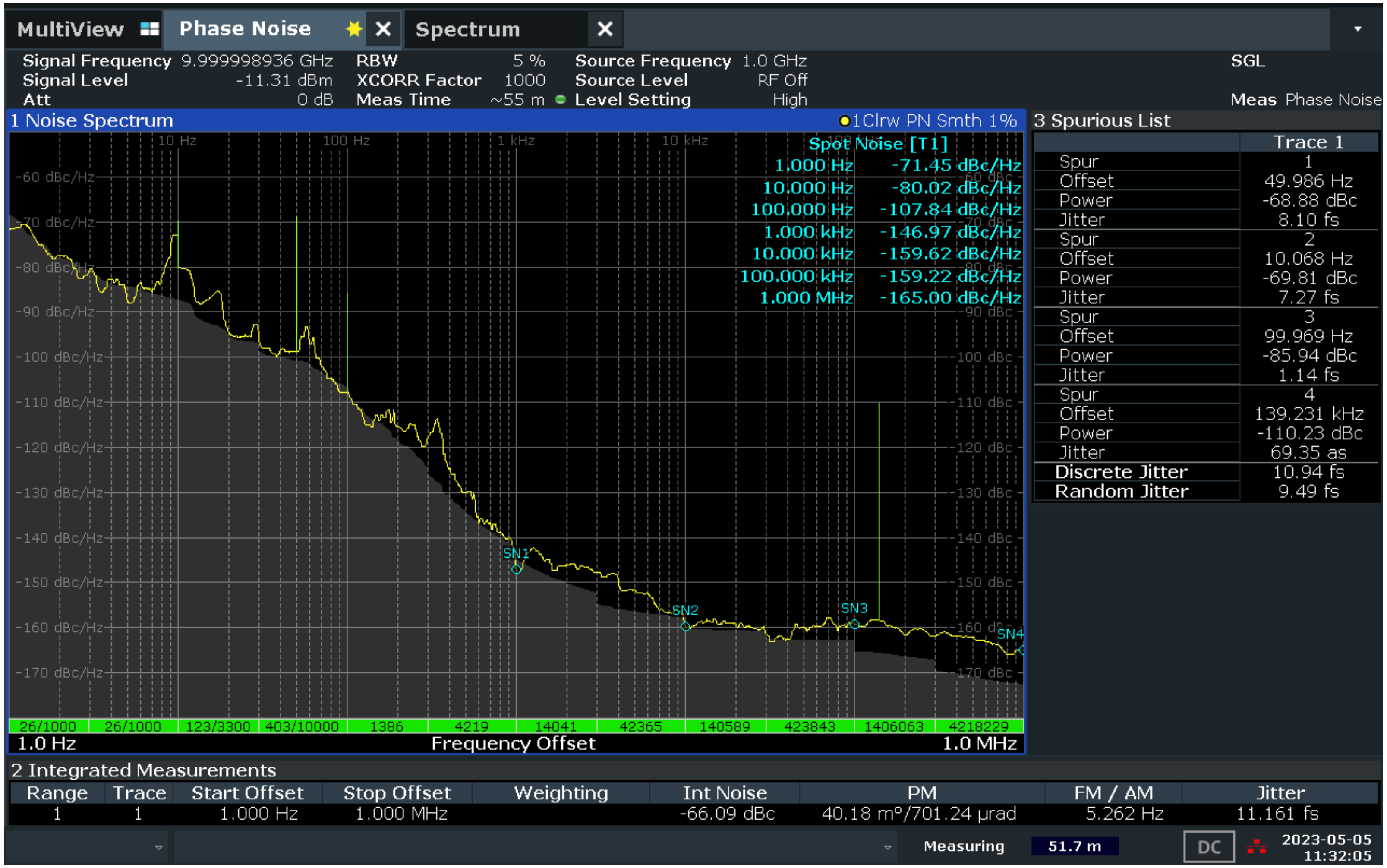
PMWG: Benchmarking



Unmeasurable with top notch instruments

Rohde & Schwarz FSWP



11:32:06 AM 05/05/2023

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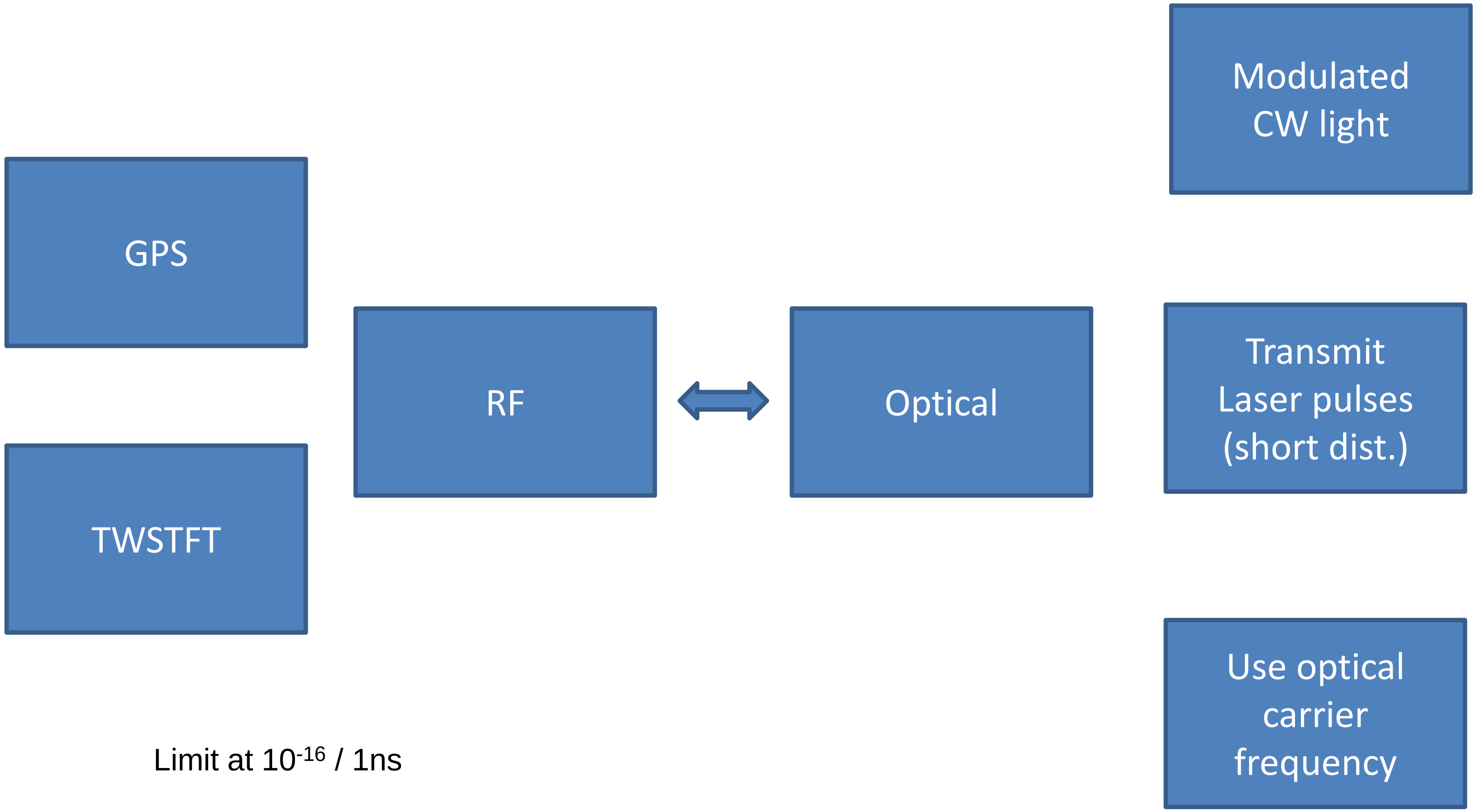
Time and Frequency Dissemination



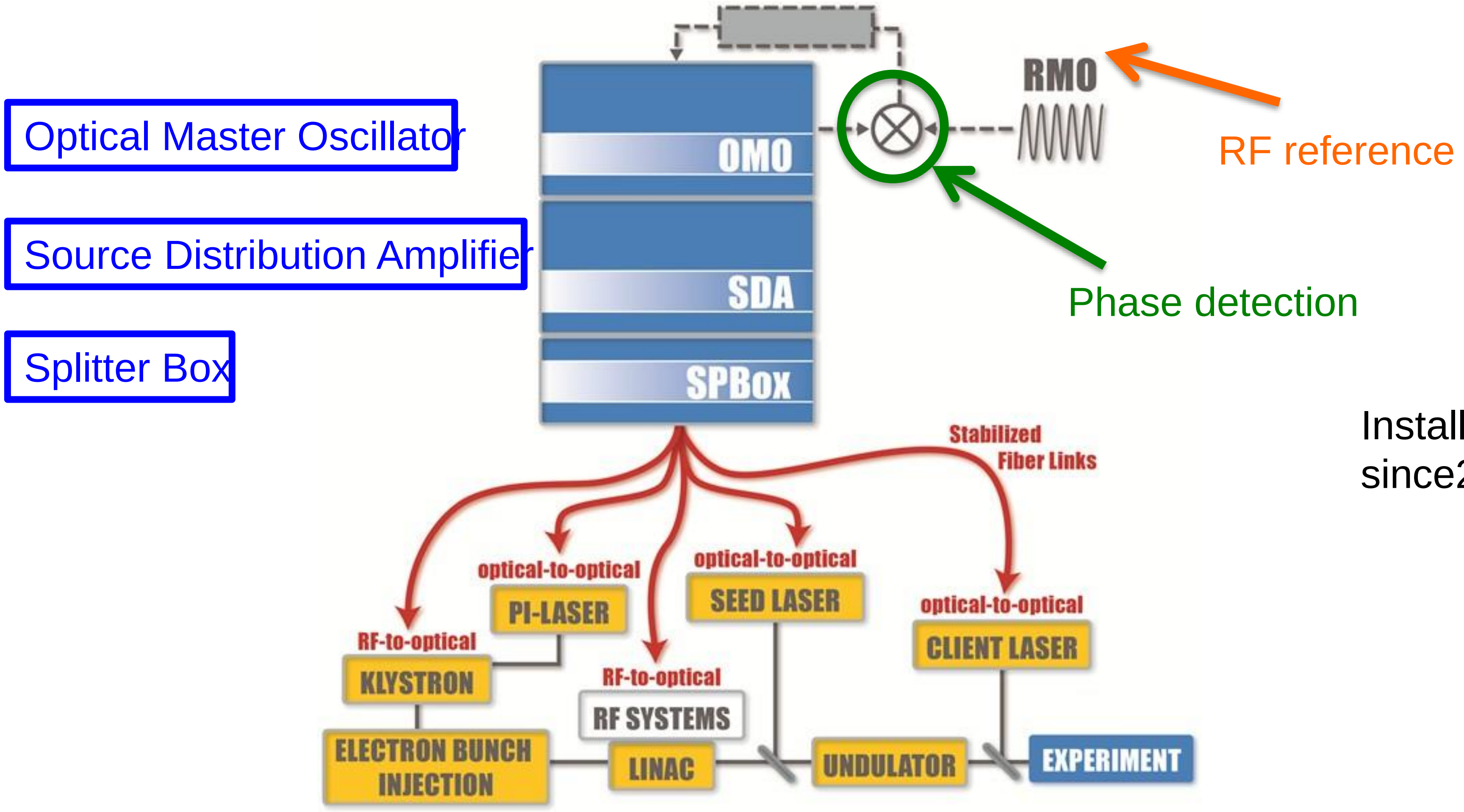
G. Santarelli et al, SYRTE

J. Ye et al, JILA
F. Kärtner, MIT

G. Santarelli et al, SYRTE
N. Newburry, NIST
K. Predehl, MPQ/PTB

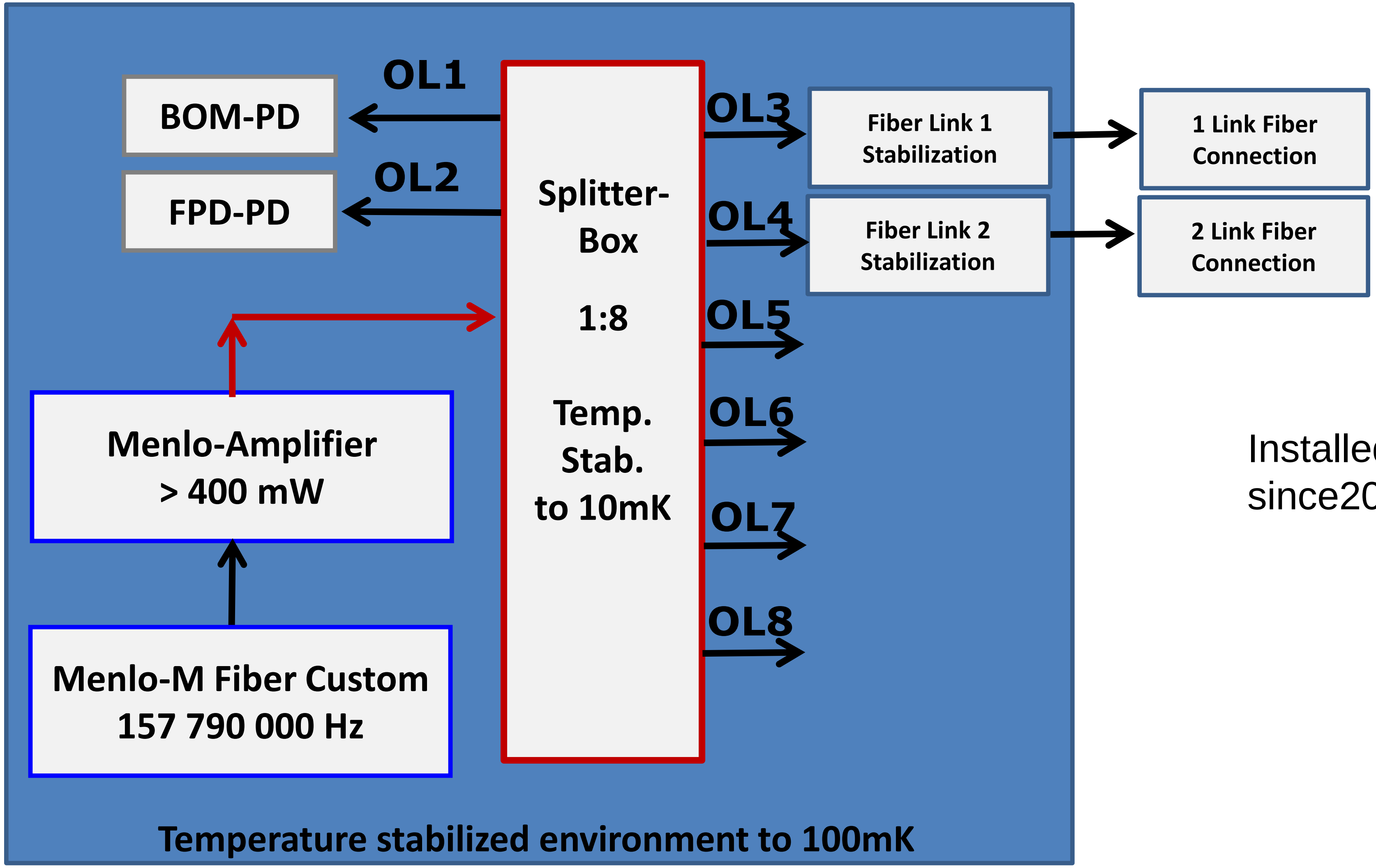
Limit at 10^{-16} / 1ns

Pulsed timing system: Fermi @ Elettra, Trieste, Italy



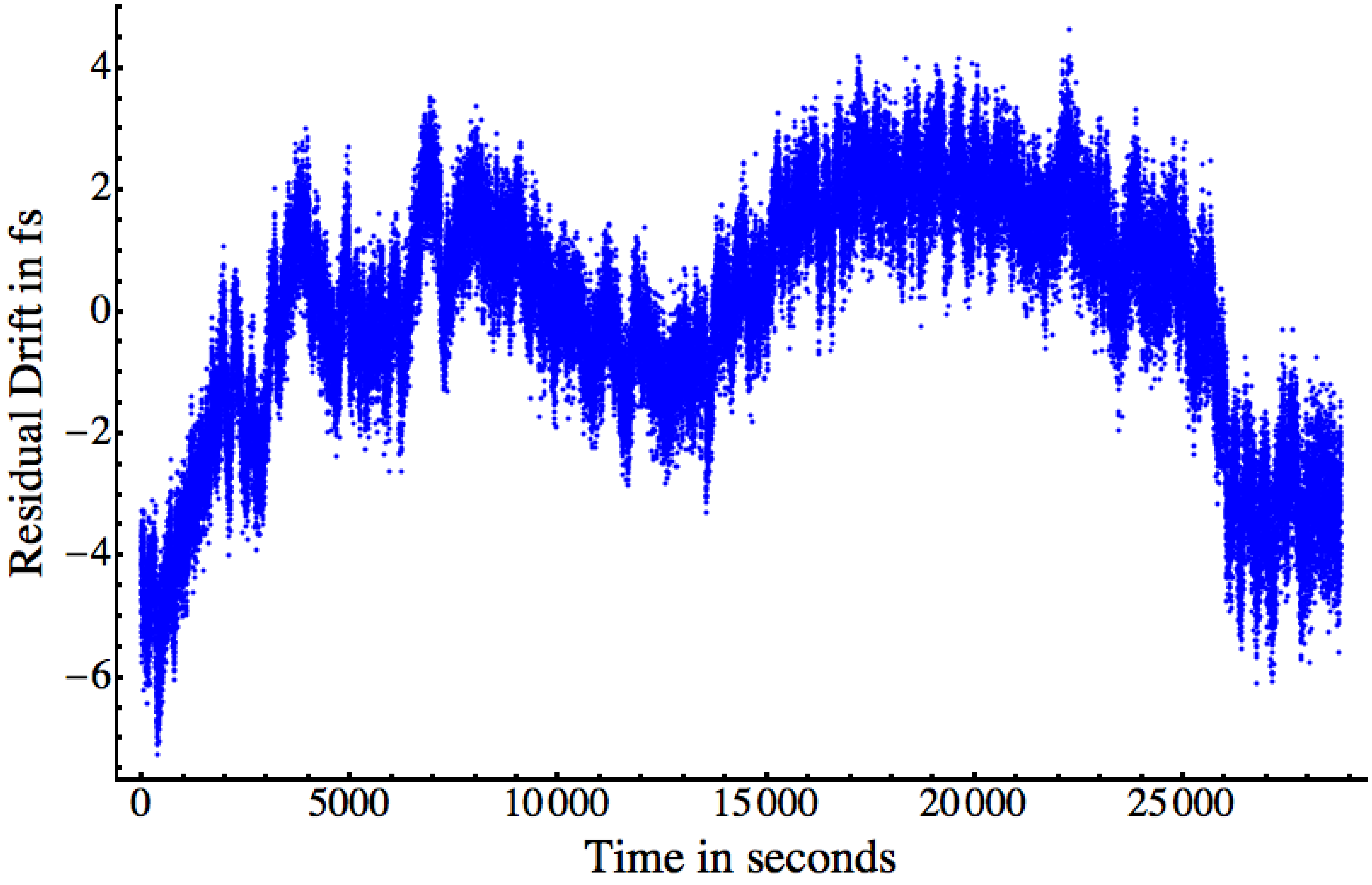
Installed and running since2009

Trieste ELETTRA – System Layout



Installed and running since2009

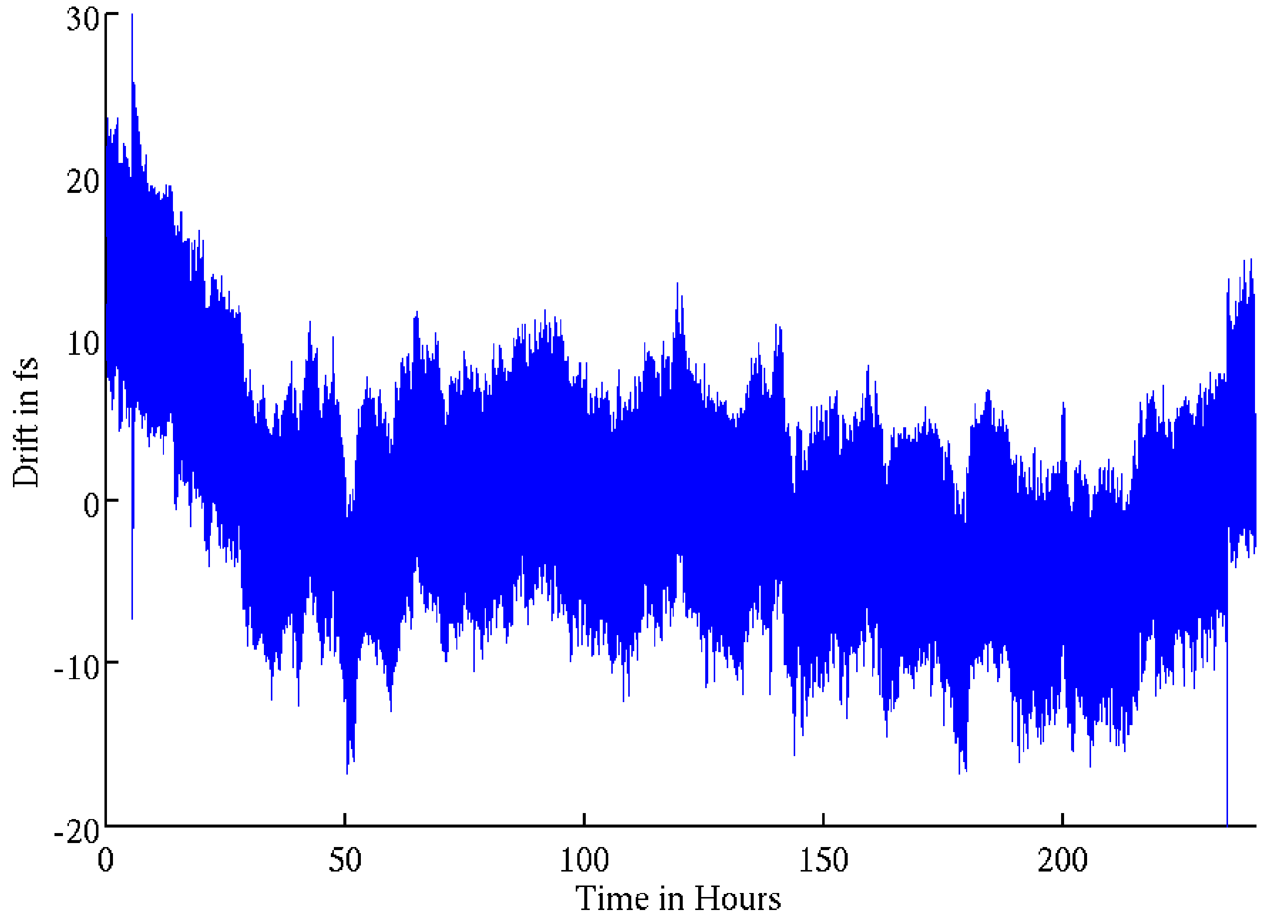
Trieste ELETTRA - Drift between RMO and OMO



Installed 2009

Long-term out-of-loop drift between the OMO and the RMO, measured with the BOM-PD. Over eight hours, the residual drift is 2 fs (rms).

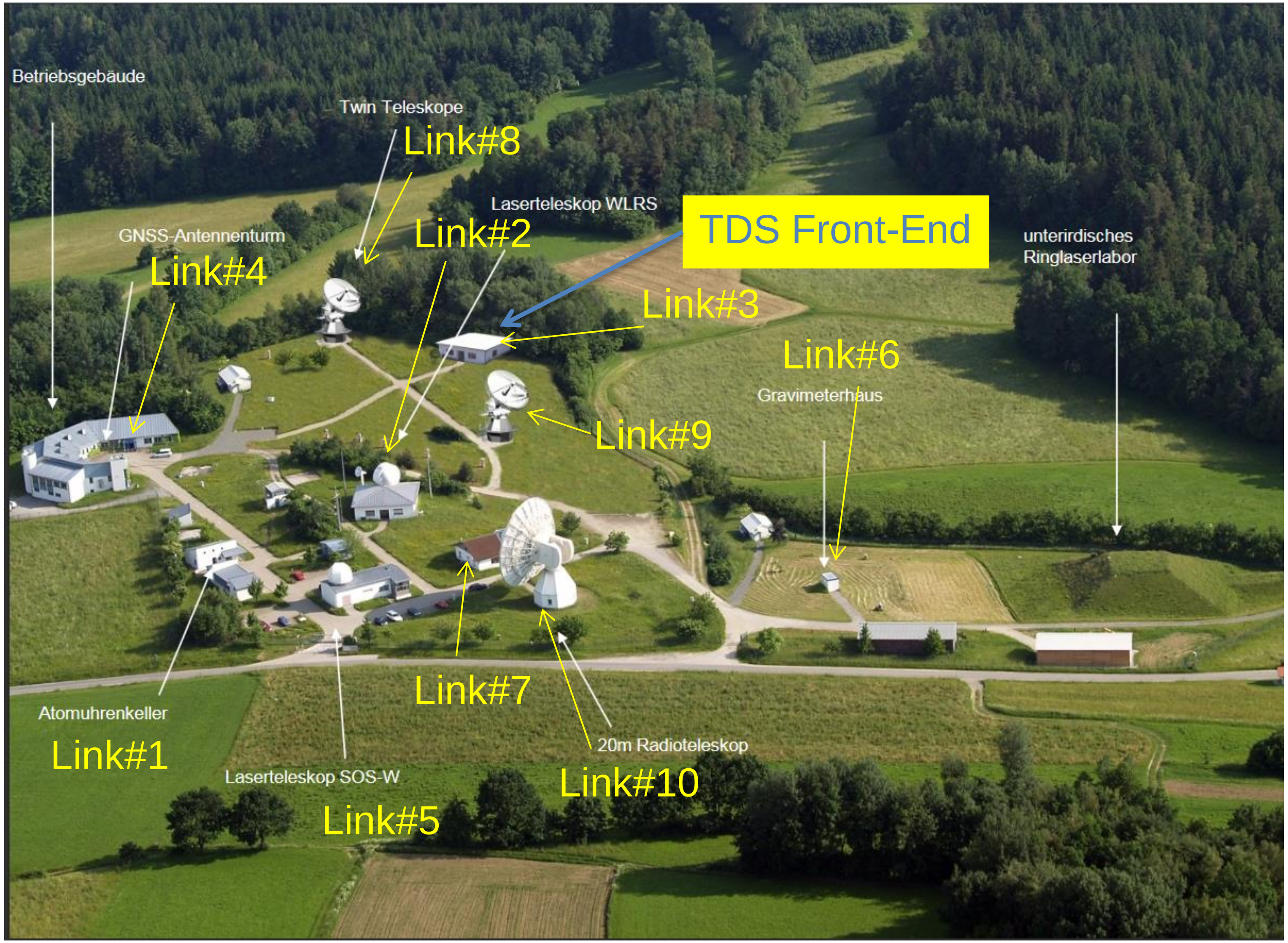
Trieste ELETTRA - Drift Between Link and OMO



Installed 2009

Long-term out-of-loop drift of dummy link output compared to an unused splitter box port. The rms drift over 10 days is 5.3 fs.

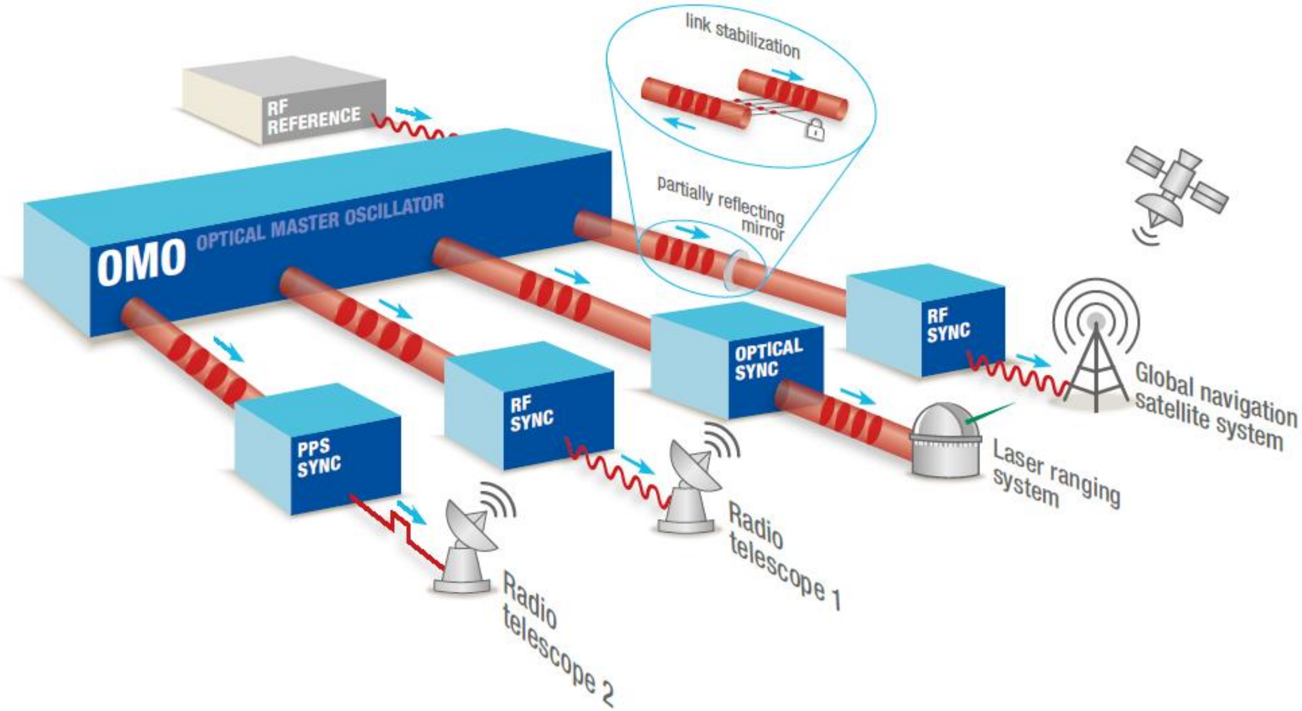
Pulsed timing system: Geodetical Observatory Wettzell



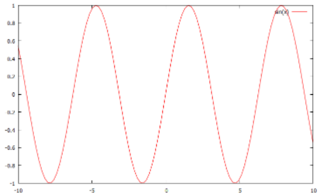
10 fs timing accuracy

Optical Pulses as time stamps

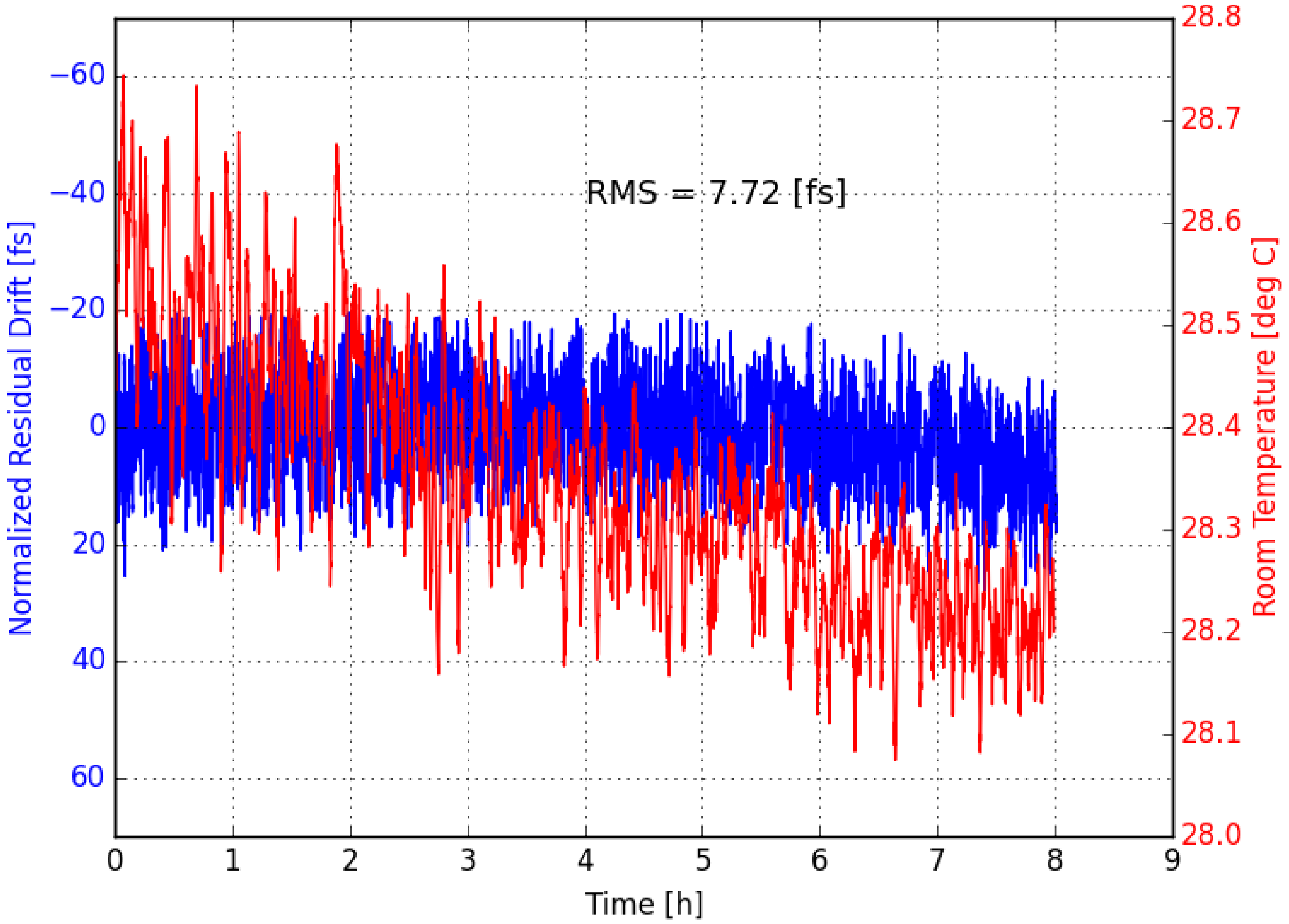
Optical Pulsed Timing System Layout



Possible stabilized output signals:

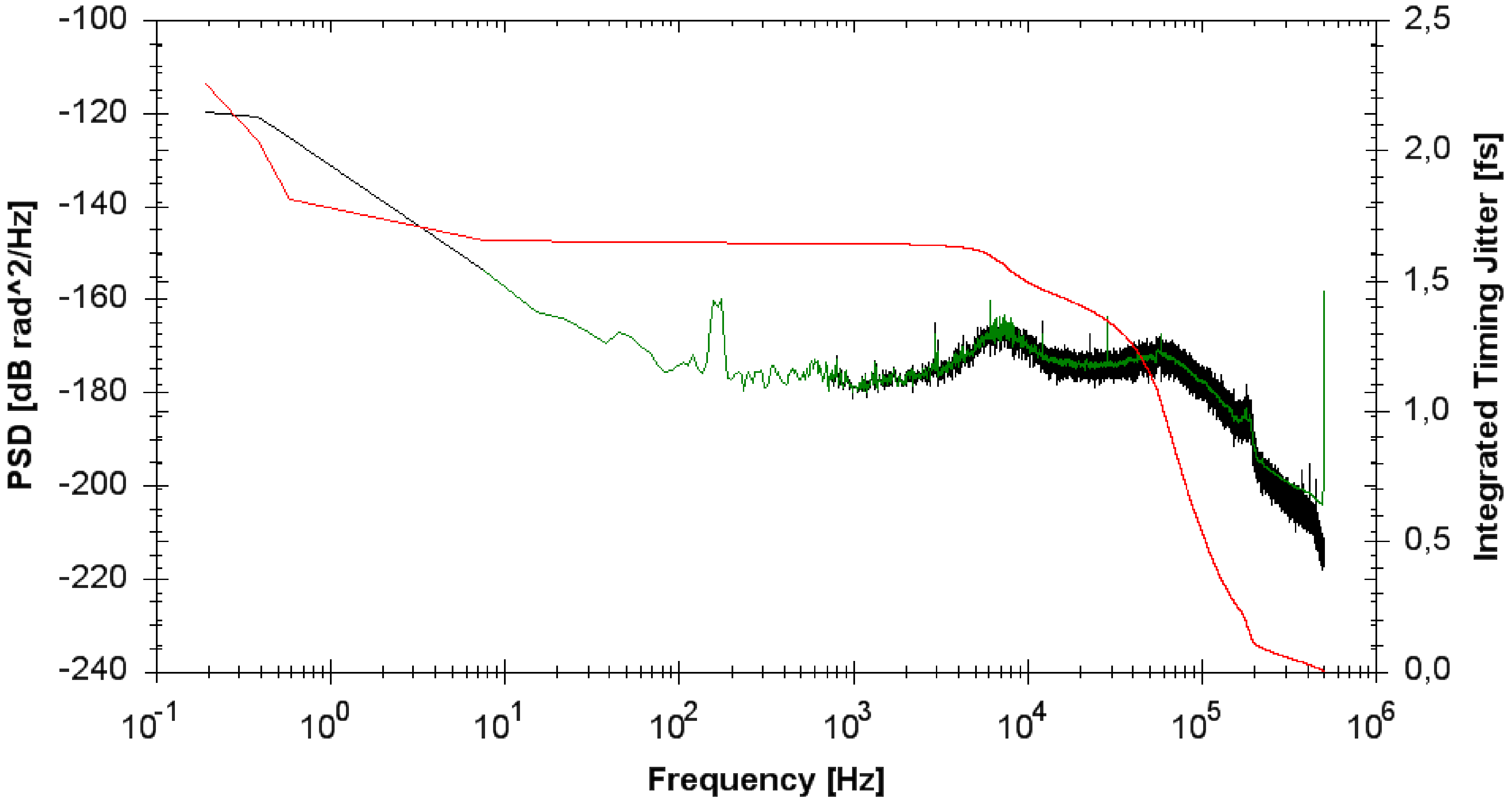
- **Optical pulses (1560nm)** 
- **Low frequency RF: 5, 10, 100 MHz** 
- **Microwaves: 1GHz – 6GHz** 
- **Timing signals: 1PPS (Pulse per second)** 

Implemented at Geodetical Observatory Wettzell



Residual timing drift between two 250 meter non pm stabilized fiber links, measured out of loop using an external cross correlator.

Implemented at Geodetical Observatory Wettzell

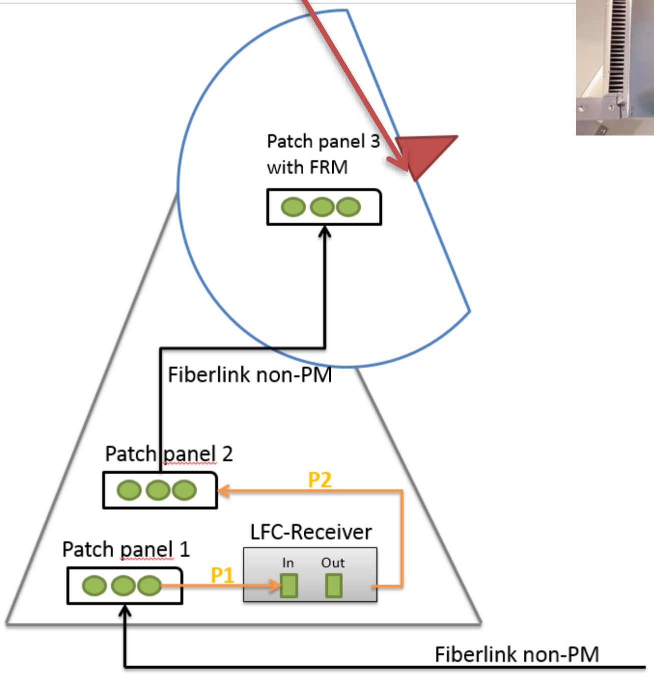


Residual phase noise between two stabilized 250 meter non pm fibre links, detected out of loop using an external balanced cross correlator.

All the way up to the dishes

Overview TDS
Wettzell

Back-End for Radiotelescopes



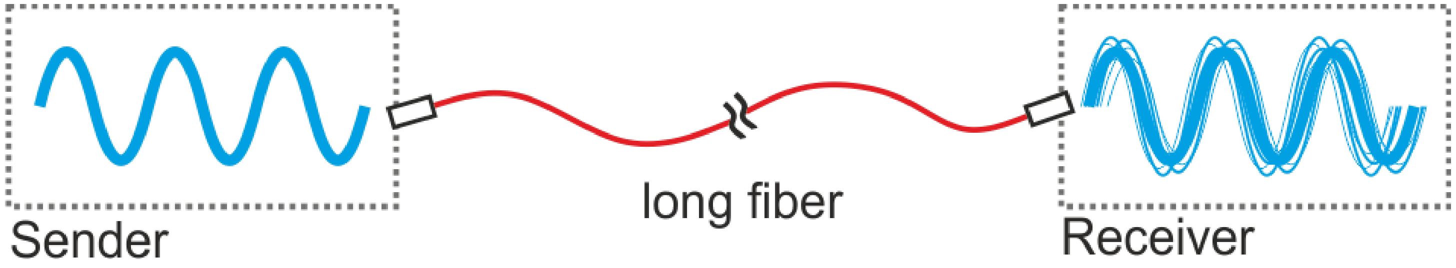
„Original“ Link 2010-2016

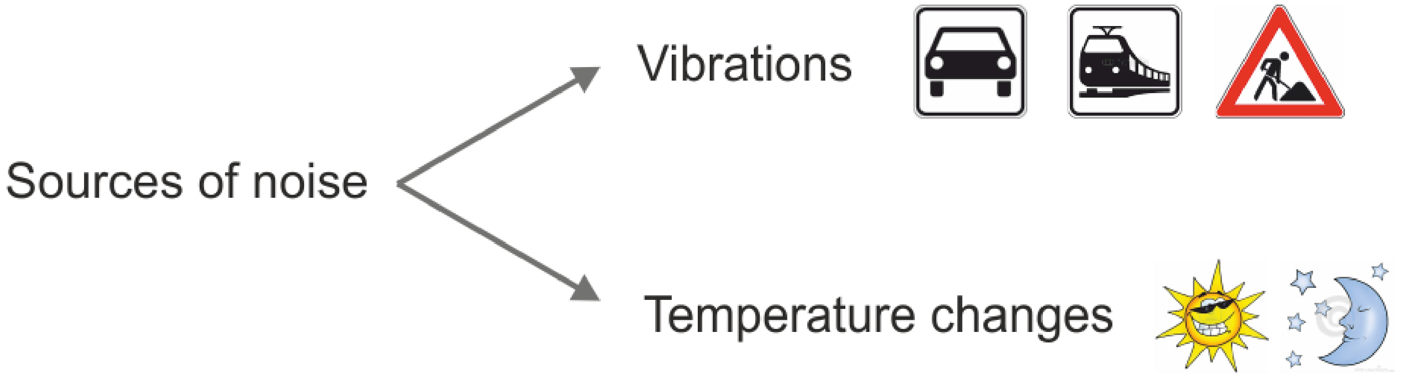
- 2 *dark* fibers (ITU-T G.652)
- n ~ 1.4681 at 1550 nm
- A~ 0.23 dB/km
- CD~18 ps/(nm·km)
- 920 km total length
- C-Band channel 44: 1542.14nm

Harald Schnatz
Gesine Grosche
Osama Terra
Fritz Riehle

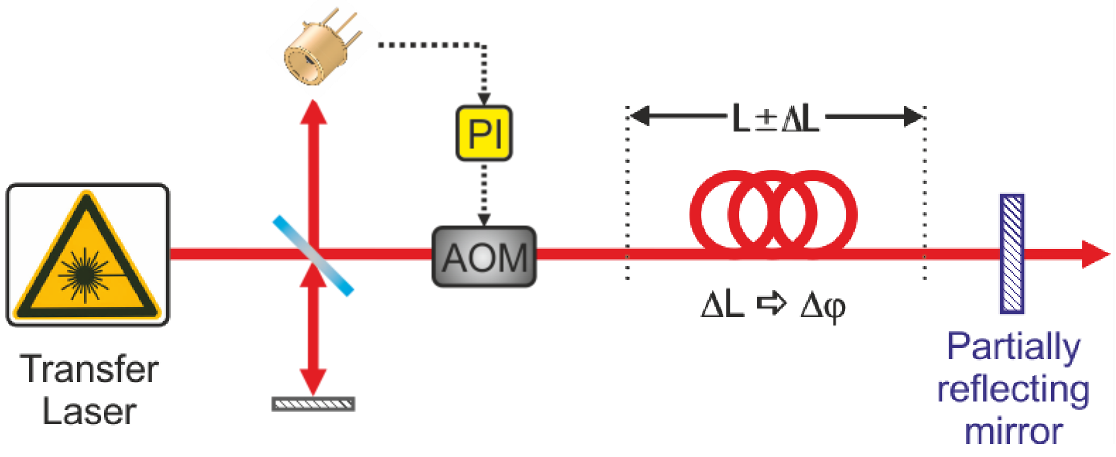
Katharina Predehl
Stefan Droste
Thomas Udem
Theodor Hänsch
Ronald Holzwarth

Problem to be solved: fibers are terrific sensors

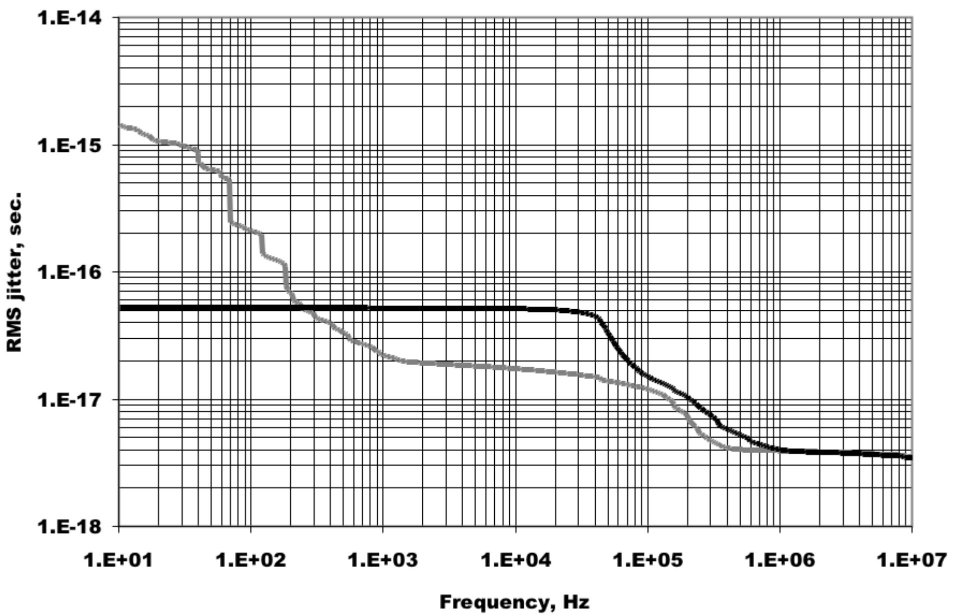




Solution: cw light with interferometric stabilization



200 THz signal carries frequency information



Works very well for short fibers:
50 as integrated jitter for 150m of fiber

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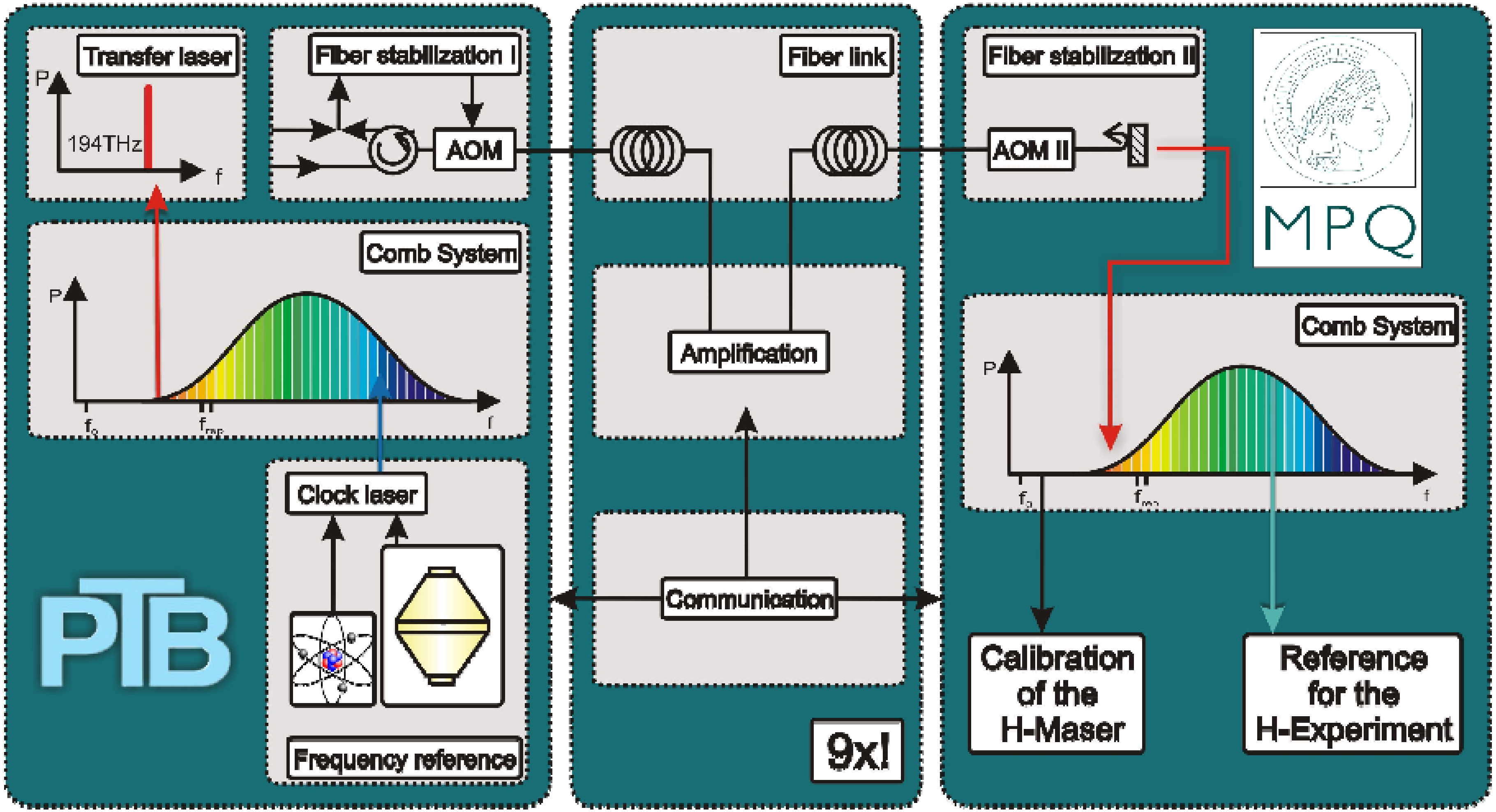
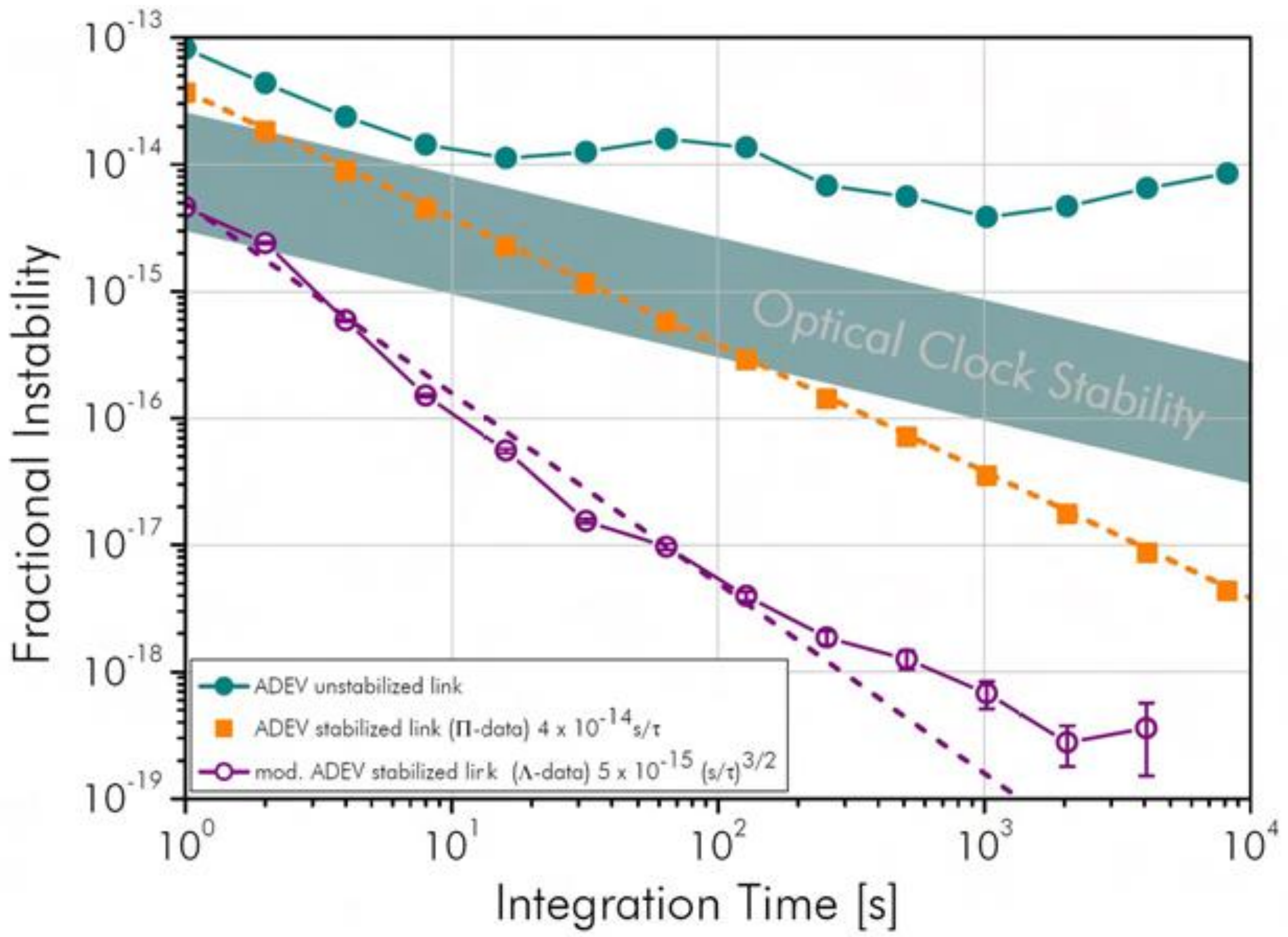
Long Distance Clock Comparison: 920 km



Predehl et al., Science vol. 336, p. 441 (2012)

Long Distance Clock Comparison: Results



A 920-Kilometer Optical Fiber Link for Frequency Metrology at the 19th Decimal Place

K. Predehl,[1*] G. Grosche,[2,3†] S. M. F. Raupach,[2†] S. Droste,[1] O. Terra,[2‡] J. Alnis,[1] Th. Legero,[2] T. W. Hänsch,[1,4] Th. Udem,[1] R. Holzwarth,[1,5] H. Schnatz[2,3]

Optical clocks show unprecedented accuracy, surpassing that of previously available clock systems by more than one order of magnitude. Precise intercomparisons will enable a variety of experiments, including tests of fundamental quantum physics and cosmology and applications in geodesy and navigation. Well-established, satellite-based techniques for microwave dissemination are not adequate to compare optical clocks. Here, we present phase-stabilized distribution of an optical frequency over 920 kilometers of telecommunication fiber. We used two antiparallel fiber links to determine their fractional frequency instability (modified Allan deviation) to 5×10^{-15} in a 1-second integration time, reaching 10^{-18} in less than 1000 seconds. For long integration times τ, the deviation from the expected frequency value has been constrained to within 4×10^{-19}. The link may serve as part of a Europe-wide optical frequency dissemination network.

Predehl et al., Science vol. 336, p. 441 (2012)

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1840 km Link

PRL **111**, 110801 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Optical-Frequency Transfer over a Single-Span 1840 km Fiber Link

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To compare the increasing number of optical frequency standards, highly stable optical signals have to be transferred over continental distances. We demonstrate optical-frequency transfer over a 1840-km underground optical fiber link using a single-span stabilization. The low inherent noise introduced by the fiber allows us to reach short term instabilities expressed as the modified Allan deviation of 2×10^{-15} for a gate time τ of 1 s reaching 4×10^{-19} in just 100 s. We find no systematic offset between the sent and transferred frequencies within the statistical uncertainty of about 3×10^{-19}. The spectral noise distribution of our fiber link at low Fourier frequencies leads to a τ^{-2} slope in the modified Allan deviation, which is also derived theoretically.

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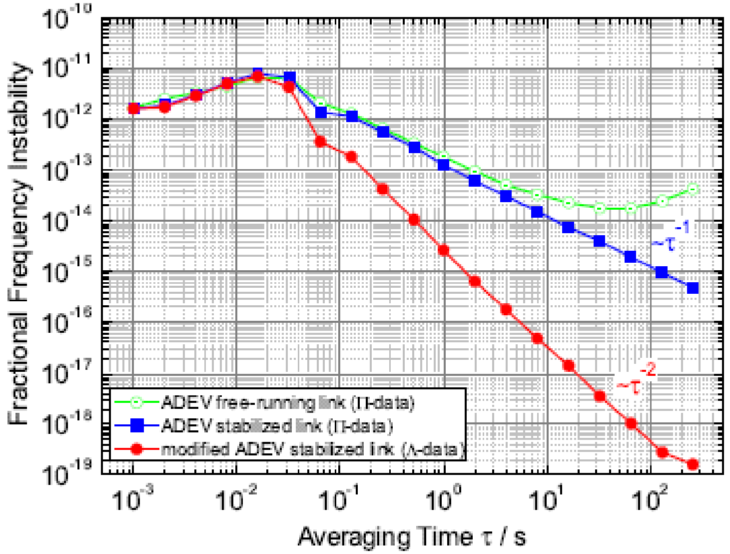


Droste st al., PRL 111, 110801 (2013)

Transportable Clock in Munich

Fiber connection
Munich - Braunschweig

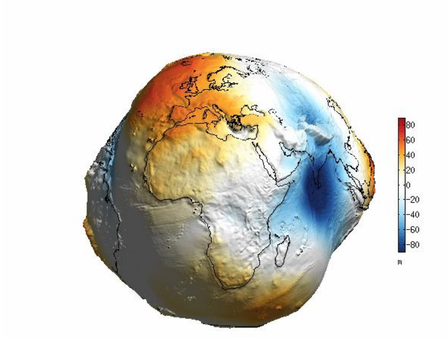
Height difference:
400m

Determined to 30cm
by clock comparison

PTB‘s lattice clock in at MPQ in Munich

PTB‘s Lattice Clock in Munich

- ▶ New chronometric levelling campaign Braunschweig – This summer
- ▶ **2018 campaign: Accuracy in height 23 cm**



PTB

ife
Institut für Erdmessung

MPQ

MenloSystems GmbH

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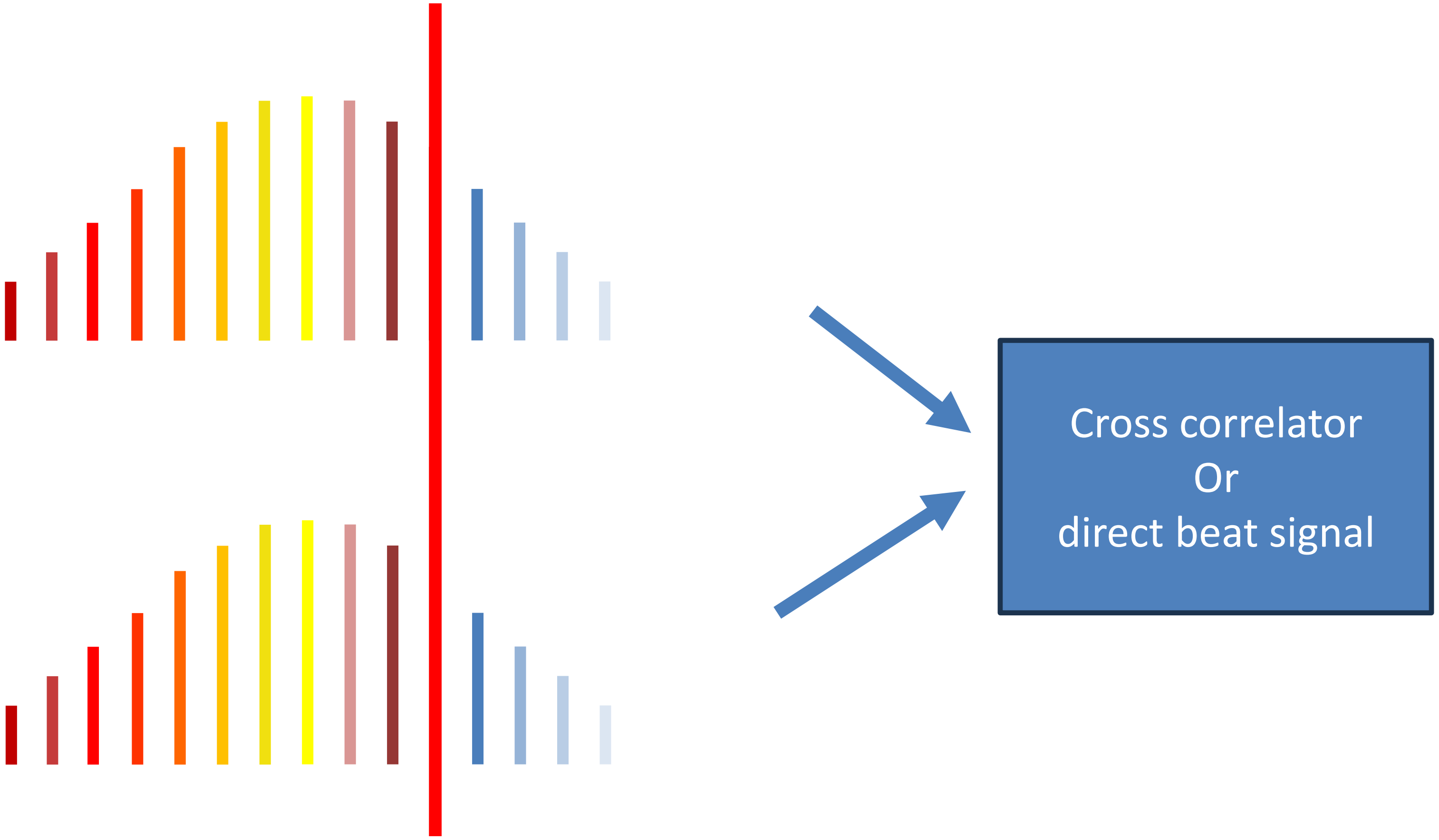
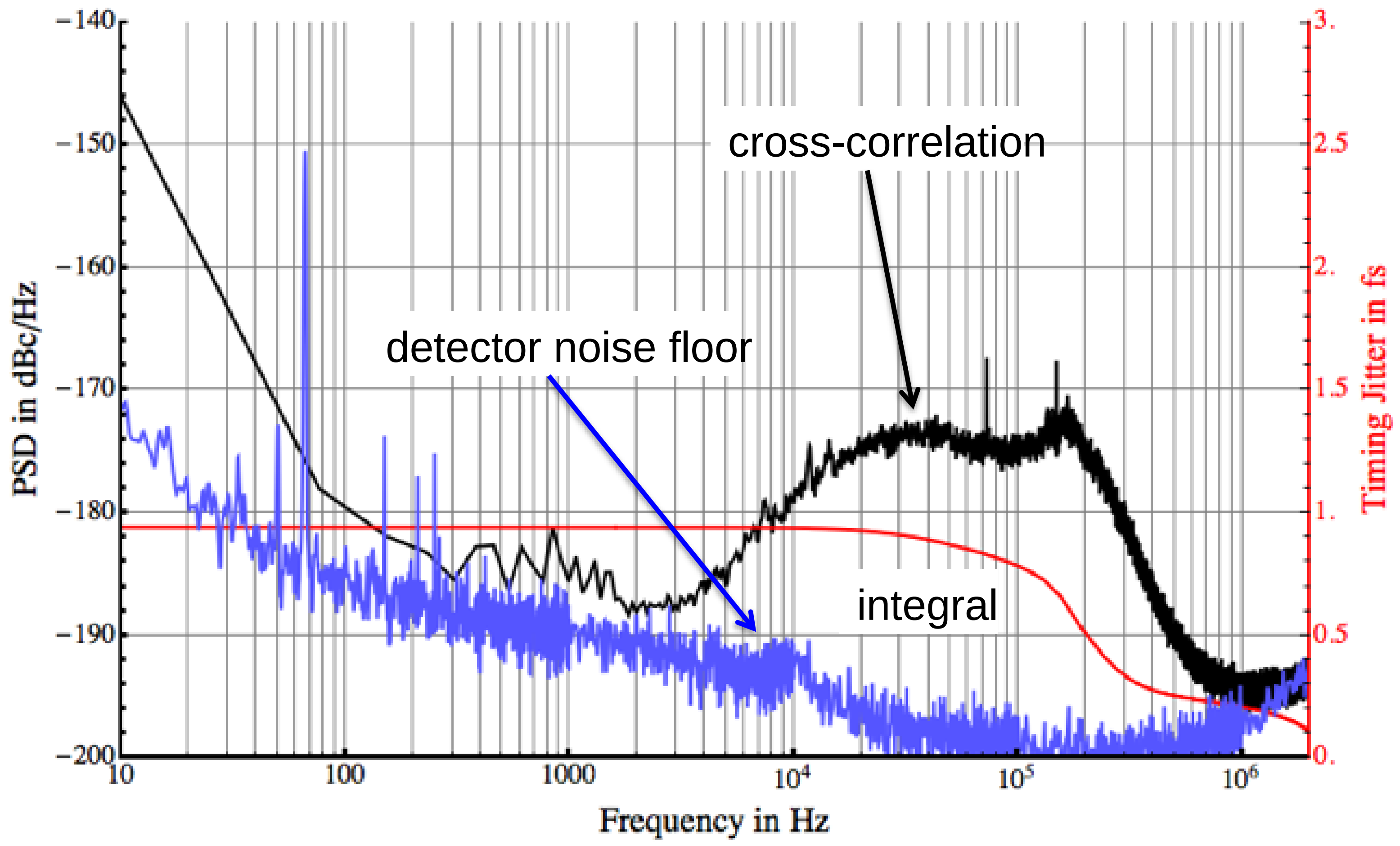
2 combs connected via a cw laser



Cross correlation between 2 cw laser connected comb lasers



In collaboration with Russell Wilcox (data presented at CLEO 2014)

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

0.9 fs integrated timeing jitter!

- EO loop bandwidth ~ 200kHz, piezo loop bandwidth ~ 10kHz
- Noise floor integrates to 0.1fs

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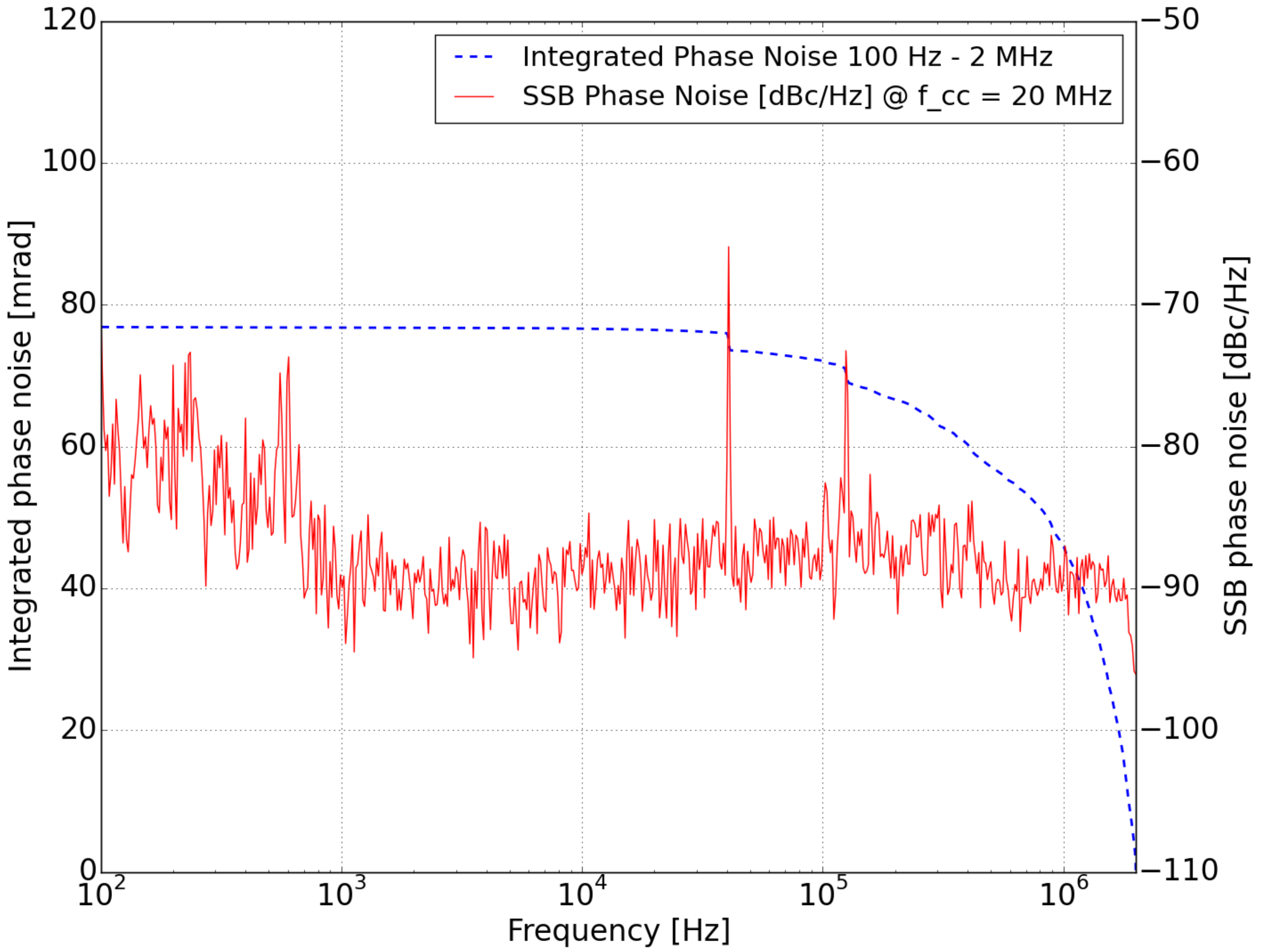
Direct beat between 2 cw laser connected comb lasers

40 as



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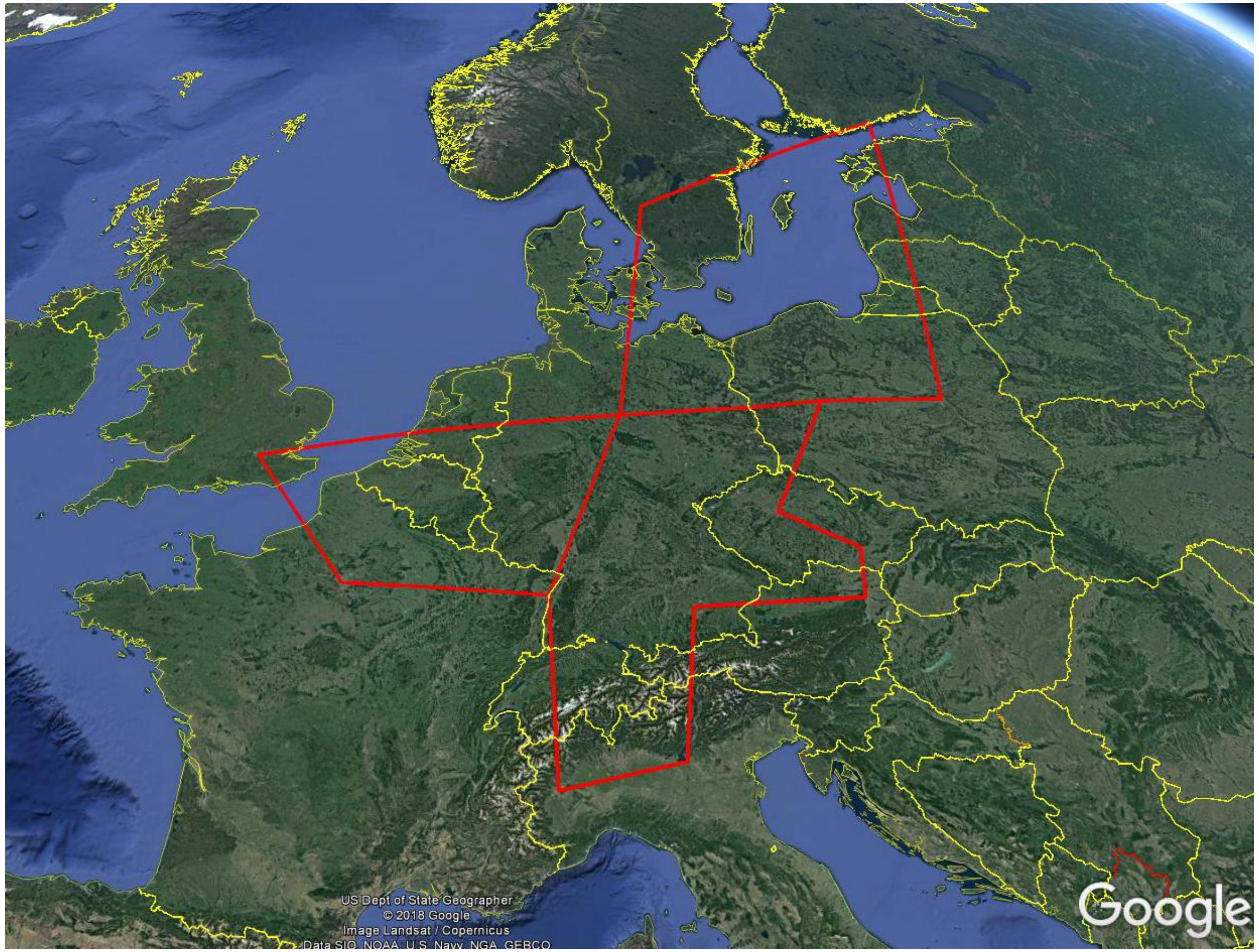
CLONETS DS



CloNetS DS
Clock Network Services Design Study

https://clonets-ds.eu/

Design study for a Time and Frequency reference system based on optical fibers across Europe

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Combs et al. are the Swiss knife of precision measurements

Optical Clocks

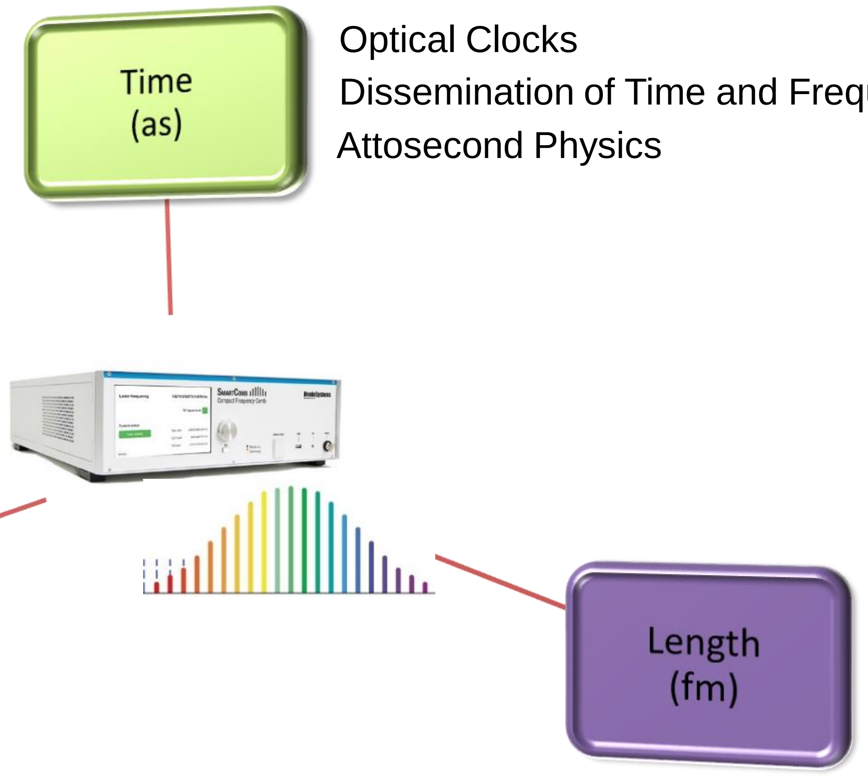
Dissemination of Time and Frequency

Attosecond Physics

Precision
Spectroscopy

Direct Comb Spectroscopy

Stable Microwaves



Distance
Measurements

Length Metrology

Harmonic Combs (UV)

Spectrograph
Calibration

Thanks

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The End

Thanks for your attention