Schweizerische Eidgenossenschaft
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Federal Institute of Metrology METAS

METAS

Dissemination of high accuracy optical frequencies in stabilized fibre optic networks

D. Husmann 02.11.2022

QT4HEP Workshop CERN
Nov 2022

SNSF Sinergia: Precision molecular spectroscopy

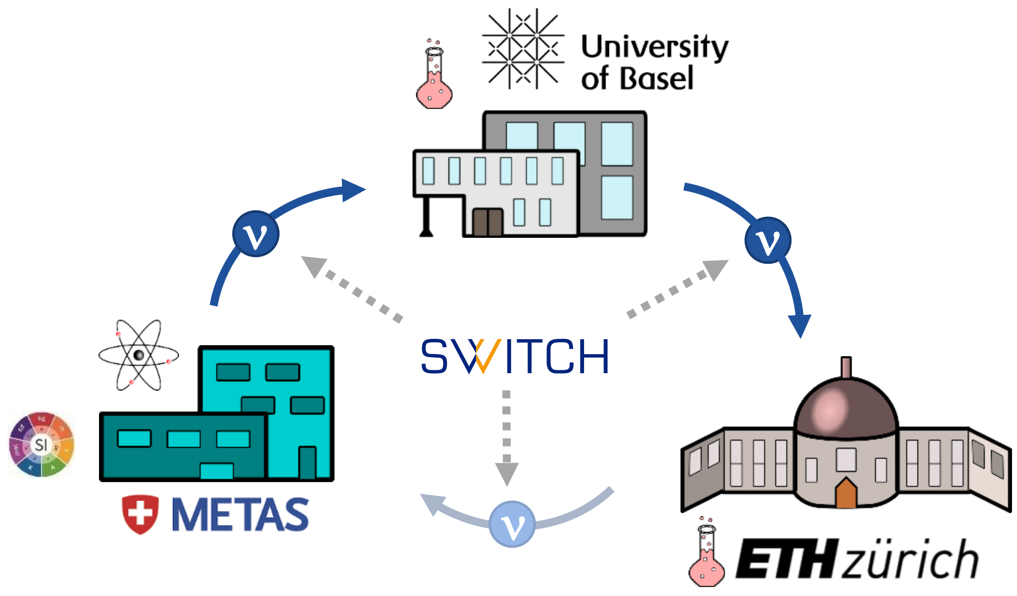
Precision molecular spectroscopy using a network for distribution of the Swiss primary frequency standard

Open questions to be adressed:

H_2 , H_2^+: Proton-charge radius

N_2^+: possible time variation of the proton-to-electron mass ratio, molecular clock experiments

Frequency resolution requirement: $\frac{\Delta\nu}{\nu} = 10^{-14}$



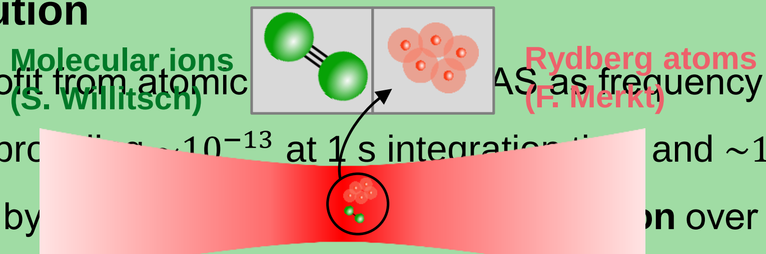
Frequency Metrology

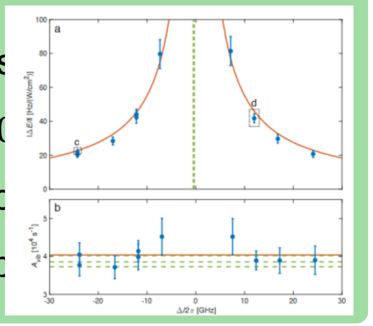
Problem

- Precision spectroscopy groups need reference frequencies to measure the frequency of their spectroscopy lasers
- Current GPSD rubidium oscillators are not good enough
  - Fractional frequency uncertainty of 10^{-11} at 1 s integration time and 10^{-13} ultimate limit

Solution

- Profit from atomic ... AS as frequency s
- …pro ... 10^{-13} at 1 s integration ... and ~10
- … by ... on over c
- … using the **Swiss academic network** provided b





Sinhal et al. Science, https://doi.org/10.1126/science.aaz9837

Overview

1. Frequency metrology and the SI second
    - How are the Second and Hertz realized?
2. Frequency dissemination
    - From satellite techniques to the need of optical fiber networks.
3. Swiss realization of a phase-stabilized frequency network
    - Spectral considerations, noise cancellation, characterization
4. Establishing SI-traceability in a user laboratory
    - How much the new reference frequency helps for accuracy
5. Conclusion

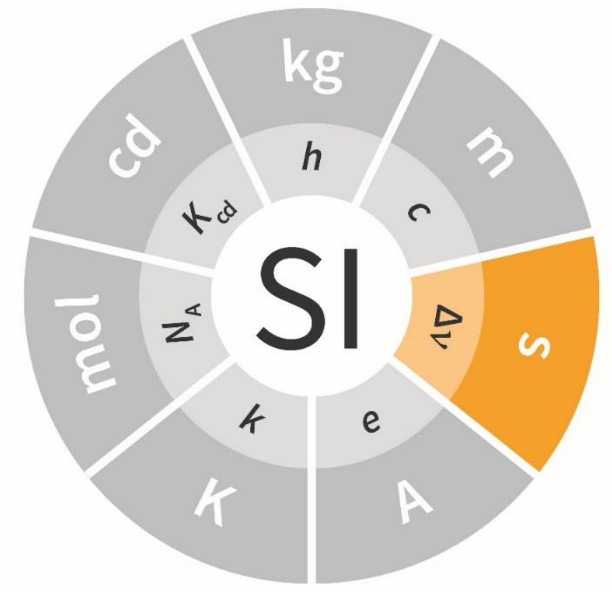
Frequency metrology: intro

ate measurement. This is what my friend and mentor Arthur Schawlow at Stanford University had in mind when he advised his students: "Never measure anything but frequency!" Measuring a frequency, i.e. counting the num-

Theodor W. Hänsch – Nobel Lecture. NobelPrize.org. Nobel Prize Outreach AB 2021. Tue. 5 Oct 2021. https://www.nobelprize.org/prizes/physics/2005/hansch/lecture/

Système international d'unités

https://www.bipm.org (CC BY-ND 2.0)



Arthur L. Schawlow

Definition of the second

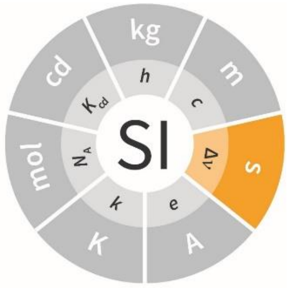
$\Delta\nu_{Cs}$: Transition between the two hyperfine levels of the unperturbed ground state of the ^{133}Cs atom.

$$1\ \mathrm{Hz} = \frac{\Delta\nu_{Cs}}{9\,192\,631\,770}$$

$$1\ \mathrm{s} = \frac{9\,192\,631\,770}{\Delta\nu_{Cs}}$$

Definition: SI-traceability
measurement trace to a realization of the second with known uncertainty for each step

Universal Time Coordinated UTC: Realization of the second



Data of about 450 atomic clocks are continuously compared worldwide

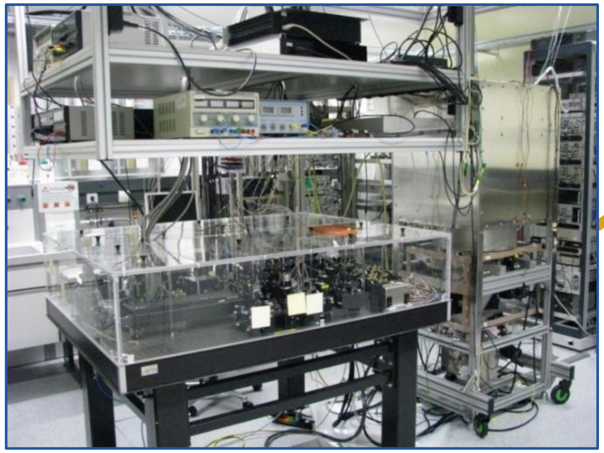
UTC(k)

Clock_i – UTC(k)

- H-Masers
- Commercial Cs

UTC(CH)

Clock_i – UTC(CH)



BIPM
Bureau International des Poids et Mesures (Paris)

Monthly Analysis with ALGOS Algorithm

EAL (Echelle Atomique Libre)
Free, uncalibrated time scale

Calibration with Cs Primary standards

TAI (Temps Atomique International)

UTC = TAI + N leap seconds

Universal Time Coordinated UTC: Realization of the second

Circular T
Monthly published

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CIRCULAR T 414                                                    ISSN 1143-1393
2022 JULY 11, 11h UTC
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                 THE INTERGOVERNMENTAL ORGANIZATION ESTABLISHED BY THE METRE CONVENTION
             PAVILLON DE BRETEUIL F-92312 SEVRES CEDEX  TEL. +33 1 45 07 70 70 tai@bipm.org

The contents of the sections of BIPM Circular T are fully described in the document "Explanatory supplement to BIPM Circular T"
available at https://webtai.bipm.org/ftp/pub/tai/other-products/notes/explanatory_supplement_v0.6.pdf

1 - Difference between UTC and its local realizations UTC(k) and corresponding uncertainties.
    From 2017 January 1, 0h UTC, TAI-UTC = 37 s.
```

Epoch

Date 2022 0h UTC	MAY 30	JUN 4	JUN 9	JUN 14	JUN 19	JUN 24	JUN 29	Uncertainty/ns uA	uB	u	Notes
MJD	59729	59734	59739	59744	59749	59754	59759				
Laboratory k	[UTC-UTC(k)]/ns										
AGGO (La Plata)	694.7	705.1	699.0	706.8	708.2	703.5	711.2	1.0	20.0	20.0	
AOS (Borowiec)	-1.2	-1.1	-1.1	-1.2	-1.3	-1.4	-1.0	0.3	3.1	3.1	
APL (Laurel)	-	-	-2.6	-0.8	-0.6	-1.1	0.4	0.3	20.0	20.0	
AUS (Sydney)	-509.4	-518.3	-521.6	-522.0	-511.2	-521.3	-508.5	0.3	11.2	11.2	
BEV (Wien)	-25.7	-19.5	-9.8	-4.2	-7.2	1.9	5.7	0.3	2.7	2.7	
BFKH (Budapest)	4968.0	5009.9	5043.7	5081.1	5123.2	5156.4	5183.6	1.5	20.0	20.1	
BIM (Sofiya)	16230.8	16260.7	16282.2	16291.4	16291.7	16308.6	16366.8	0.3	7.2	7.2	
BIRM (Beijing)	22.8	25.2	34.6	41.9	46.3	53.9	54.8	0.3	3.0	3.0	
BOM (Skopje)	-	-				-	-				
BY (Minsk)	-0.9	-1.5				-1.5	-2.1	1.5	2.9	3.2	
CAO (Cagliari)	-36238.8	-36357.2	-36474.4	-36592.6	-36703.8	-36817.9	-36930.9	1.5	20.0	20.1	
CH (Bern-Wabern)	-2.7	-2.1	-1.3	-0.3	0.5	0.8	-0.1	0.3	1.5	1.6	
CNES (Toulouse)	4.2	9.8	11.8	3.9	-0.9	-4.3	-6.2	0.3	2.7	2.7	
CNM (Queretaro)	4.8	6.9	4.5	2.9	-1.7	6.6	7.5	1.5	4.0	4.2	

UTC(k)

UTC – UTC(k) / ns

METAS: UTC(CH)

UTC = TAI + N leap seconds

Universal Time Coordinated UTC: calibration of time interval

FoCS-2 the Swiss Primary Frequency Standard

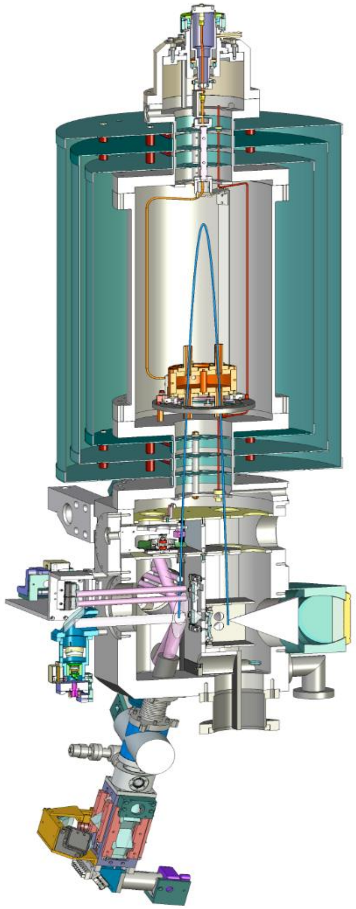
Calibration with Cs Primary standards

↓

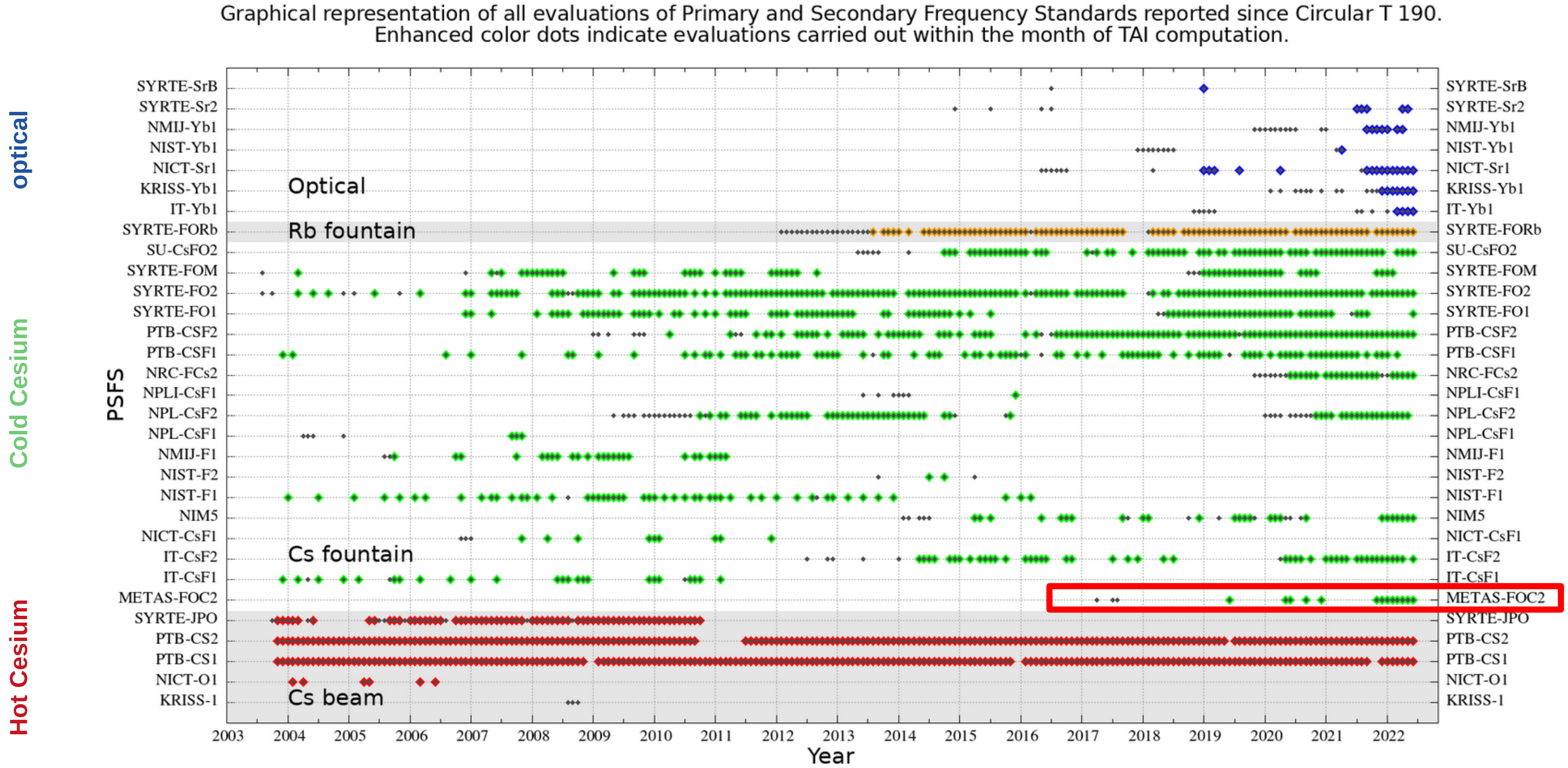
TAI (Temps Atomique International)

↓

UTC = TAI + N leap seconds

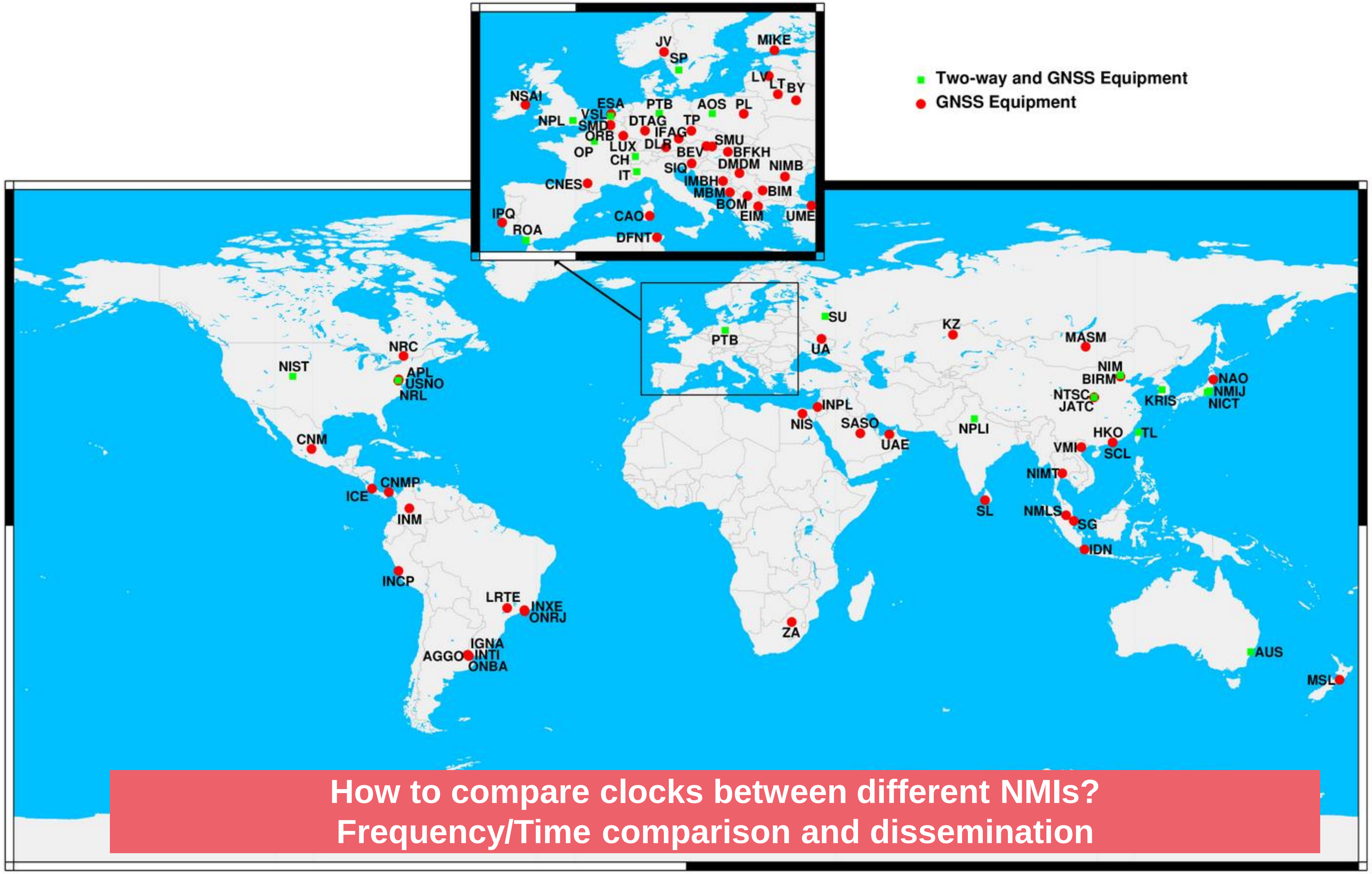


Participation of frequency standards to realization of TAI/UTC



https://webtai.bipm.org/database/show_psfs.html, 24.06.2022

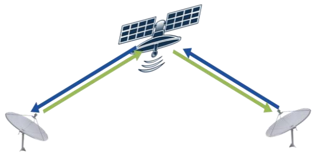
Geographical distribution of the laboratories that contribute to TAI and time transfer equipment (2021)



How to compare clocks between different NMIs?
Frequency/Time comparison and dissemination

Source: BIPM, https://webtai.bipm.org/ftp/pub/tai/other-products/maps/planisphere-2021.png

Universal Time Coordinated UTC: comparison methods



Data of about 450 atomic clocks are continuously compared worldwide

UTC(k)

$Clock_i$ – UTC(k)

UTC(CH)

$Clock_i$ – UTC(CH)

BIPM
Bureau International des Poids et Mesures (Paris)

- **Comparison with Satellite techniques** (GNSS, TWSTFT)

1 - Difference between UTC and its local realizations UTC(k) and corresponding uncertainties.
From 2017 January 1, 0h UTC, TAI-UTC = 37 s.

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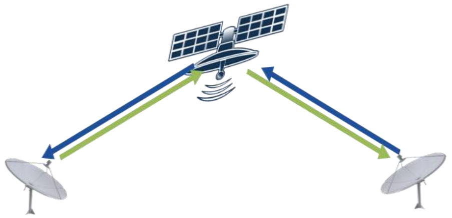
CNES (Toulouse)	4.2	9.8	11.8	3.9	-0.9	-4.3	-6.2	0.3	2.7	2.7	

- Best performances reach the ns level

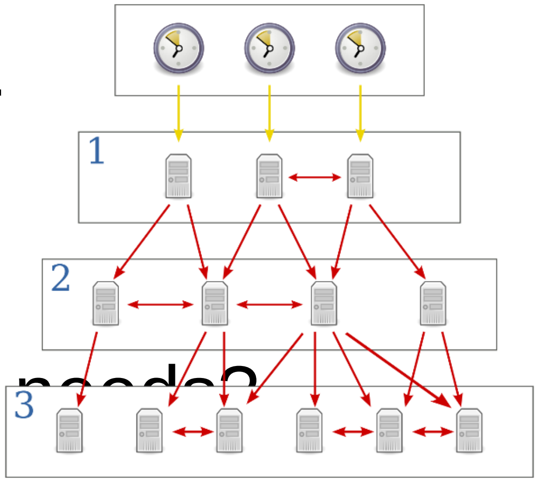
Time and frequency dissemination

- **Satellite techniques** (GNSS, TWSTFT)
  - Based on RF (few GHz) frequencies
  - Time comparison: limit ~ few ns
  - Frequency comparison: limit $\sim 10^{-16}$, reached after days



Established, but reaching their limits

- **Networks-based techniques** (NTP, PTP) **to realize time transfer**
  - Limits (100 ms, 1µs)



https://en.wikipedia.org/wiki/Network_Time_Protocol

Do these techniques meet today and future's needs?

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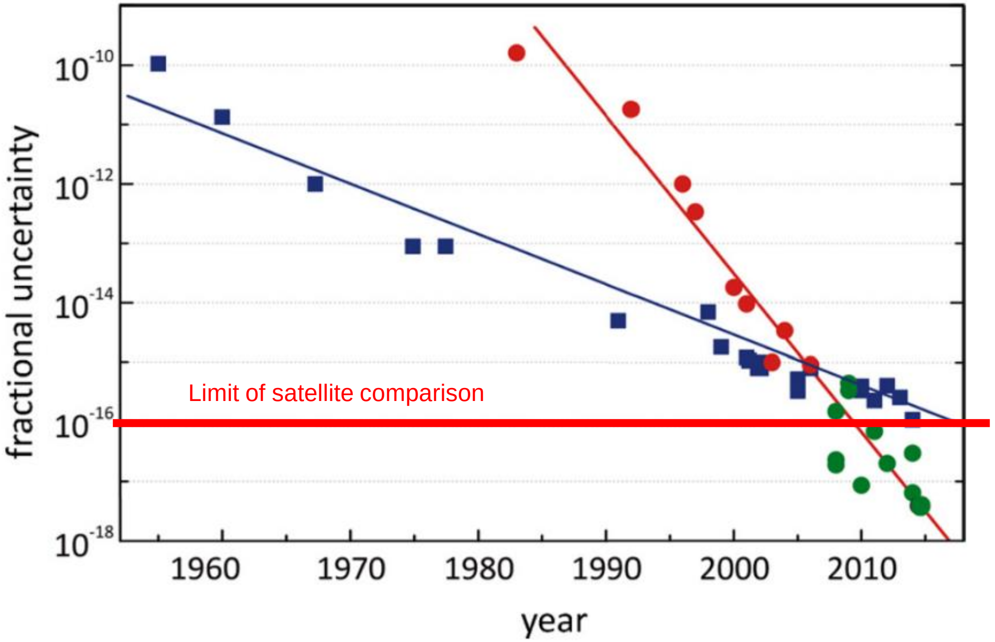
New requirements for the Time and Frequency domain



F. Riehle, Comptes Rendus Physique, Volume 16, Issue 5, June 2015, Pages 506-515
https://doi.org/10.1016/j.crhy.2015.03.012

■ Cs Primary Frequency Standard

● ● Optical clocks

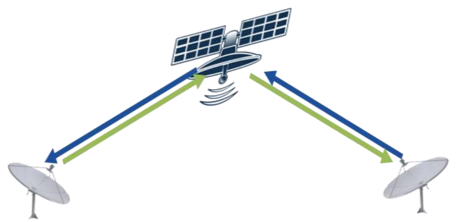
2 orders of magnitude better

- **New definition of the second: optical clocks**

⇒ New methods are required to compare this new generation of atomic clocks and to change the definition of the second

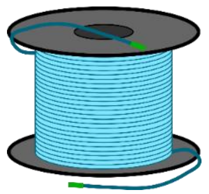
State of the art

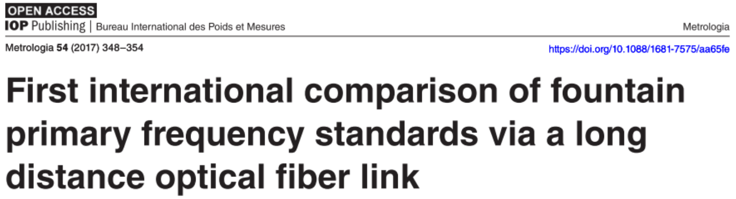
- **Satellite techniques** (GNSS, TWSTFT)
  - Based on RF (few GHz) frequencies
  - Time comparison: limit ~ few ns
  - Frequency comparison: limit $\sim 10^{-16}$, reached after days



With optical fiber networks, we can push those limits

- **Optical fiber networks**
  - Based on optical telecom (190 THz) frequencies
  - Limit $\sim 10^{-19}$, reached after hours
  - Limit ~1 ps level
  - Redundancy to satellite techniques
  - New method/protocol (White Rabbit (WR), ELSTAB, Phase cancellation)





OPEN ACCESS
IOP Publishing | Bureau International des Poids et Mesures Metrologia
Metrologia 54 (2017) 348–354 https://doi.org/10.1088/1681-7575/aa65fe

First international comparison of fountain primary frequency standards via a long distance optical fiber link

Time and frequency networks: Situation in Europe

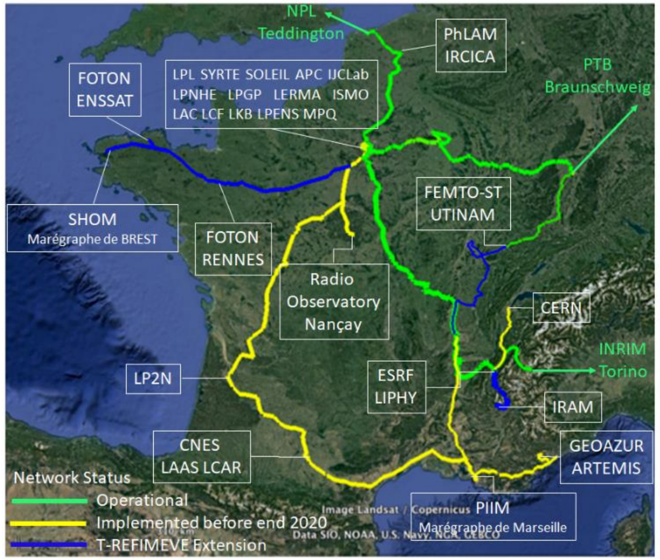
H. Schnatz: Towards a European fiber network
ESA ACES Workshop, Zürich, June 2017

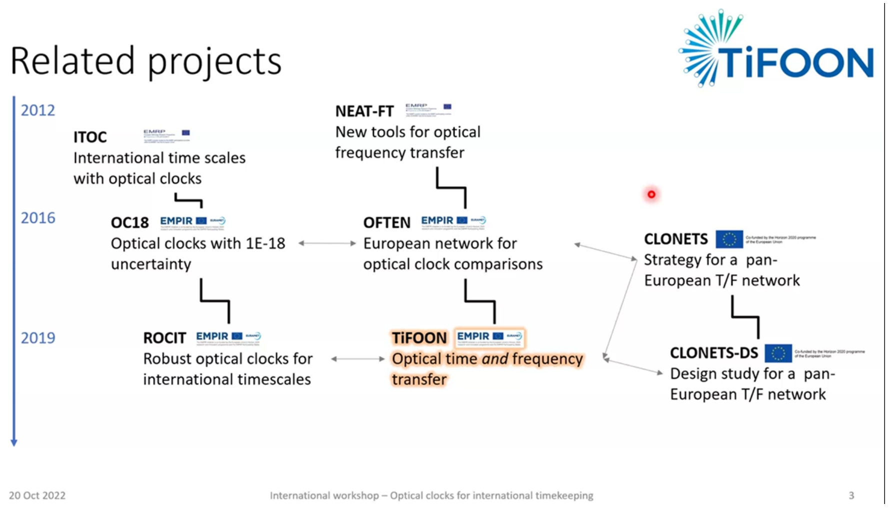
France: REFIMEVE

Réseau fibré métrologique à vocation européenne

Dissemination of metrological frequencies for:

- precision spectroscopy
- clock comparisons
- quantum technologies





Jochen Kronjäger, ROCIT Workshop October 2022

Italy: IQB
Italian Quantum Backbone

- Time and frequency over fiber
- Precision spectroscopy
- Twin-field QKD
- Seismology
- VLBI radio telescope synchronization

New requirements for the Time and Frequency domain

- **Geodesy**
  - 1 m accuracy means 10^{-16}
  - 1 cm means 10^{-18}
- **Astronomy**
  - Very Long Base Interferometry
- **Particle physics**
  - At CERN with White Rabbit
- **Spectroscopy**
  - Need better frequency reference
  - Traceability
- **Quantum communication**
  - Networks for quantum physics
  - Quantum time transfer
  - QKD

Geodetic determination of the gravitational potential difference for an optical lattice clock comparison in the Kanto region in Japan

Yoshiyuki Tanaka[1], Yosuke Aoki[2], and Ryuichi Nishiyama[2]
[1]University of Tokyo, Earth and Planetary Science, Tokyo, Japan (y-tanaka@eps.s.u-tokyo.ac.jp)
[2]University of Tokyo, Earthquake Research Institute, Tokyo, Japan

VLBI experiments with the dissemination of a common clock via coherent optical fiber link

R. Ricci*, *M. Negusini, F. Perini, C. Bortolotti, M. Roma, G. Maccaferri, M. Stagni, C. Clivati, A. Mura, F. Levi, D. Calonico, G. Bianco, L. Santamaria Amato, M. Siciliani de Cumis, A. Melis, G. Valente, C. Migoni and N.M. Iacolina*

Cerretto, G., Calonico, D., Cantoni, E., Levi, F., Mura, A., Sellone, M., Gnesi, I., "Timing Requirements Analysis for Particle Physics and Astrophysics: A Metrological Point of View," *Proceedings of the 52nd Annual Precise Time and Time Interval Systems and Applications Meeting*, January 2021, pp. 376-405.
https://doi.org/10.33012/2021.17794

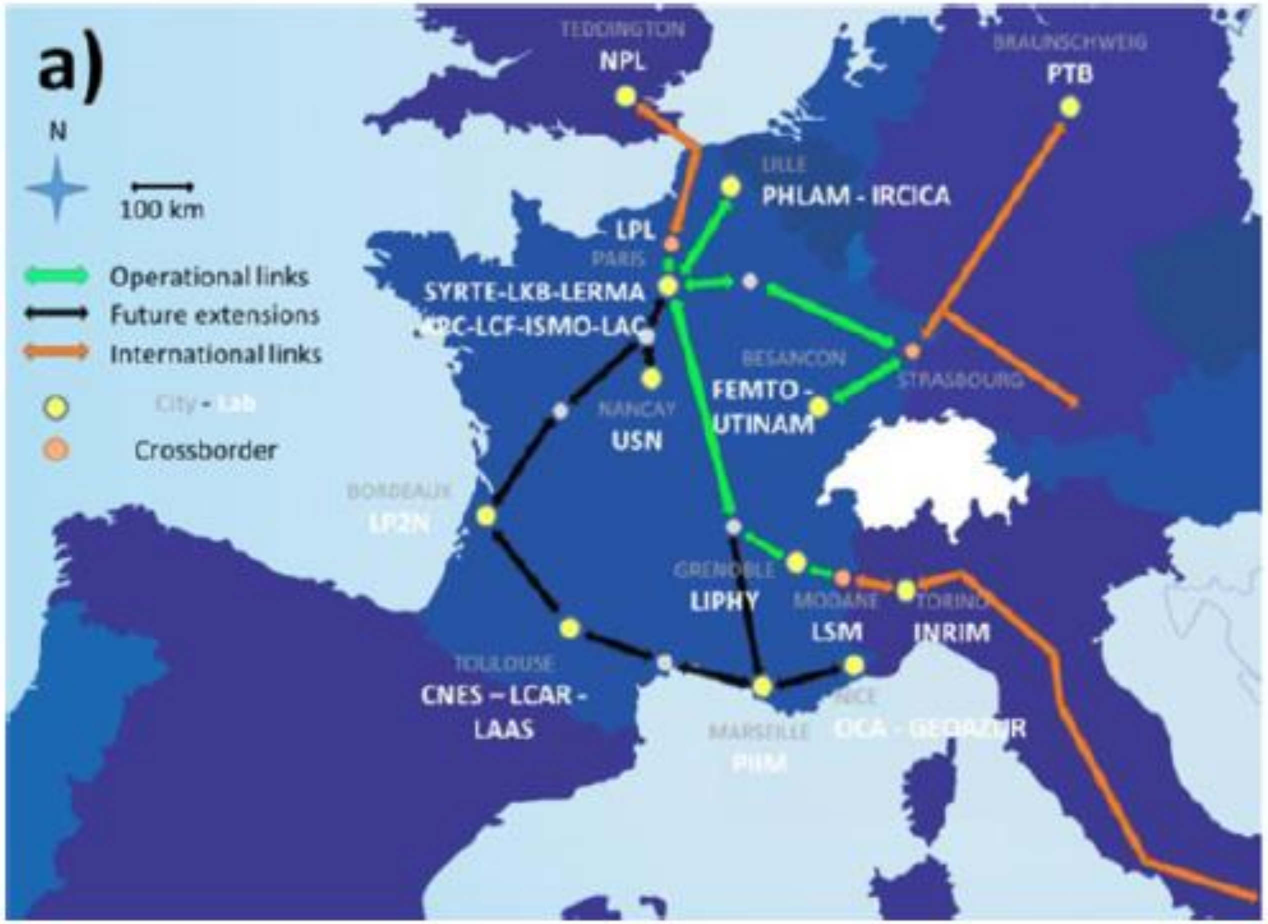
SI-traceable frequency dissemination at 1572.06 nm in a stabilized fiber network with ring topology

Dominik Husmann, Laurent-Guy Bernier, Mathieu Bertrand, Davide Calonico, Konstantinos Chaloulos, Gloria Clausen, Cecilia Clivati, Jérôme Faist, Ernst Heiri, Urs Hollenstein, Anatoly Johnson, Fabian Mauchle, Ziv Meir, Frédéric Merkt, Alberto Mura, Giacomo Scalari, Simon Scheidegger, Hansjürg Schmutz, Mudit Sinhal, Stefan Willitsch, and Jacques Morel

Fiber-optic two-way quantum time transfer with frequency-entangled pulses

Feiyan Hou, Runai Quan, Ruifang Dong, Xiao Xiang, Baihong Li, Tao Liu, Xiaoyan Yang, Hao Li, Lixing You, Zhen Wang, and Shougang Zhang
Phys. Rev. A **100**, 023849 – Published 29 August 2019

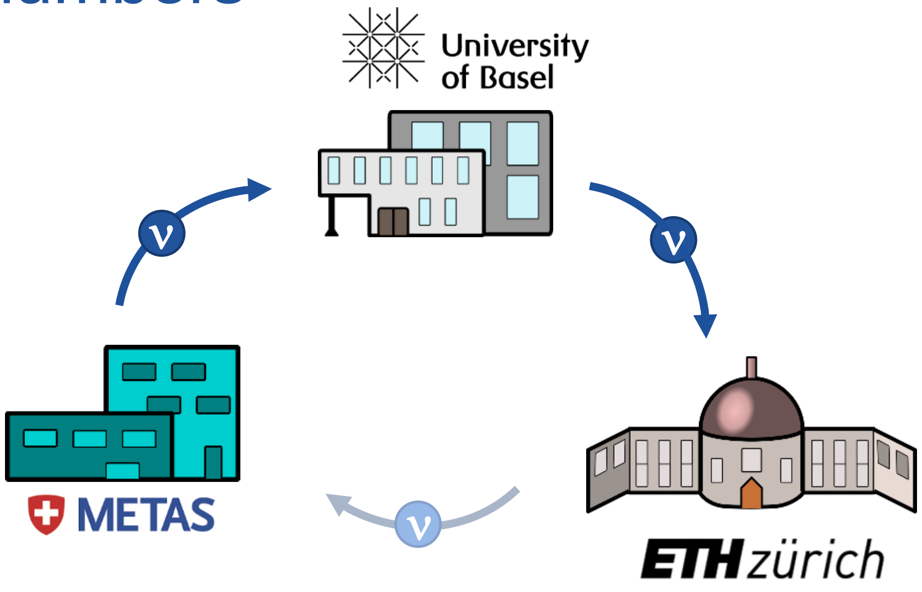
So what is happening in Switzerland?

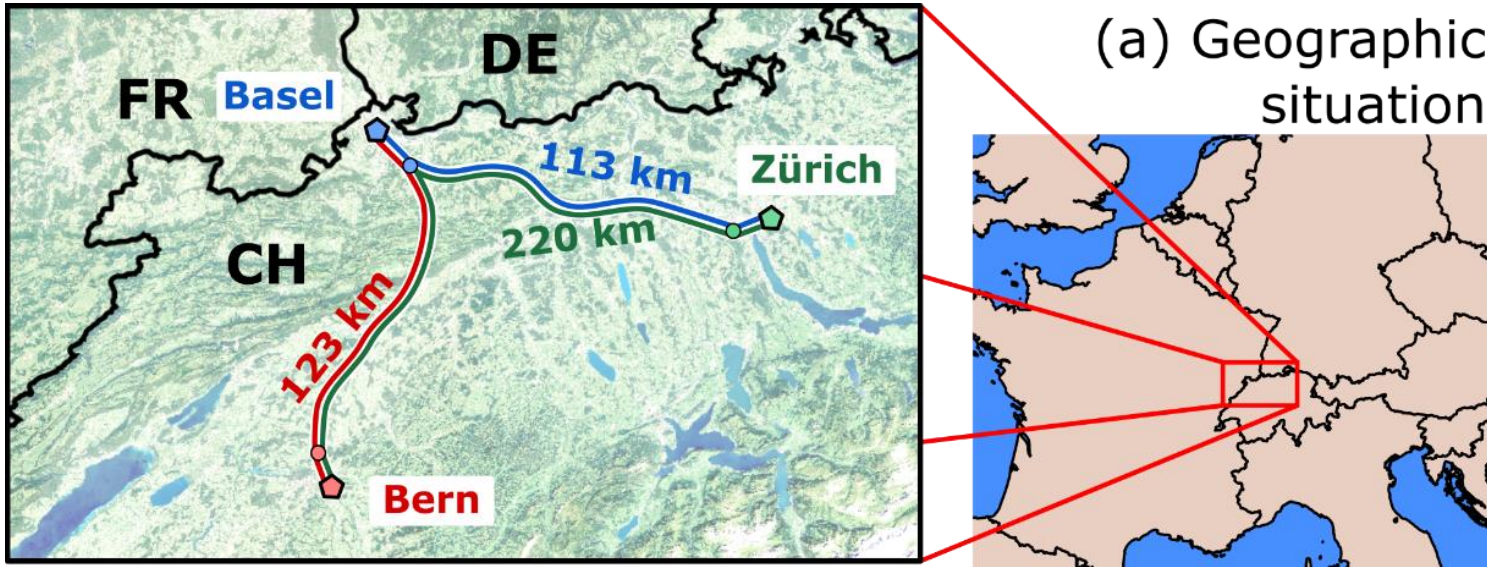


Cantin et al., New J. Phys. 23 (2021) 053027

Swiss frequency metrology network: numbers

Item	Value
Operating wavelength	1572.06 nm
ITU-T Channel	CH07
Total length	456 km
# Segments	3
# Bidir EDFA	2 / 2 / 3
# Regeneration stations	2 (Basel, Zurich)





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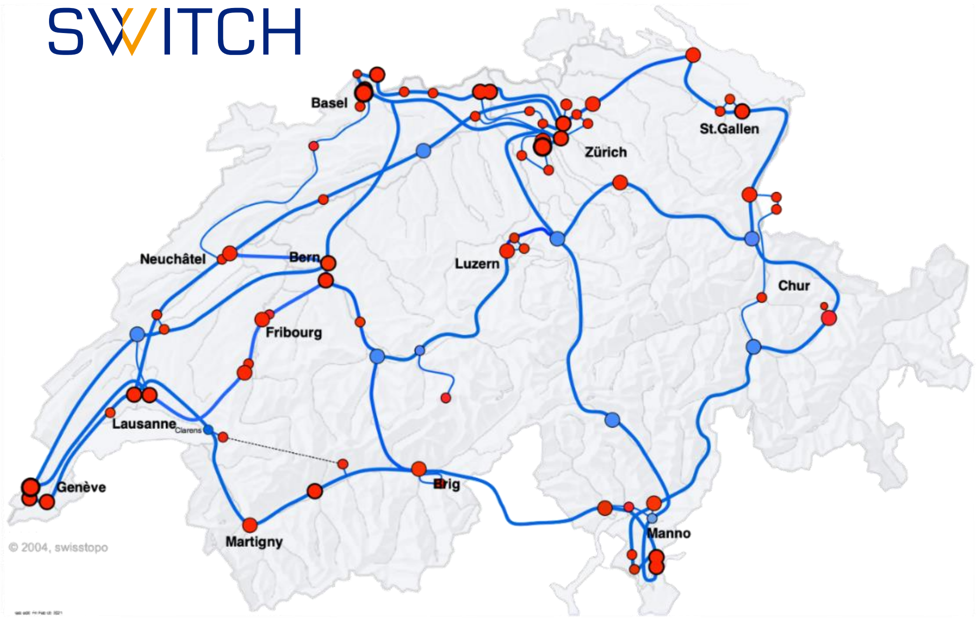
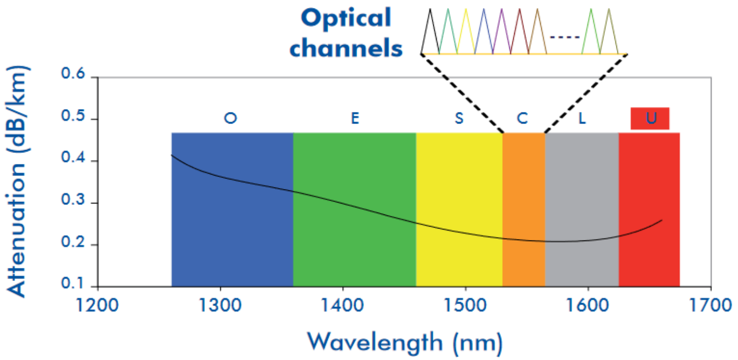
Network implementation: practical aspects

- Dedicated (dark) fibers are difficult to obtain
- Share fibers with existing data network infrastructure
- The canonical C-band is exhausted by telecom application
- L-band DWDM channel as versatile alternative, needs validation as it was never tested before

SWITCH fiber network backbone





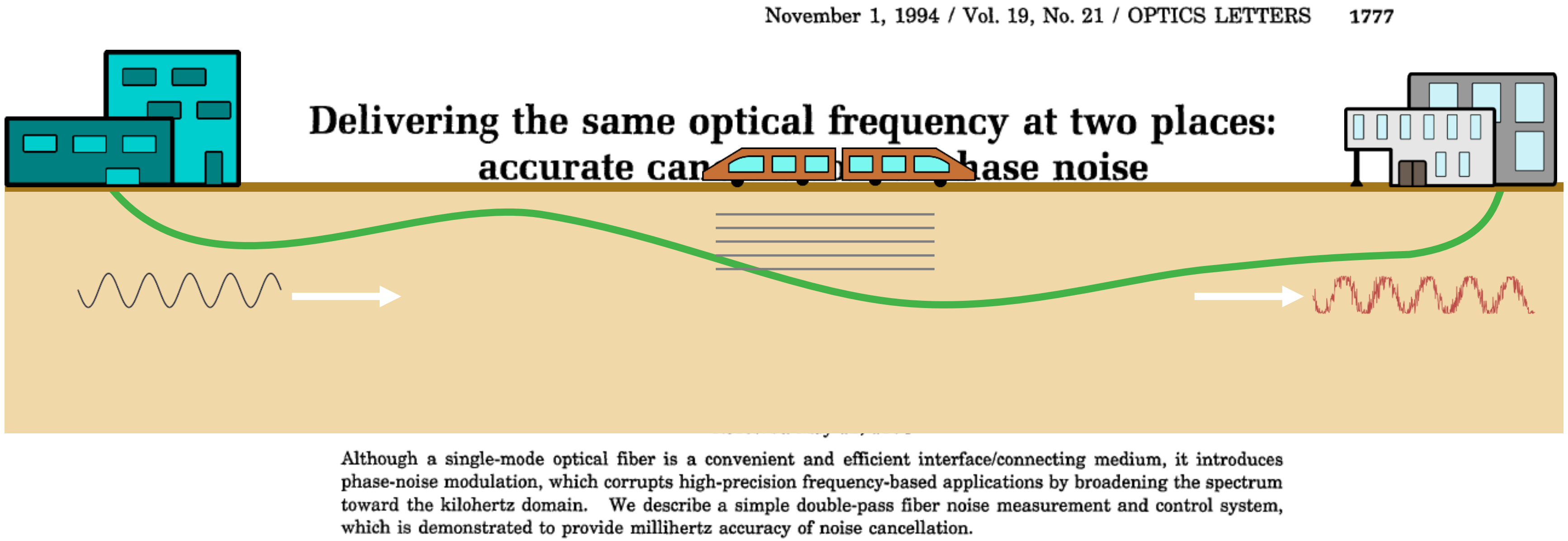
✓ **Fibers**

? **What wavelength?**

Telecom L-band: $\lambda = 1572.06$ nm

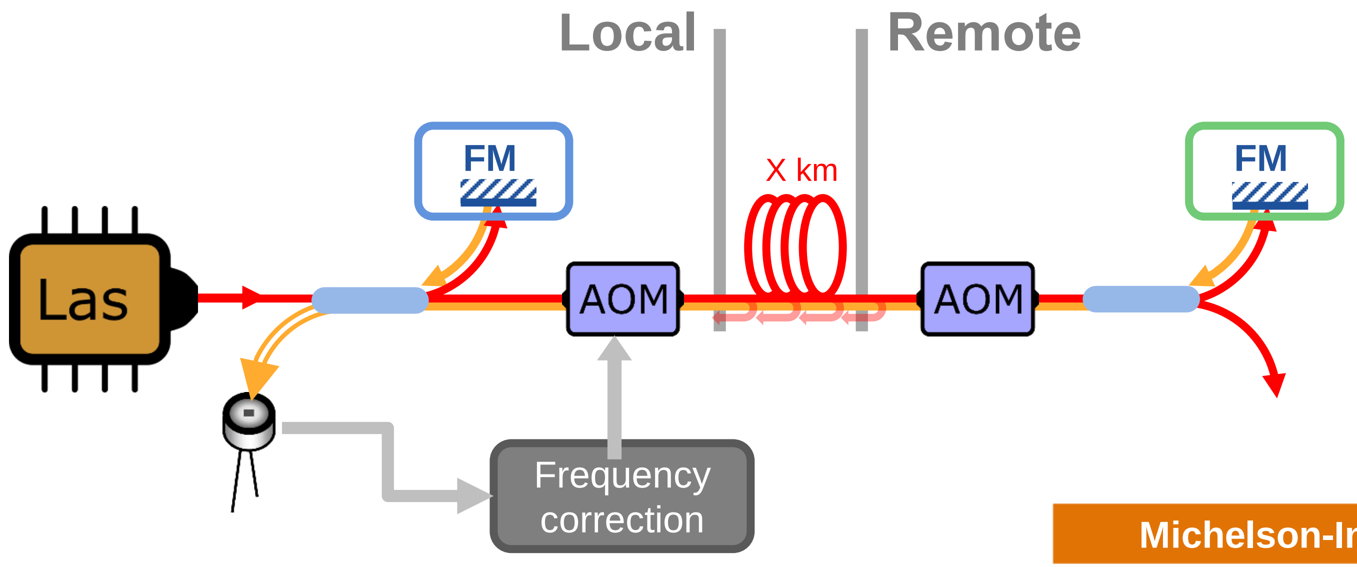
Environmental noise

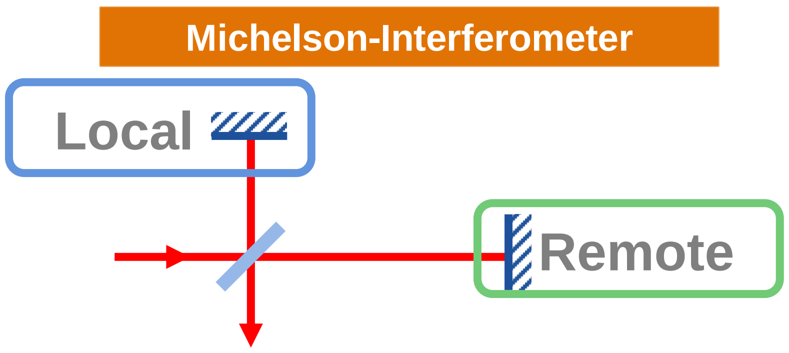
- Fibers act as microphones …
- … picking up noise from environment (temperature, acoustic vibrations)
- Causes variation of optical path length and thus phase
- Distorts the stable frequency at the recipient end
- $\rightarrow$ Requires phase noise read-out and compensation



Phase noise cancellation

Self-heterodyne detection of phase noise

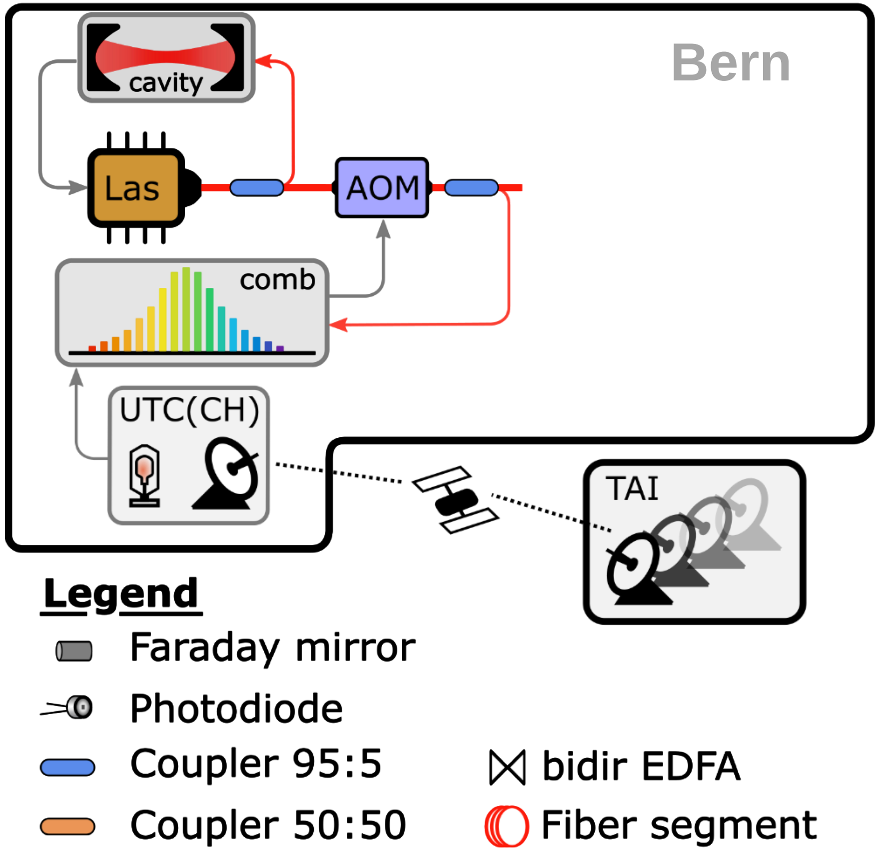




- Coherent detection of round-trip phase noise
- Frequency correction acting on acousto-optic modulator
- Cancellation of Doppler-induced phase noise
- Bandwidth limited by round-trip delay time (~ 500 Hz for 100 km)
- AOM for spectral marking at remote end

Laboratory side: implementation

☑ SI-traceable



Ultrastable SI-traceable laser

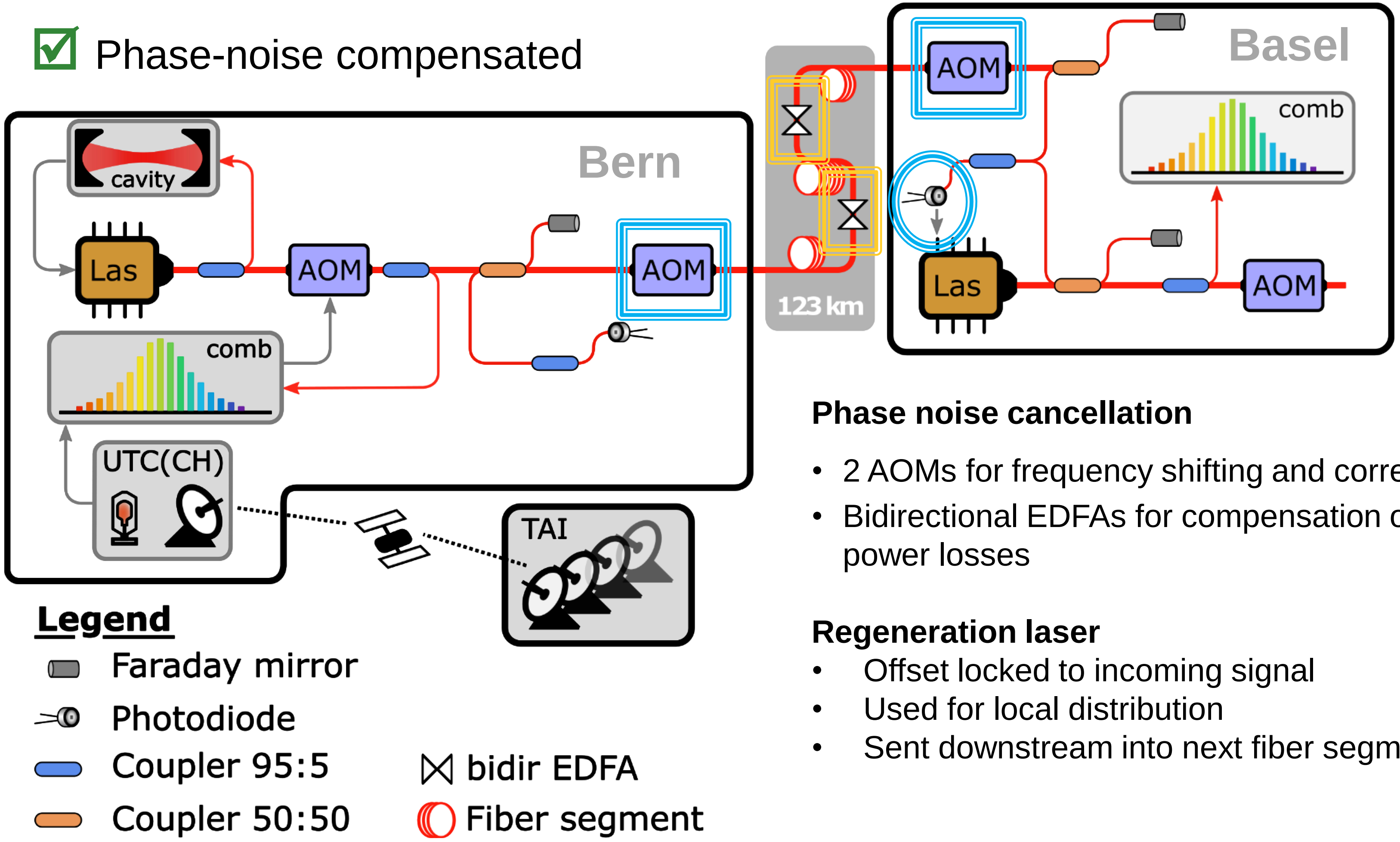
- Stabilized to cavity for Hz-level linewidth
  - ~0.1 Hz/s residual drift of cavity
- Stabilized to frequency comb for absolute reference
- Comb referenced to active maser
- Maser is part of UTC(CH)
- Maser is compared to TAI via UTC(CH)

>> SI-traceable

DH et al., Optics Express
Vol. 29, Issue 16, 24592-24605, 2021
10.1364/OE.427921

Laboratory side: implementation

- ☑ SI-traceable
- ☑ Phase-noise compensated



Phase noise cancellation

- 2 AOMs for frequency shifting and correcting
- Bidirectional EDFAs for compensation of power losses

Regeneration laser

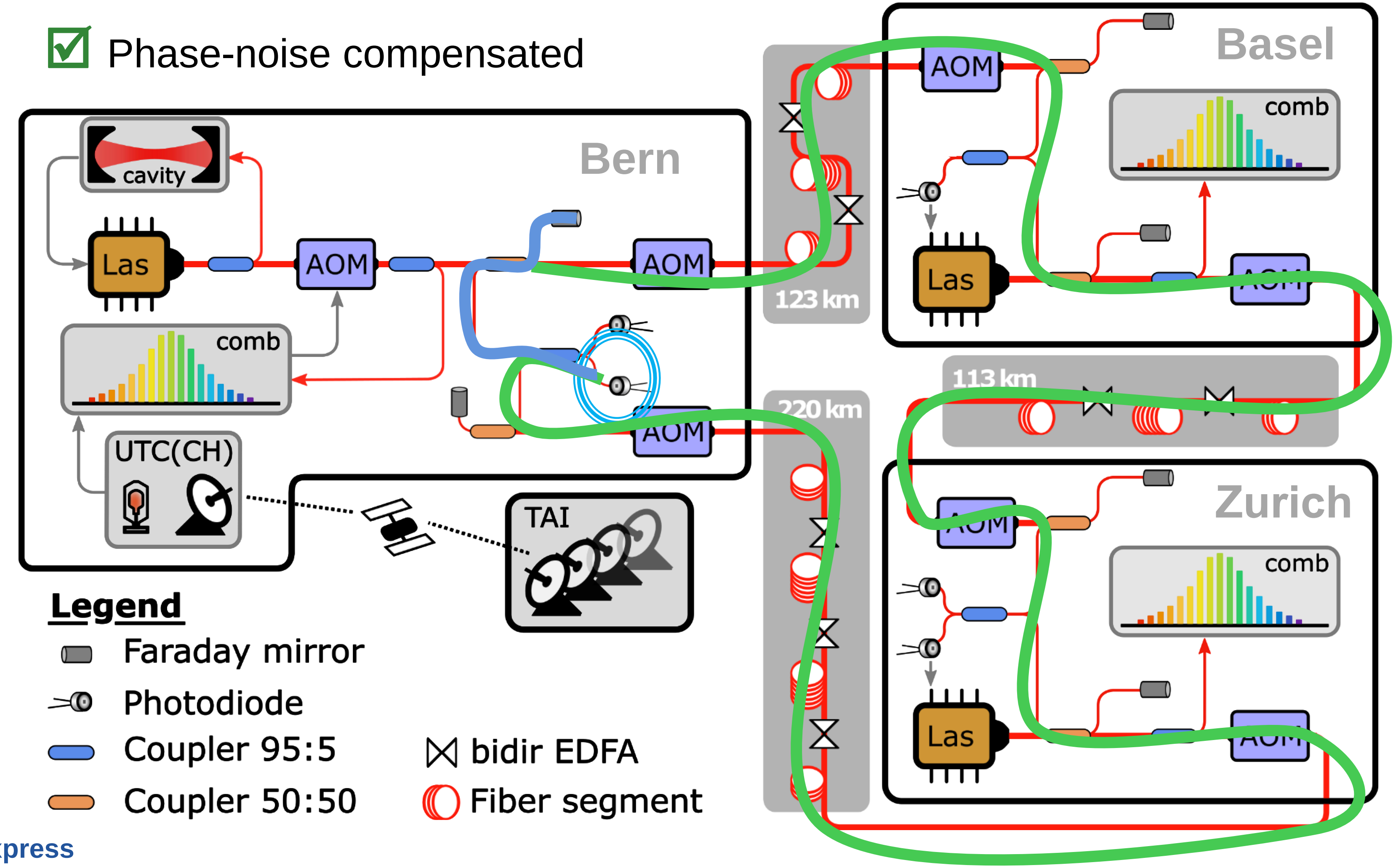
- Offset locked to incoming signal
- Used for local distribution
- Sent downstream into next fiber segment

DH et al., Optics Express
Vol. 29, Issue 16, 24592-24605, 2021
10.1364/OE.427921

Laboratory side: implementation

☑ SI-traceable ☑ Verified on round-trip signal

☑ Phase-noise compensated



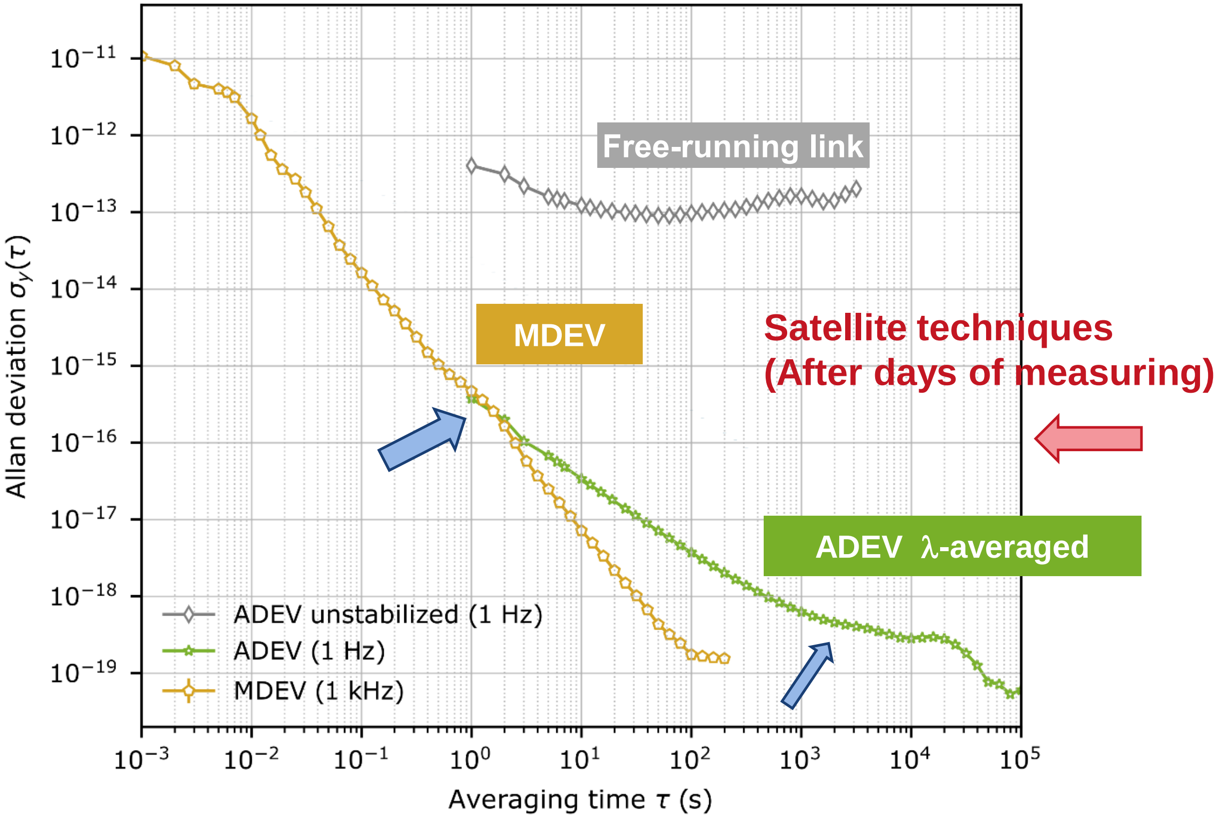
DH et al., Optics Express
Vol. 29, Issue 16, 24592-24605, 2021
10.1364/OE.427921

Long term stability: Allan deviation

- 4.7×10^{-16} at 1 s
- 3.8×10^{-19} at 2000 s

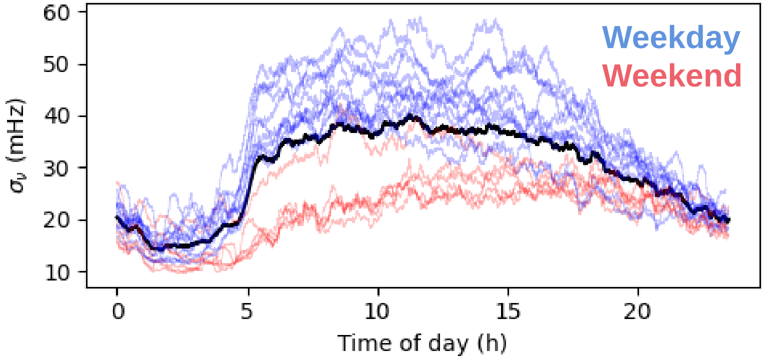
Validation that the fiber link will not inject significant noise to the metrological frequency

Fractional frequency uncertainty

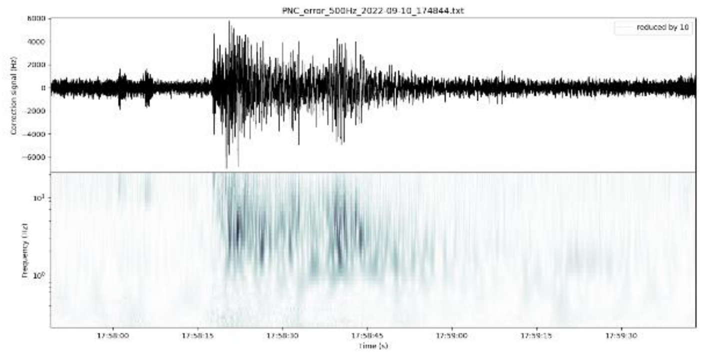


DH et al., Optics Express, Vol. 29, Issue 16, 24592-24605, 2021
10.1364/OE.427921

- **Anthropogenic effects**
  - Decreased residual frequency noise at night and on weekends

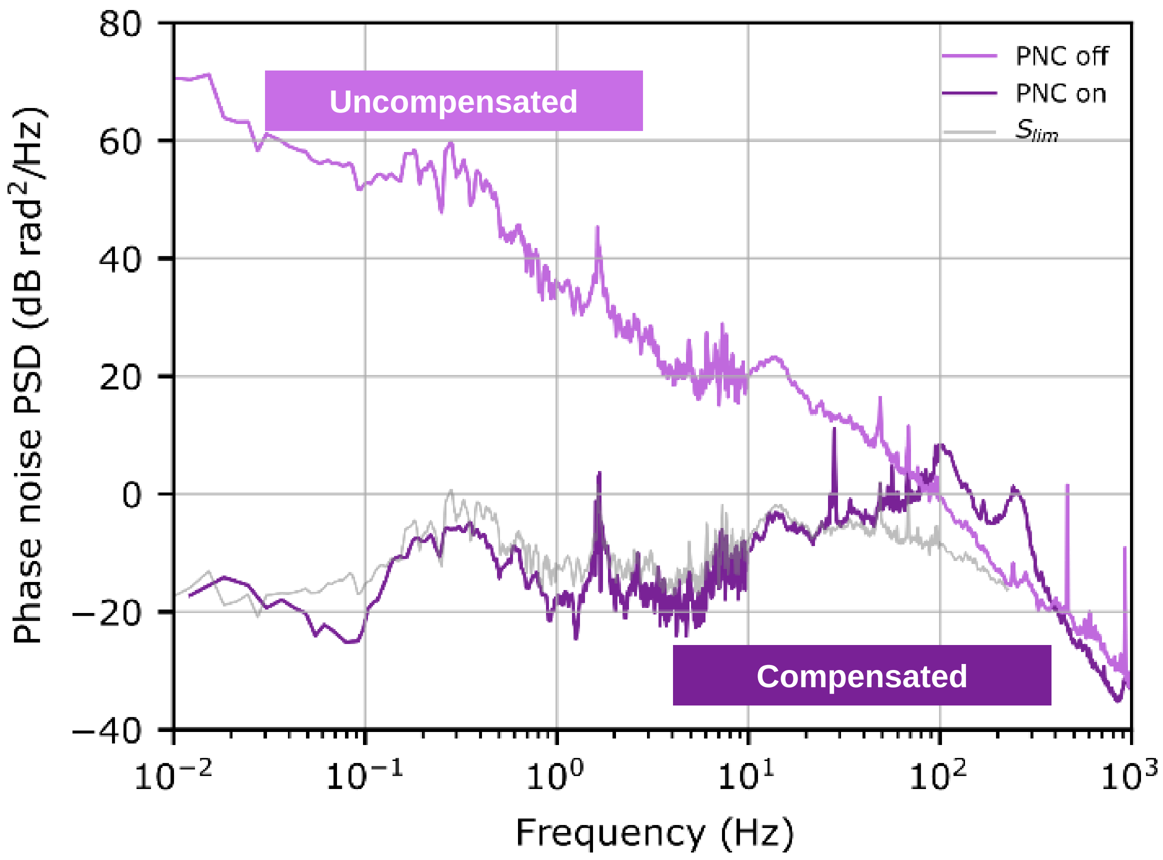


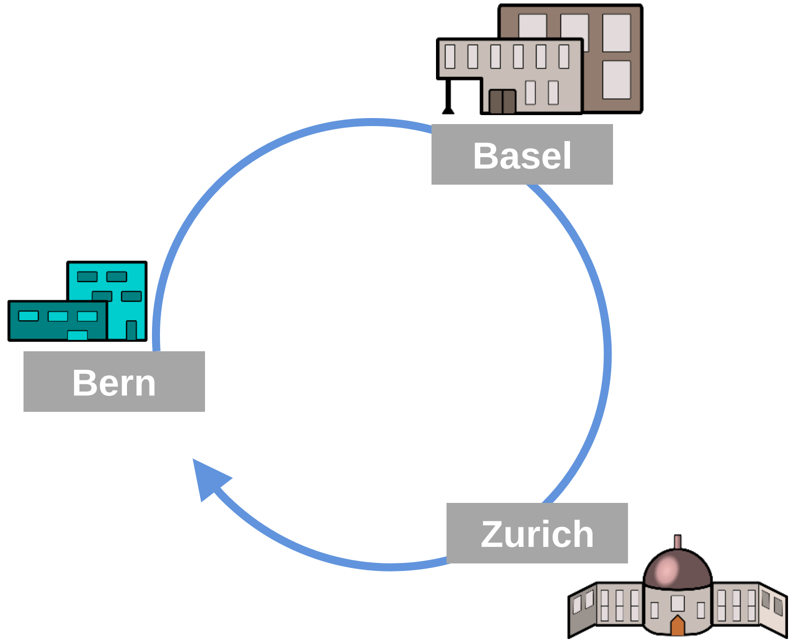
- **Seismic effects**
  - Sept 10, 2022: Earthquake Mag 4.7



Phase noise: end-to-end

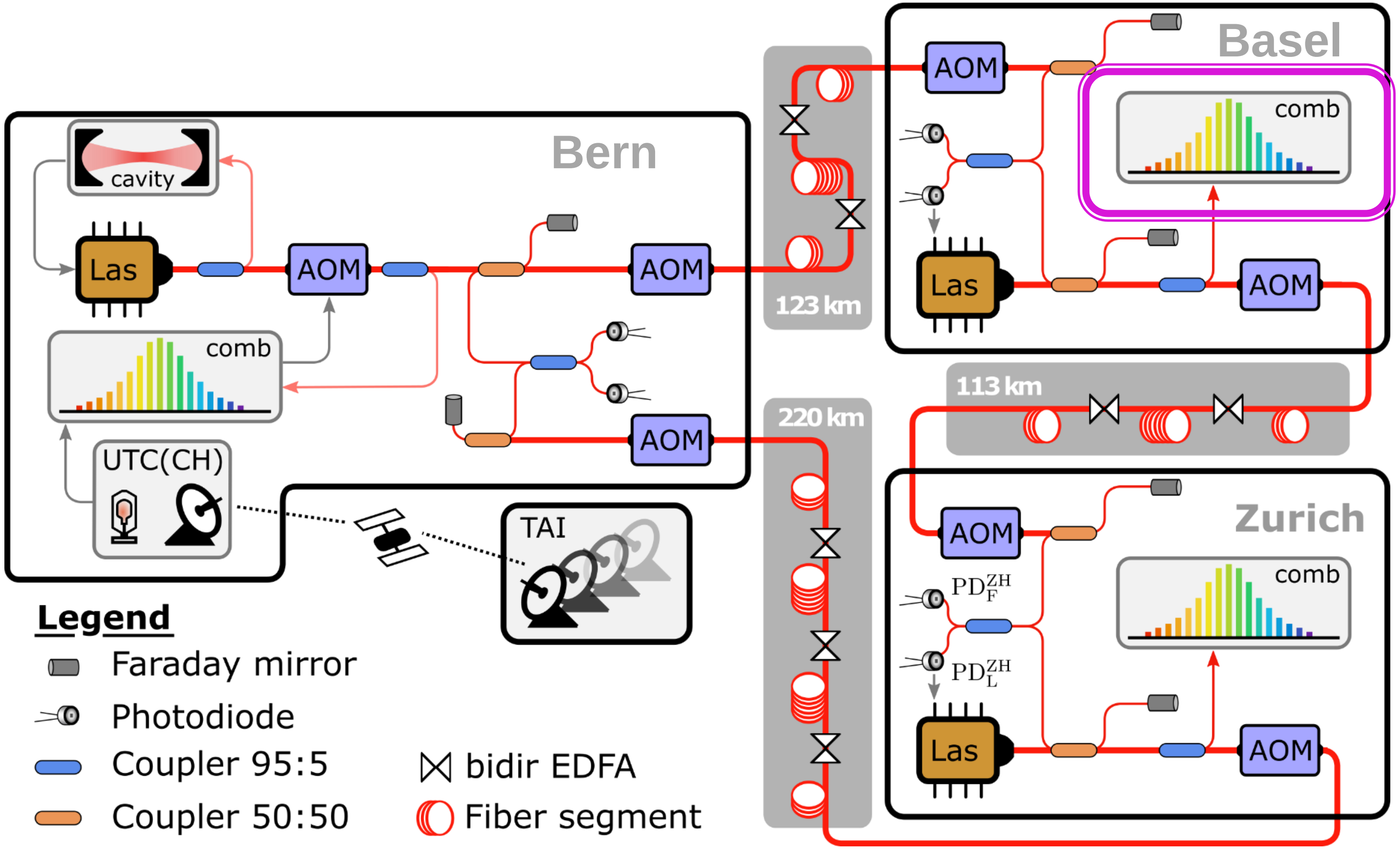
Theoretical limit: $S_{lim} \propto (f\tau)^2 \times S_{fiber}$





- Bandwidth ~ 100 Hz
- Noise suppression of around 50 dB at 1 Hz
- Limited by longest leg
- Theoretical limit: residual delay-unsuppressed noise

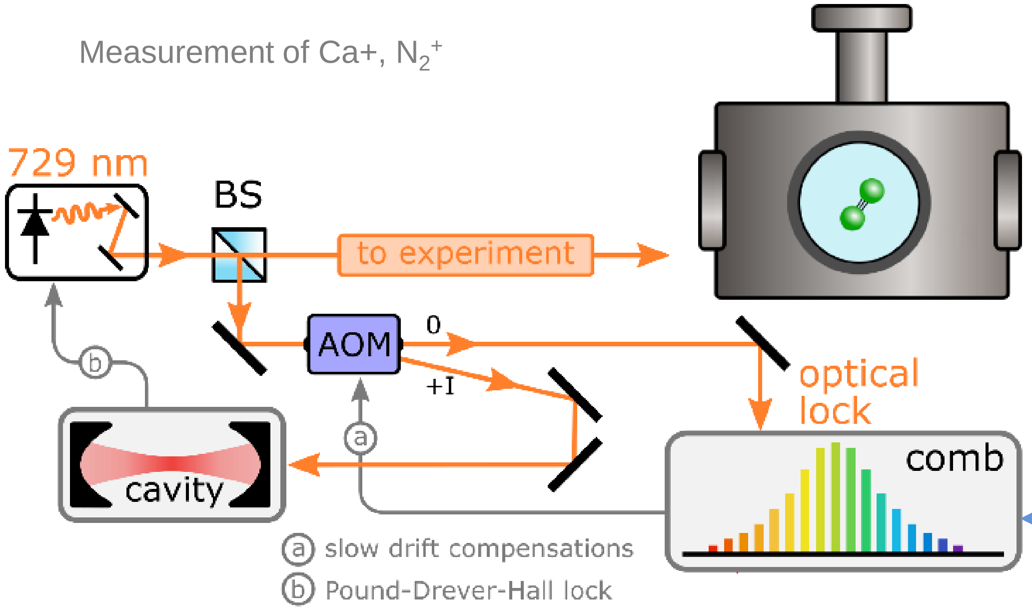
SI-traceable measurement of a laser in a remote lab



SI-traceable measurement of a laser in a remote lab

Basel (Prof. Willitsch)
Molecular spectroscopy lab

Measurement of Ca+, N_2^+

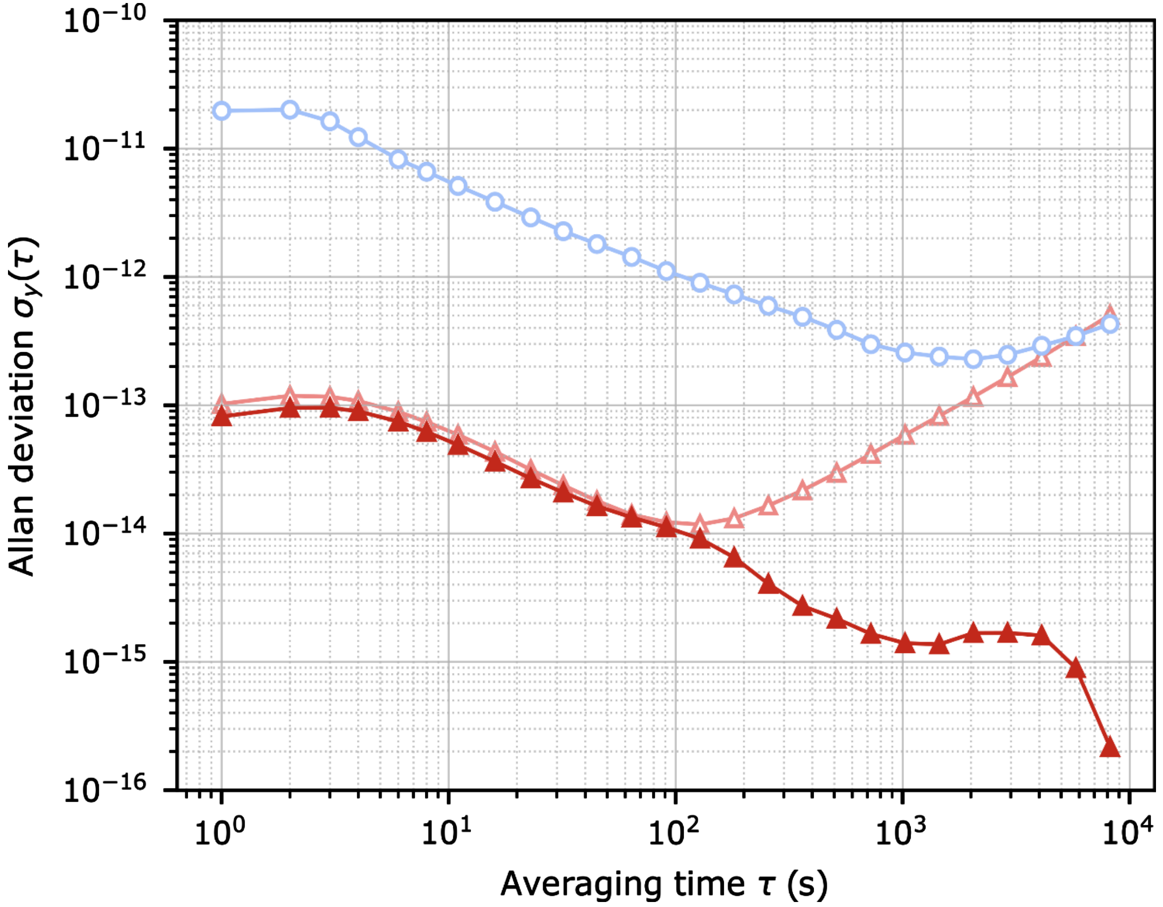


- **Spectroscopy laser (729 nm) locked to cavity**
- **Frequency comb locked to spectroscopy laser**
- **Frequency comb referenced by**
  - **a) GPSD rubidium clock**
  - **b) METAS frequency**

GPSD Rb clock

SI-traceable measurement of a laser in a remote lab

Measured frequency uncertainty of a spectroscopy laser in Basel



Referenced against GPSD Rb clock

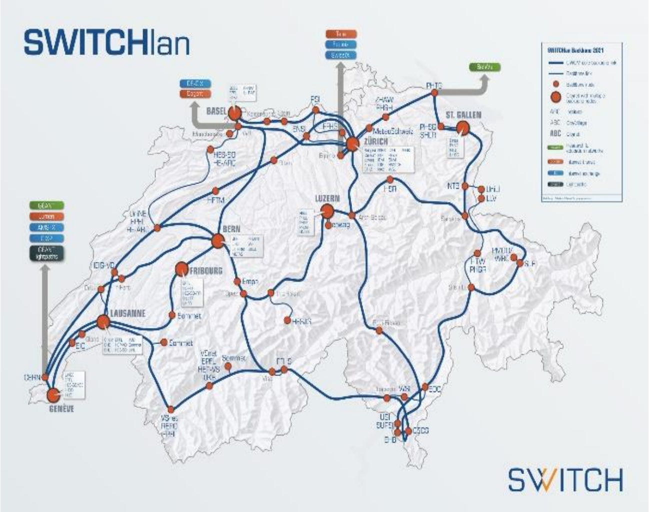
Referenced against METAS frequency

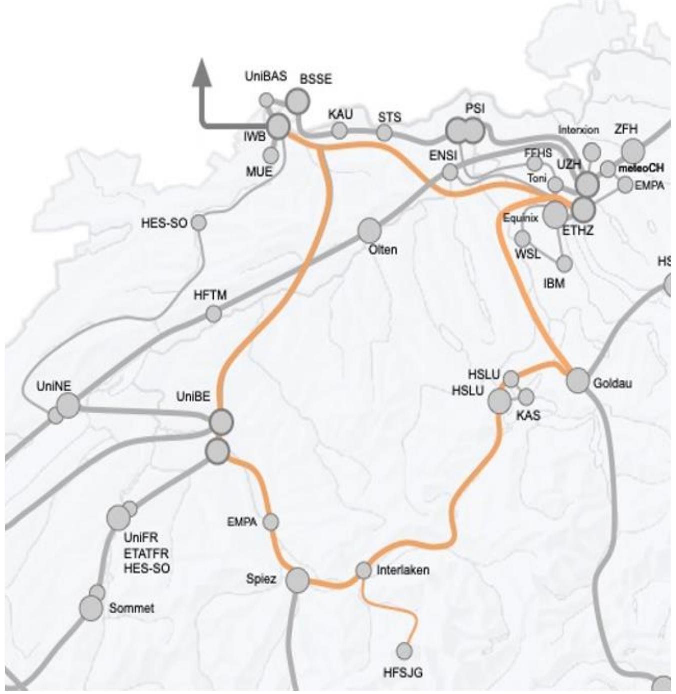
Improvement of measurement uncertainty by two orders of magnitude!

DH et al., Optics Express
Vol. 29, Issue 16, 24592-24605, 2021
10.1364/OE.427921

Dissemination of high accuracy timescales in Switzerland

- Demonstration of accurate, traceable and resilient time dissemination over fibre optic networks using **White Rabbit** technology.

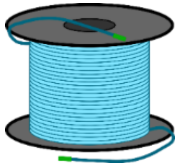




- Switch network: L-band
- Wavelength around 1590 nm

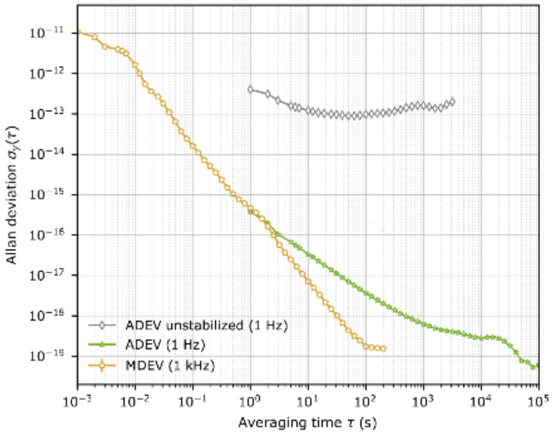
- Synchronicity: ~ 100 ps
- Resilience through dedicated topology and redundant technologies

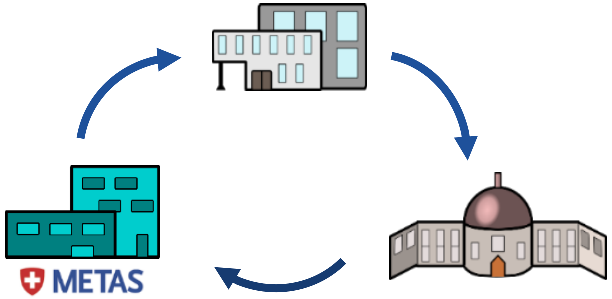
Conclusion

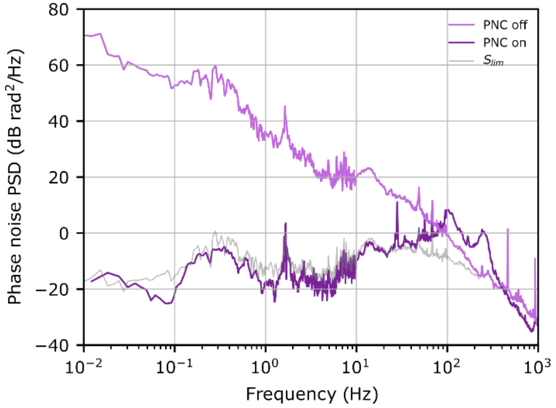


Time and Frequency dissemination with optical fiber networks pave the way to:

- Resilience to satellite T&F techniques,
- Dissemination of more accurate and more stable Time and Frequency signals for:
  - Fundamental researches (variation of fundamental constants),
  - Metrology (New definition of the second, new time scales),
  - Industries (finance, telecom, …),
- Technology is generally compatible with telecommunication network architecture
- National fiber infrastructure for time and frequency dissemination in sinergy with quantum communication networks is highly desirable.
  - Important step has been made in that direction, under coordination of Rob Thew







Schweizerische Eidgenossenschaft
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Confederazione Svizzera
Confederaziun svizra

Federal Institute of Metrology METAS

SWITCH METAS

Thank you very much for your attention!

The Swiss Metrology link team

METAS

Jacques Morel
Antoine Jallageas
Dominik Husmann

SWITCH

Daniel Bertolo
Ernst Heiri
Konstantinos Chaloulos
Fabian Mauchle
Felix Kugler

University of Basel

Stefan Willitsch
Ziv Meir
Mudit Sinhal
Anatoly Johnson
Aleksandr Shlykov

ETH zürich

Frédéric Merkt
Hansjürg Schmutz
Gloria Clausen
Simon Scheidegger
Urs Hollenstein

ETH zürich

Jérôme Faist
Giacomo Scalari
Mathieu Bertrand

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Davide Calonico
Cecilia Clivati
Alberto Mura

FNSNF SWISS NATIONAL SCIENCE FOUNDATION

TiFOON