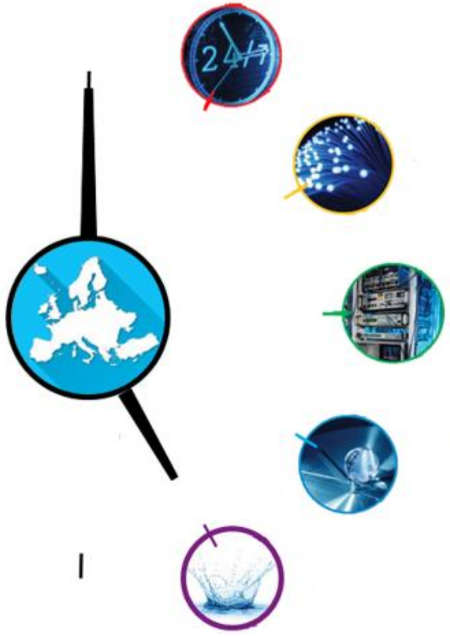
Robust optical clocks for international timescales (ROCIT)

Helen Margolis, NPL

9th Symposium on Frequency Standards and Metrology, Kingscliff, New South Wales, Australia, 18th October 2023

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States



The ROCIT consortium

M9 consortium meeting
at INRIM, February 2020

Aim:

To enable European optical clocks to contribute regularly to International Atomic Time (TAI)

– a significant milestone on the path to the **redefinition of the second**

8 internal partners:
- NPL (UK)
- CMI (Czech Republic)
- GUM (Poland)
- INRIM (Italy)
- LNE (France)
- OBSPARIS (France)
- PTB (Germany)
- VTT (Finland)

6 external partners:
- BGU (Israel)
- CNRS (France)
- LUH (Germany)
- POLITO (Italy)
- SRC PAS (Poland)
- UMK (Poland)

2 Researcher Mobility Grants:
- ROA (Spain) → NPL
- ROA (Spain) → OBSPARIS

2 collaborators:
- AIST/NMIJ (Japan)
- TiFOON consortium (Europe)

Roadmap for the redefinition of the second

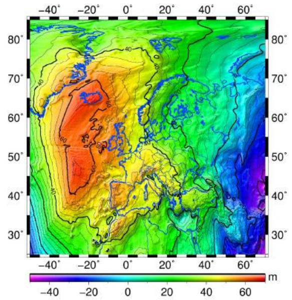
CCTF

Mandatory criteria

Must be achieved before changing the definition

Achieved

- **Validation that optical frequency standards (OFS) are at a level 100 × better than Cs**
- **Continuity with the definition based on Cs**
- **Regular contributions of OFS to TAI as secondary representations of the second**
- Availability of sustainable techniques for OFS comparisons
- **Knowledge of the local geopotential with a sufficient uncertainty level** ITOC
- Definition allowing future more accurate realisations
- Access to the realisation of the new definition



Accuracy ~ 0.2 m^2s^{-2}
or
2×10^{-18} clock accuracy

Ancillary conditions

Status should be advanced, even if not completely achieved at the time of redefinition

In progress

- **High reliability of optical frequency standards**
- High reliability of ultra high stability T/F links
- Continuous improvement of the realization and time scales after redefinition
- **Regular contributions of optical clocks to UTC(k)**
- Availability of commercial optical clocks
- Improved quality of the dissemination towards users

arXiv:2307.14141v1

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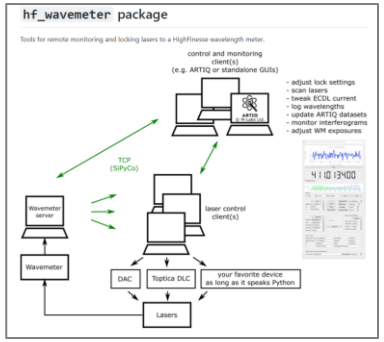
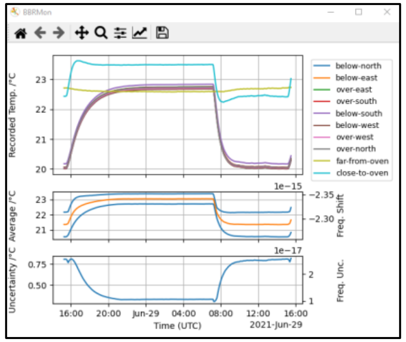
Robust optical clocks

NPL National Physical Laboratory

Leibniz Universität Hannover



INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA



Automatic control systems (some open source)

- Robust & autonomous frequency stabilisation of laser systems
- Automated optical alignment
- Remote monitoring and control
- Software to schedule and perform operational checks, e.g. minimisation of micromotion in trapped ion clocks, magic wavelength calibration in lattice clocks

Tools for on-the-fly correction of systematic frequency shifts

- With sufficiently low latency for UTC(*k*) steering
- Also useful for timely contributions to TAI and faster data analysis in international comparisons

SYRTE-Sr2, PTB-Yb1E3 and NPL-Sr1 all achieved **uptimes > 80%** over 2 weeks

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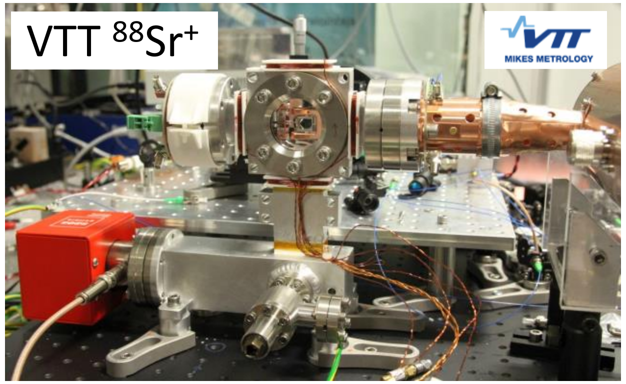
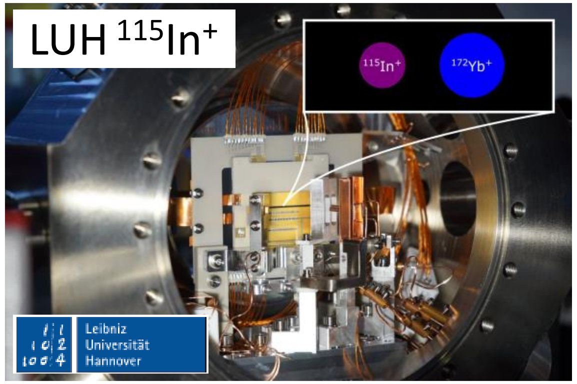
New optical clocks and a new fibre link

New optical clocks

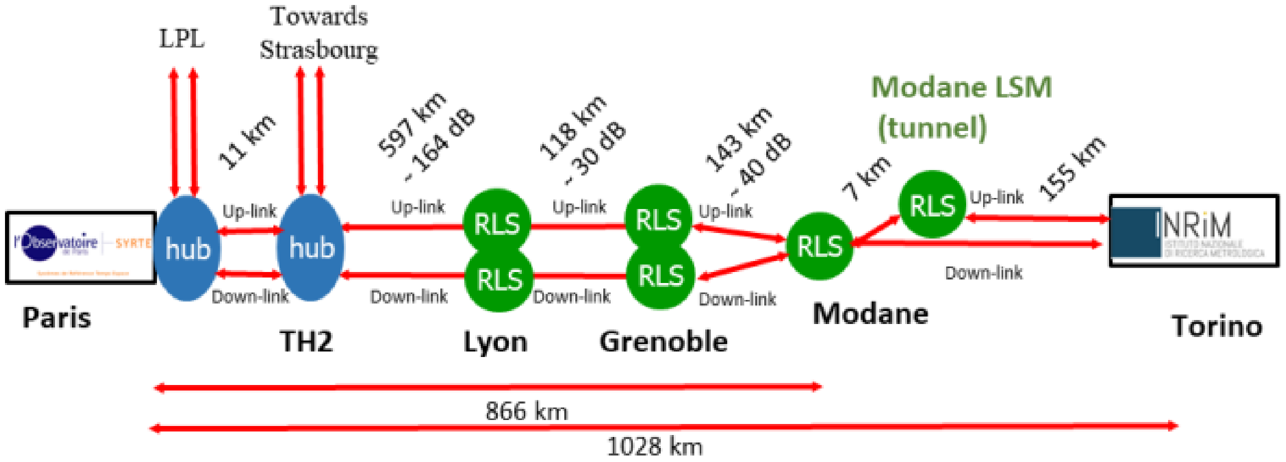
- $^{88}Sr^+$ at VTT and $^{115}In^+$ at LUH were completed and operated for the first time as part of the project
- ^{88}Sr at UMK joined international comparisons for the first time
- Data also shared from $^{88}Sr^+$ at PTB





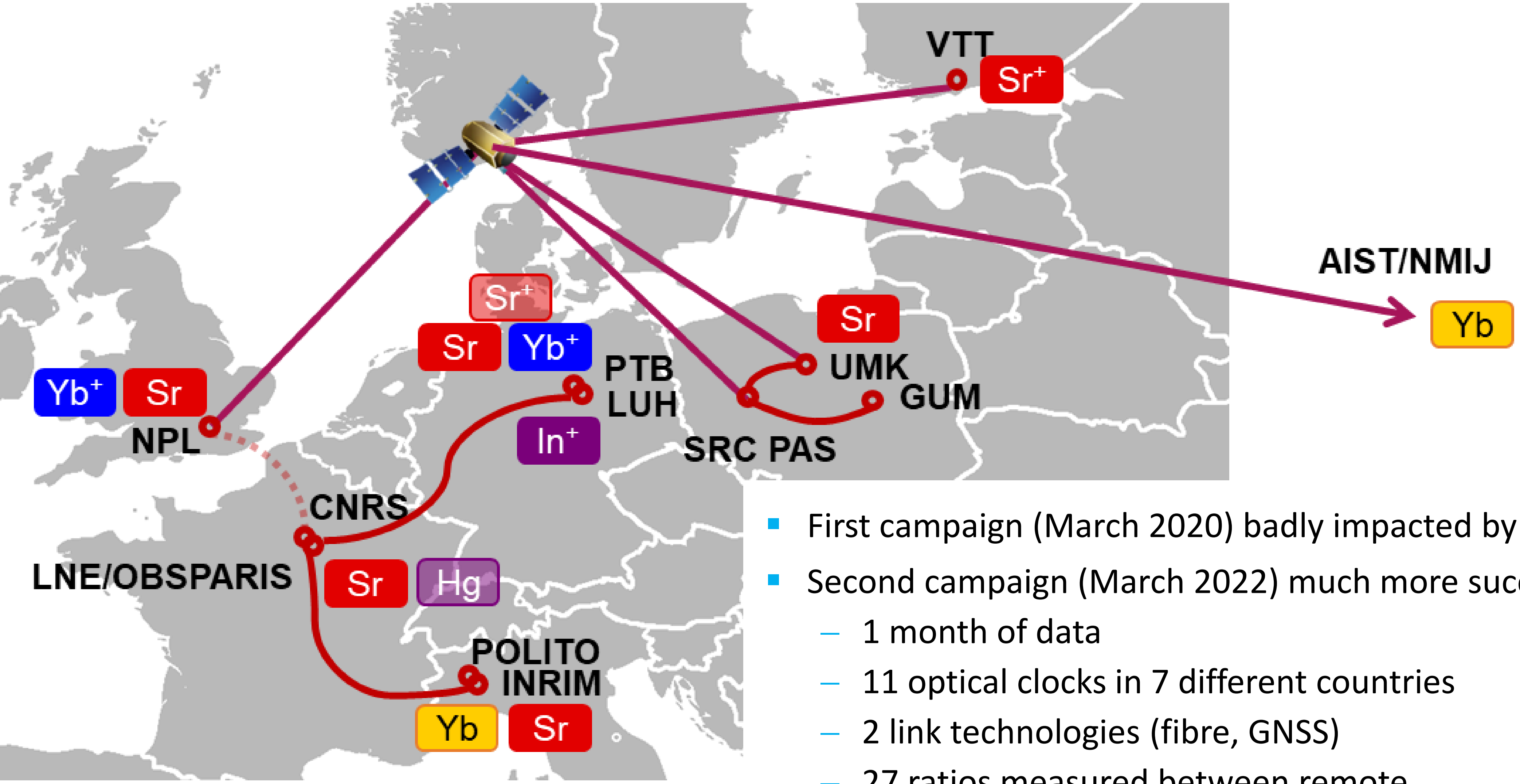
New optical fibre link established from Paris to Turin

- Robust performance with long-term fractional instability and accuracy below 10^{-18}
- High-accuracy optical clock comparisons can be performed between more European laboratories



C. Clivati *et al.*, Phys. Rev. Applied 18, 054009 (2022)

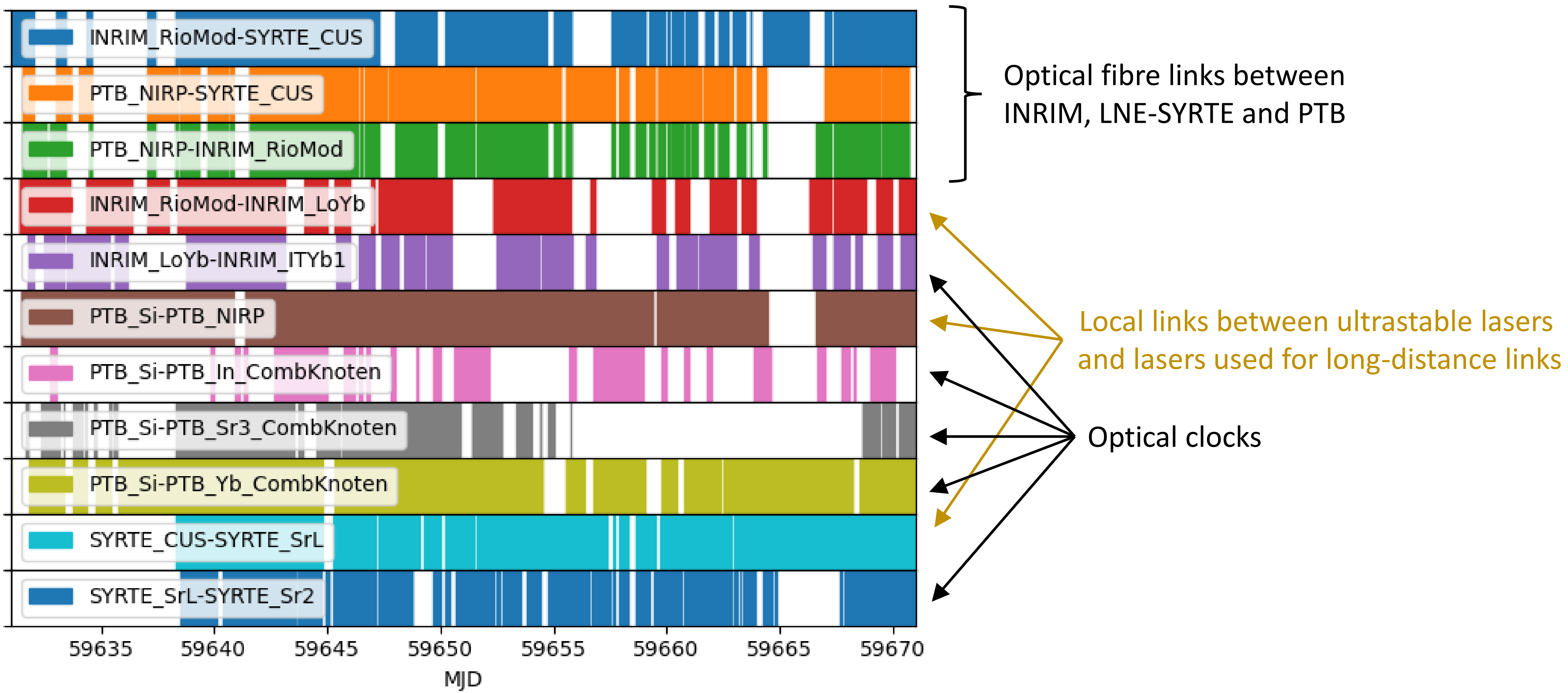
Coordinated comparison campaigns



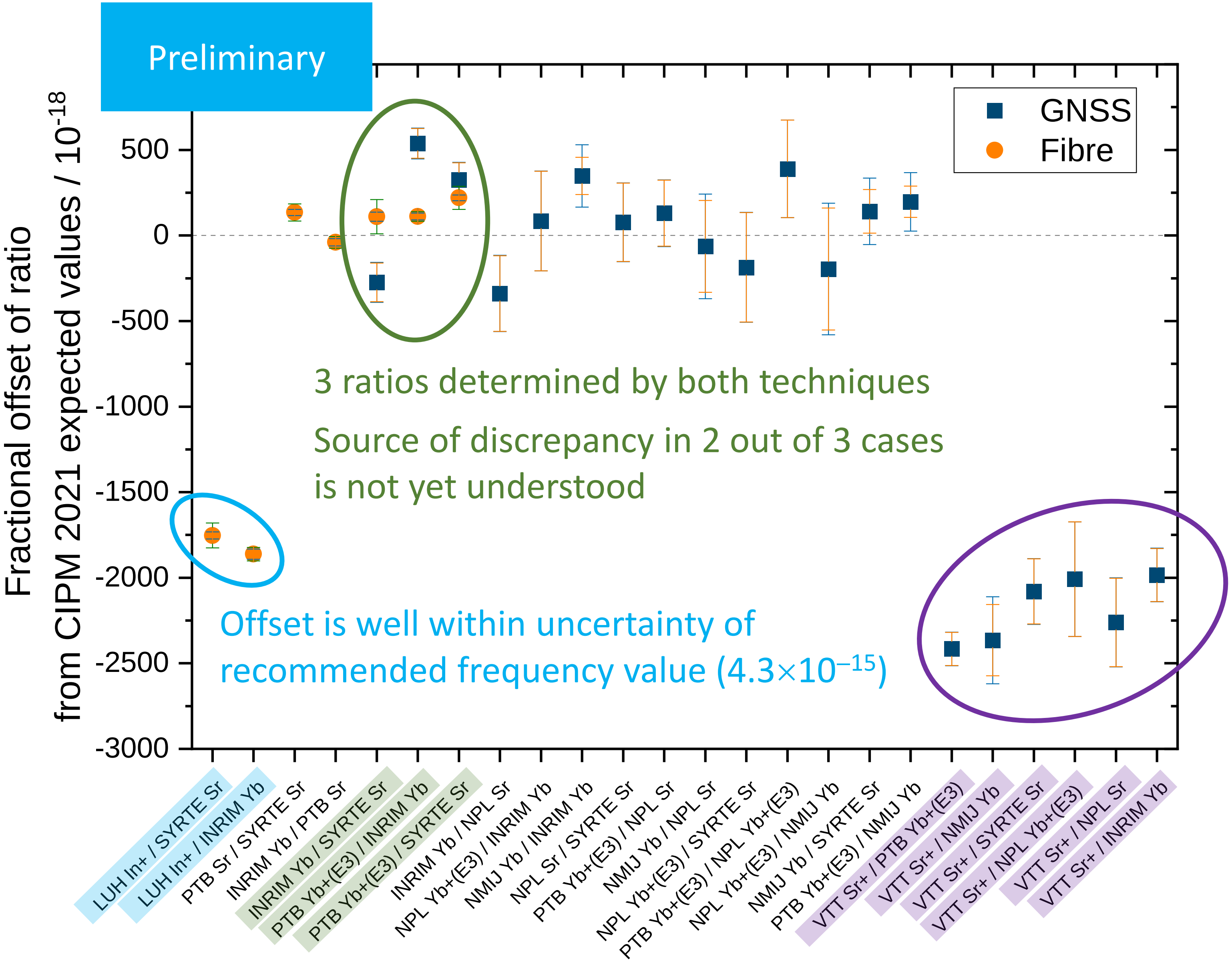
- First campaign (March 2020) badly impacted by COVID-19 pandemic
- Second campaign (March 2022) much more successful
  - 1 month of data
  - 11 optical clocks in 7 different countries
  - 2 link technologies (fibre, GNSS)
  - 27 ratios measured between remote optical clocks (20 via GNSS, 7 via fibre)

March 2022 comparison campaign

Uptimes for comparisons via fibre links:



Remote frequency ratio measurements



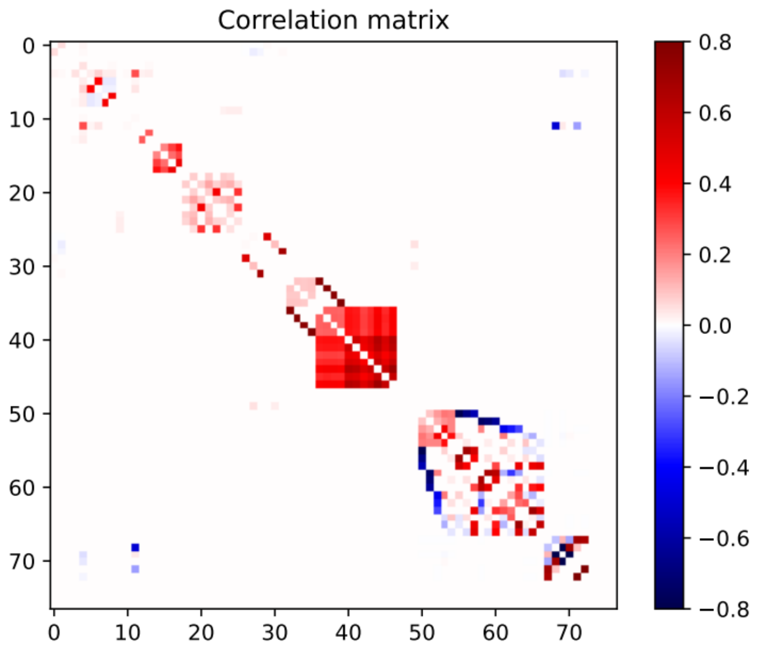
Offset is statistically significant

There is growing evidence that the problem lies with the recommended frequency value

Complete body of data

79 new frequency ratio measurements

- 28 ratios between remote optical clocks
- 51 local frequency ratios
  - 33 absolute frequencies (26 referenced to Cs, 7 against TAI)
  - 15 optical frequency ratios
  - 3 optical v ^{87}Rb frequency ratios



Measurements are correlated

- 79 ratios implies up to 3081 correlation coefficients (N.B. some will be zero)
- 313 non-zero correlation coefficients were calculated
  - 40 with magnitude ≥ 0.5
  - 135 with magnitude ≥ 0.1

Roadmap for the redefinition of the second

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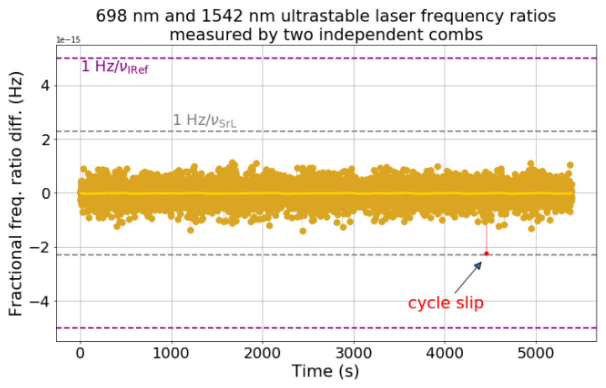
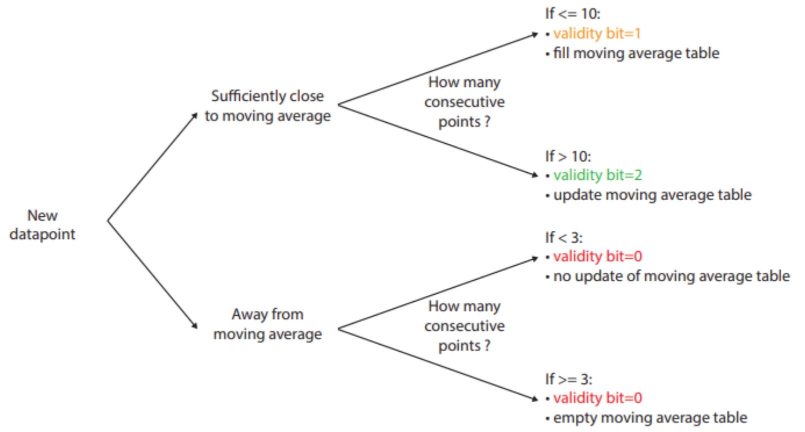
arXiv:2307.14141v1

Real-time validation of optical clock data

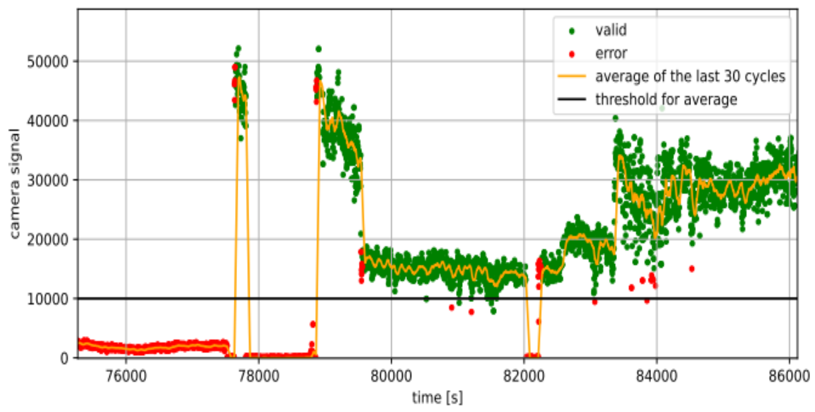
- Considered the whole metrological chain connecting optical clocks to the flywheel oscillators (H masers)
  - Local phase-compensated fibre links
  - Frequency combs used for optical-microwave comparison
  - Optical clocks
- Effectiveness of different approaches compared



Cycle slip detection through dual measurements



Algorithms for detecting sudden changes in frequency measurements

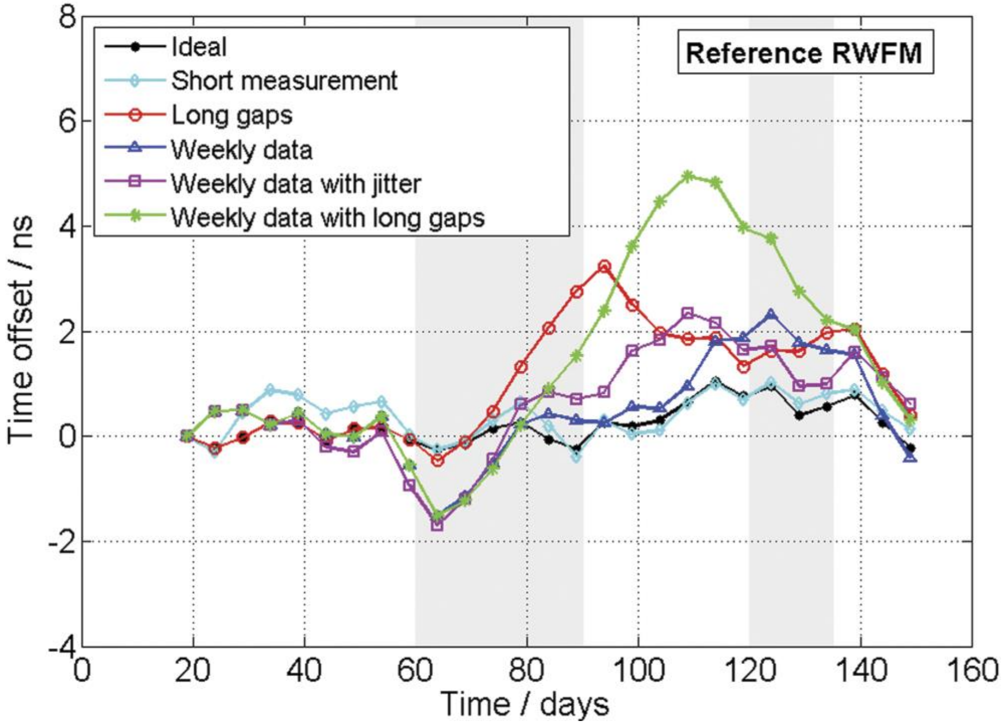


Validation of atom number in a Sr lattice clock

Steering algorithms

V. Formichella, L. Galleani, G. Signorile and I. Sesia, Metrologia 59, 015002 (2022)

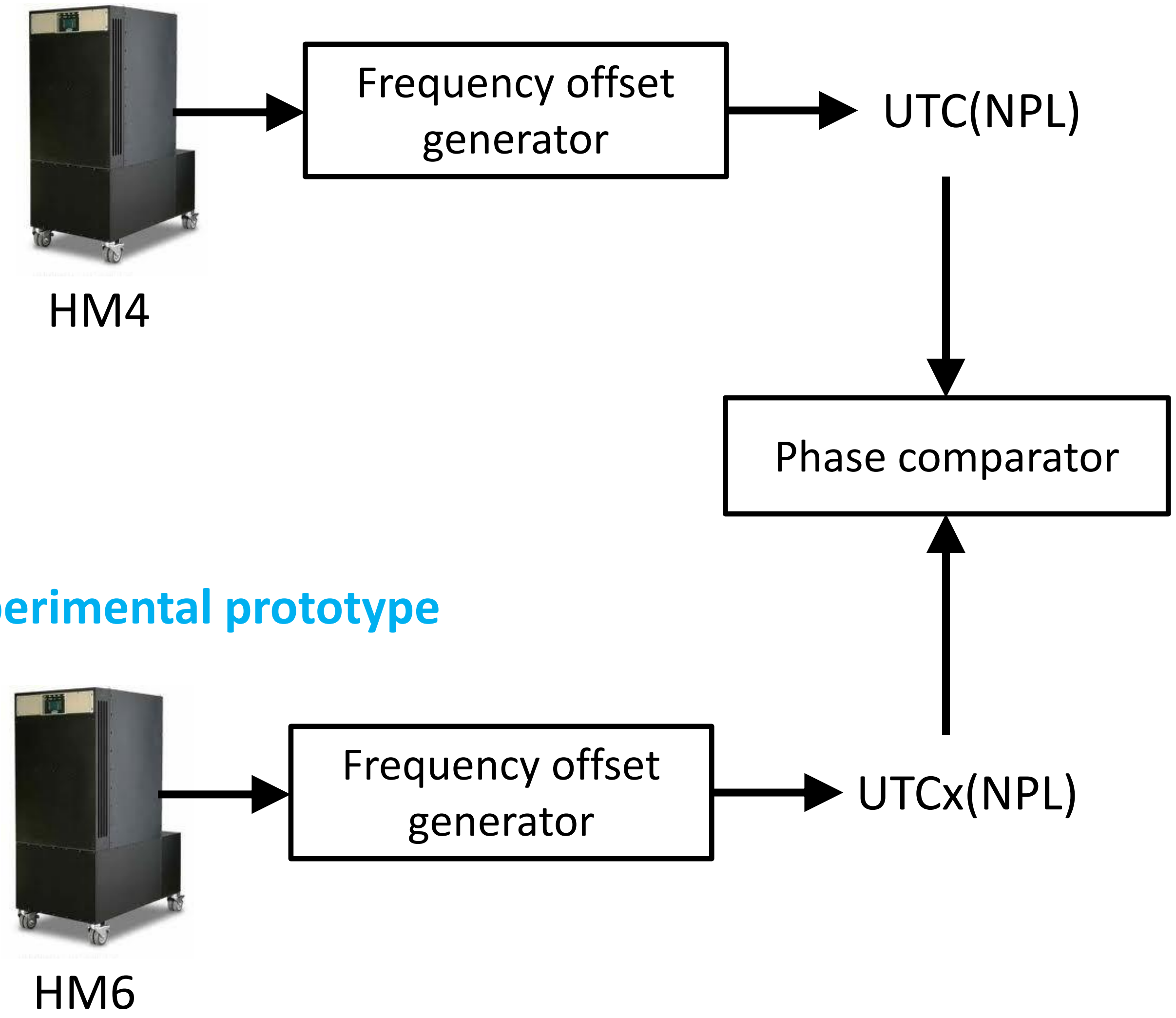
- Robust algorithm developed for generation of a time scale based on steering an Active Hydrogen Maser (AHM) with an optical clock
  - Can deal with low uptime and long periods of unavailability of the optical clock
  - Can take advantage of high uptime periods of the optical clock
- Tested on both simulated and experimental (historical) data



Optical steering of UTC(*k*) time scales

UK time scale

Experimental prototype



Frequency steers applied **3 times a week**, based on data from **NPL-CsF2** and **Circular T**

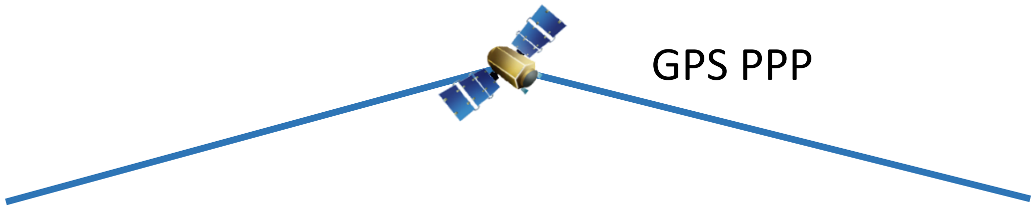
Frequency steers applied **hourly**, based on data from **Sr and Yb$^+$ optical clocks**

Prototype optically steered time scales

UTC(NPL)

v

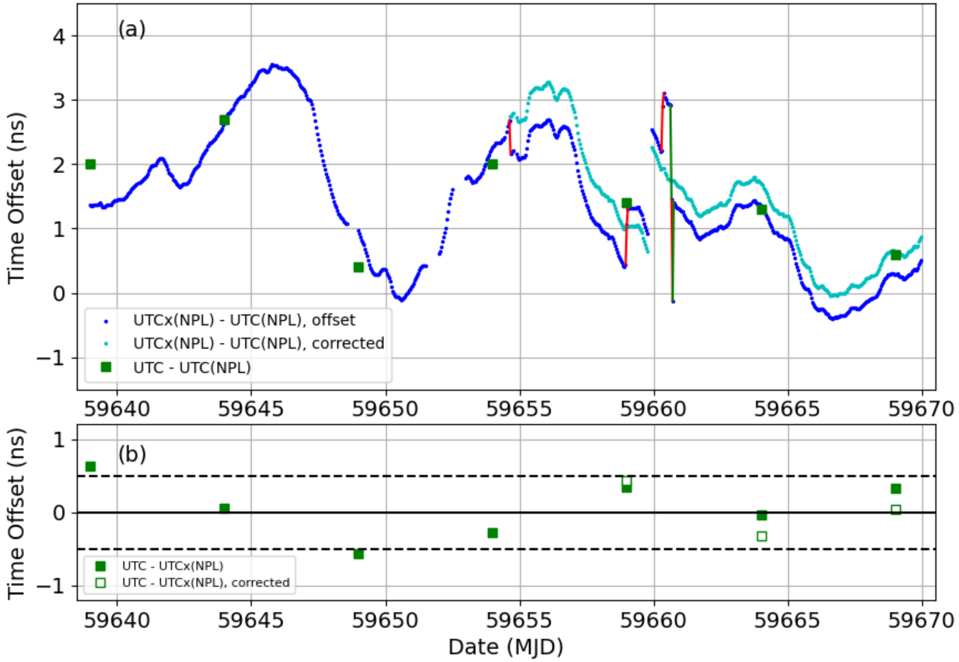
UTCx(NPL)



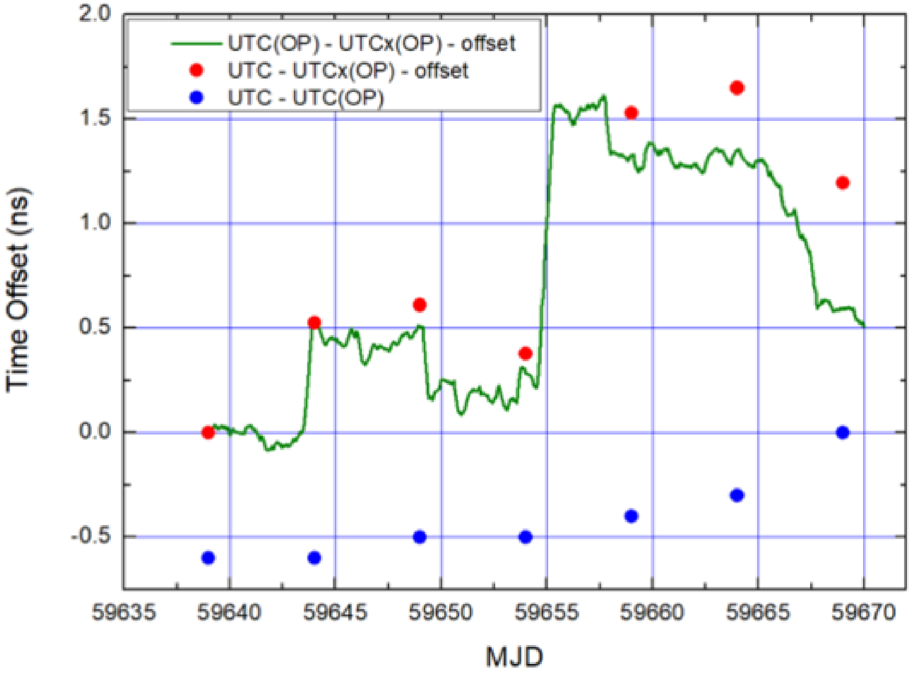
UTC(OP)

v

UTCx(OP)



Sub-ns deviation from UTC, despite technical glitches and gaps in optical clock data (32.3%)



Offset between the two prototype optically steered time scales lower than the typical offset between the two operational UTC(k) time scales

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arXiv:2307.14141v1

Recommended values of standard frequencies

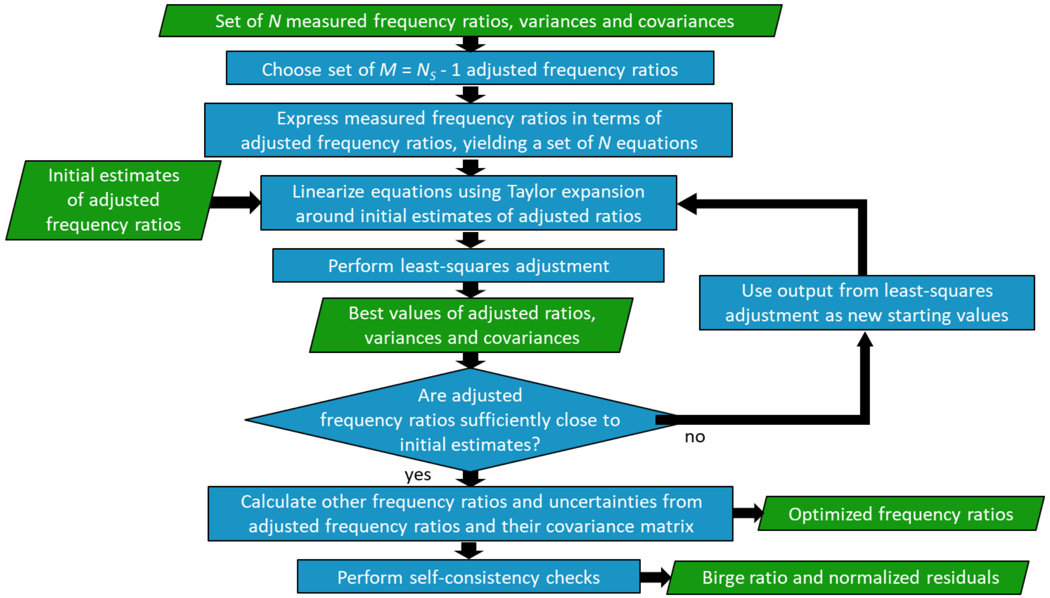
http://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies-second

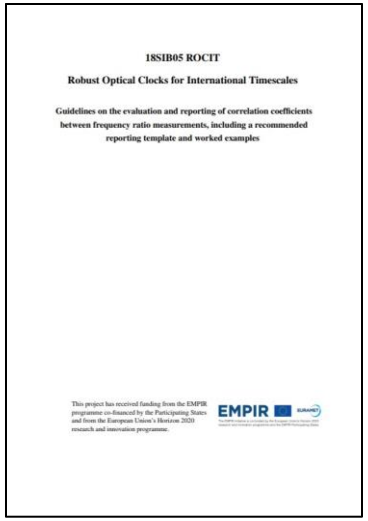
Least-squares analysis procedure

- Based on the approach used by CODATA to provide a self-consistent set of recommended values of the fundamental physical constants

  H. S. Margolis and P. Gill, Metrologia 52, 628 (2015)

- First used to update the list of recommended frequency values in September 2015





18SIB05 ROCIT

Robust Optical Clocks for International Timescales

Guidelines on the evaluation and reporting of correlation coefficients between frequency ratio measurements, including a recommended reporting template and worked examples

This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

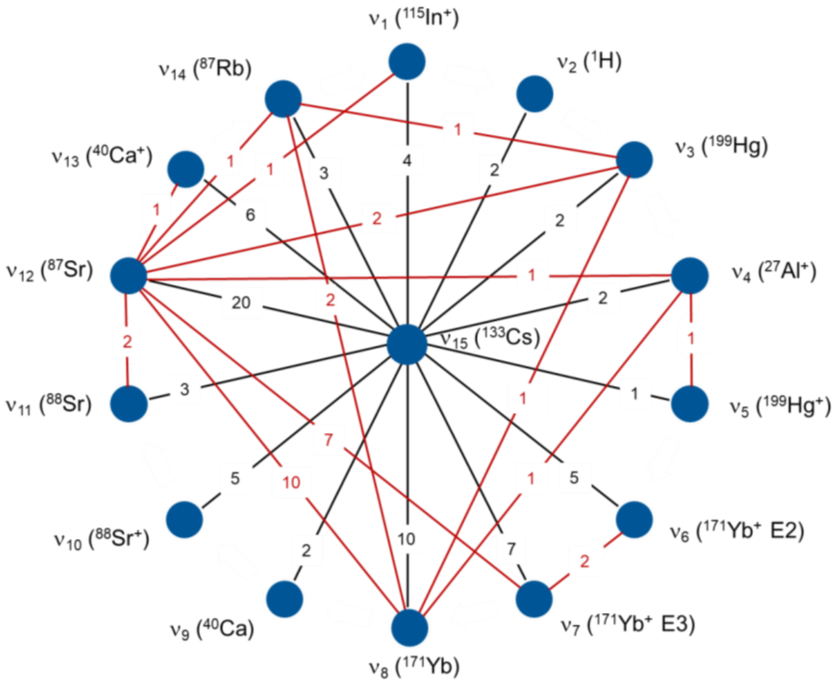
EMPIR

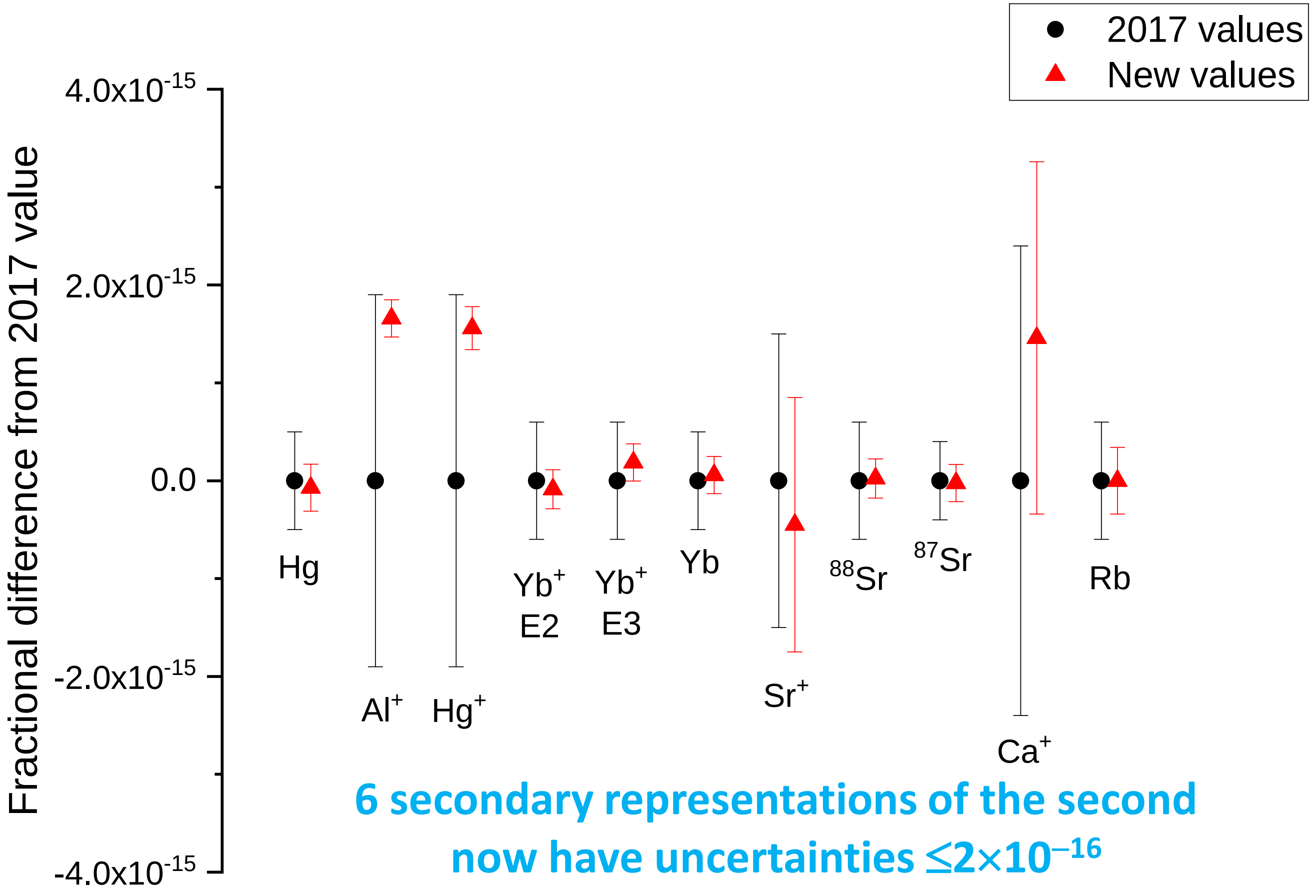
Importance of correlations

- Must be included to avoid biased frequency values and (usually) underestimated uncertainties
- Guidelines prepared on the evaluation & reporting of correlation coefficients between frequency ratio measurements (http://empir.npl.co.uk/rocit/project-outputs/)
- Shared with the CCL-CCTF Frequency Standards Working Group (WGFS)

2021 update

- 105 input data points (72 absolute frequencies, 33 ratios)
- Correlations included for the first time (483 correlation coefficients)
  - Mostly arising through the use of the same primary or secondary frequency standard to access the SI second
  - 86 computed on an ad-hoc basis (common data, common coefficients …)

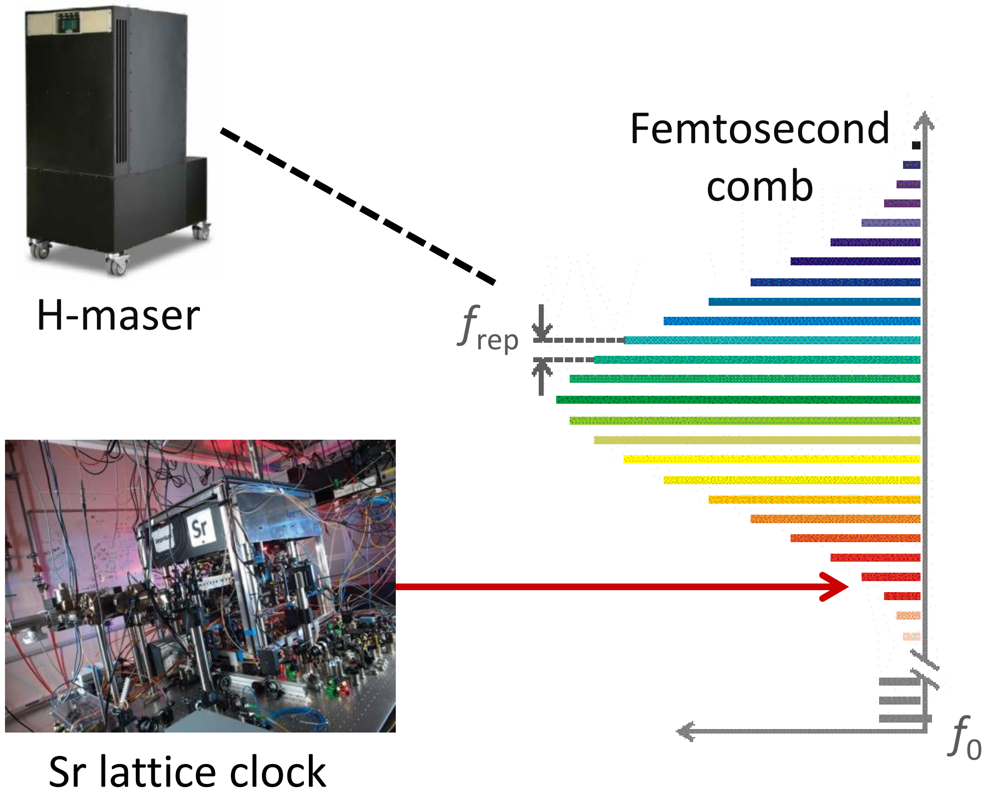




6 secondary representations of the second now have uncertainties $\leq 2\times10^{-16}$

Optical clock contributions to TAI

- Similar to the approach used for primary frequency standards
- Calibrate a commercial clock for which phase comparison data is submitted on a continuous basis to the BIPM
- Use the frequency of the optical clock as listed in the “Recommended values of standard frequencies”



- For first submission of a new standard
  - Several calibration values must be provided (do not need to be contiguous)
  - Operation of the frequency standard and its uncertainty evaluation must be described in a peer-reviewed publication
- Material must be reviewed and approved by the CCTF Working Group on Primary and Secondary Frequency Standards before the clock can be used for steering of TAI

Optical clock contributions to TAI

SYRTE-Sr2

5 contributions used for TAI steering (Jun – Aug 2021 and Mar – Apr 2022)

One contribution so far in 2023

IT-Yb1

First contribution in Nov 2019

9 further contributions used for TAI steering (Feb – Oct 2022)

7 more since then

Highest-weight clock in July 2022!

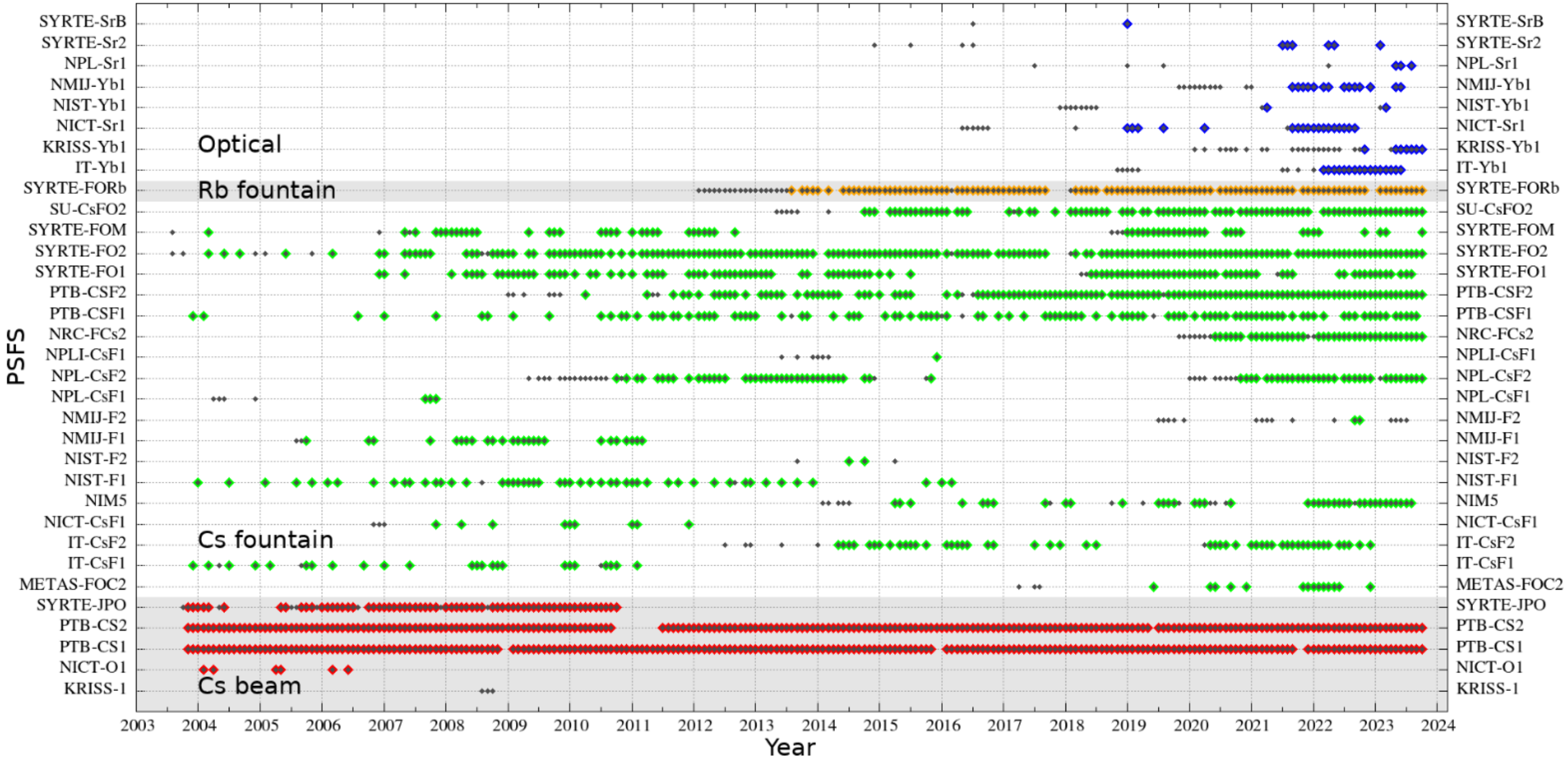
NPL-Sr1

First contribution in March 2023

3 more since then

Almost 40% of the "on time" contributions from optical clocks

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



Suitable data also gathered from other optical clocks …

12 optical clocks, 55 periods ranging from 5 – 35 days, total cumulative data acquisition period > 1000 days

New record set in March 2022

Circular T no. 411 – 5 optical clocks contributing

3 - Duration of the TAI scale interval d.

Table 1: Estimate of d by individual PSFS measurements and corresponding uncertainty.
All values are expressed in 10**-15 and are valid only for the stated period of estimation.

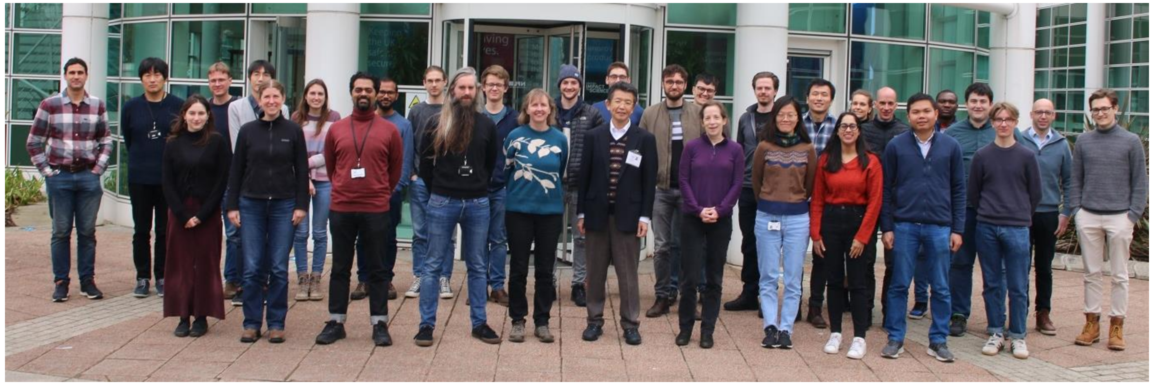
Standard	Period of Estimation	d	uA	uB	uA/Lab	uB/Lab	ul/Tai	u	uSrep	Ref(uS)	Ref(uB)	uB(Ref)	Uptime %	LastRep	Nrep3y	Steer	Note
PTB-CS1	59634 59669	-18.88	8.00	8.00	0.00	0.00	0.06	11.31	PFS/NA		T148	8.00	100.0	T410	34	Y	(1)
PTB-CS2	59634 59669	-8.50	5.00	12.00	0.00	0.00	0.06	13.00	PFS/NA		T148	12.00	100.0	T410	35	Y	(1)
METAS-FOC2	59639 59669	-0.82	0.07	1.48	0.25	0.05	0.20	1.52	PFS/NA		T371	1.99	74.0	T410	10	Y	(2)
IT-CsF2	59634 59669	0.10	0.15	0.23	0.12	0.01	0.17	0.34	PFS/NA		T318	0.19	88.2	T410	23	Y	(3)
IT-Yb1	59634 59669	-0.51	0.00	0.02	0.08	0.02	0.17	0.19	0.5	[1]	T383	0.03	45.8	T410	10	Y	(4)
KRISS-Yb1	59634 59669	0.10	0.00	0.04	0.17	0.07	0.17	0.25	0.5	[1]	T405	0.03	21.8	T410	16	Y	(5)
NICT-Sr1	59634 59669	0.11	0.02	0.07	0.14	0.02	0.17	0.23	0.4	[1]	T371	0.06	5.5	T410	10	Y	(6)
NIM5	59634 59669	-0.03	0.32	0.90	0.10	0.01	0.17	0.98	PFS/NA		T340	1.40	99.5	T410	18	Y	(7)
NMIJ-Yb1	59634 59654	-0.03	0.01	0.12	0.04	0.10	0.28	0.33	0.5	[1]	T392	0.36	97.0	T410	18	Y	(8)
NMIJ-Yb1	59659 59669	-0.03	0.01	0.12	0.15	0.10	0.53	0.57	0.5	[1]	T392	0.36	92.4	T410	18	Y	(8)
NPL-CsF2	59639 59669	0.08	0.07	0.62	0.05	0.03	0.20	0.66	PFS/NA		T284	0.23	92.2	T410	25	Y	(9)
NRC-FCs2	59634 59669	-0.18	0.09	0.35	0.11	0.00	0.17	0.41	PFS/NA		T389	0.23	92.2	T410	28	Y	(10)
SYRTE-FO2	59634 59644	-0.07	0.30	0.24	0.08	0.00	0.53	0.66	PFS/NA		T301	0.23	85.6	T410	35	Y	(11)
SYRTE-FORb	59634 59669	0.26	0.20	0.25	0.09	0.00	0.17	0.37	0.6	[1]	T328	0.34	73.8	T410	35	Y	(11)
SYRTE-Sr2	59639 59669	-0.30	0.01	0.02	0.10	0.03	0.20	0.22	0.4	[1]	T350	0.05	56.9	T404	3	Y	(11)
PTB-CSF2	59634 59669	-0.35	0.12	0.17	0.01	0.00	0.06	0.22	PFS/NA		T370	0.17	95.2	T410	40	Y	(12)
SU-CsFO2	59634 59669	-0.34	0.34	0.22	0.13	0.00	0.17	0.46	PFS/NA		T315	0.50	86.3	T410	32	Y	(13)

Summary

- **More robust optical clocks**, achieving unattended uptimes > 80 % over a few weeks
- Tools for **on-the-fly evaluation of systematic frequency shifts** and **real-time validation of optical clock data**
- **An extensive programme of optical clock comparisons** to check performance levels
- First direct comparison of **two prototype optically steered time scales**
- **Guidelines on evaluating correlations between frequency ratio measurements** influenced the 2021 update to the CIPM list of recommended values of standard frequencies
- **3 European optical clocks now contributing to TAI** as secondary representations of the second

Future perspectives

International comparisons using transportable optical clocks (ICON project)



Intercontinental clock comparisons using optical fibre?

- Transatlantic fibre linking Halifax and Southport (5860 km long)
- So far mainly used for environmental sensing
  - G. Marra et al., Science 361, 486 (2018)
  - G. Marra et al., Science 376, 874 (2022)
- Also offers prospects for intercontinental clock comparisons
  - Environmentally induced noise lower than for terrestrial fibre

Thank you for listening!

http://empir.npl.co.uk/rocit/

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EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States