

NPL's optical frequency metrology programme: our contributions towards a redefinition of the SI second

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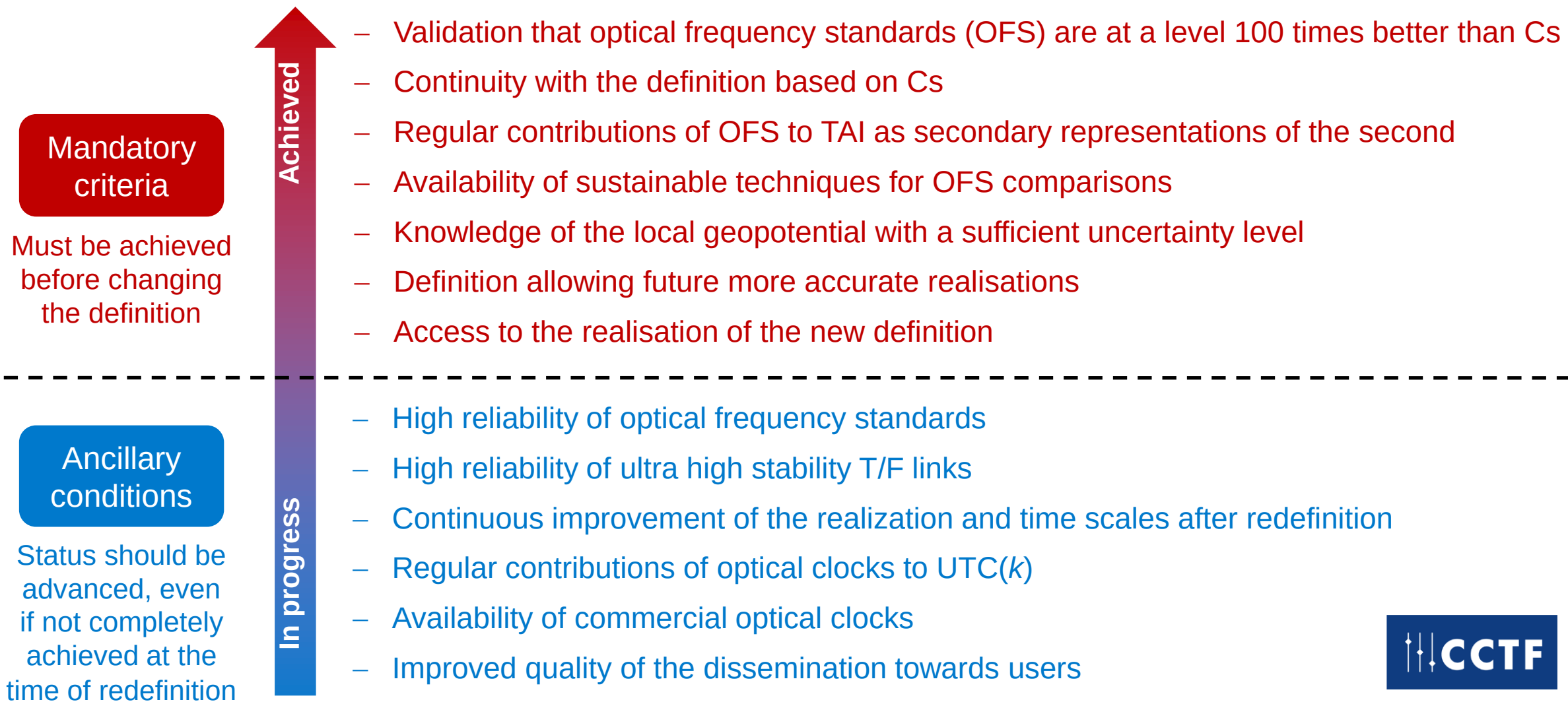
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1. Introduction

A new generation of optical frequency standards is now outperforming the best caesium fountain primary frequency standards in terms of both systematic frequency uncertainty and frequency instability.

This situation has led to the international community developing a roadmap towards a future redefinition of the second [1].

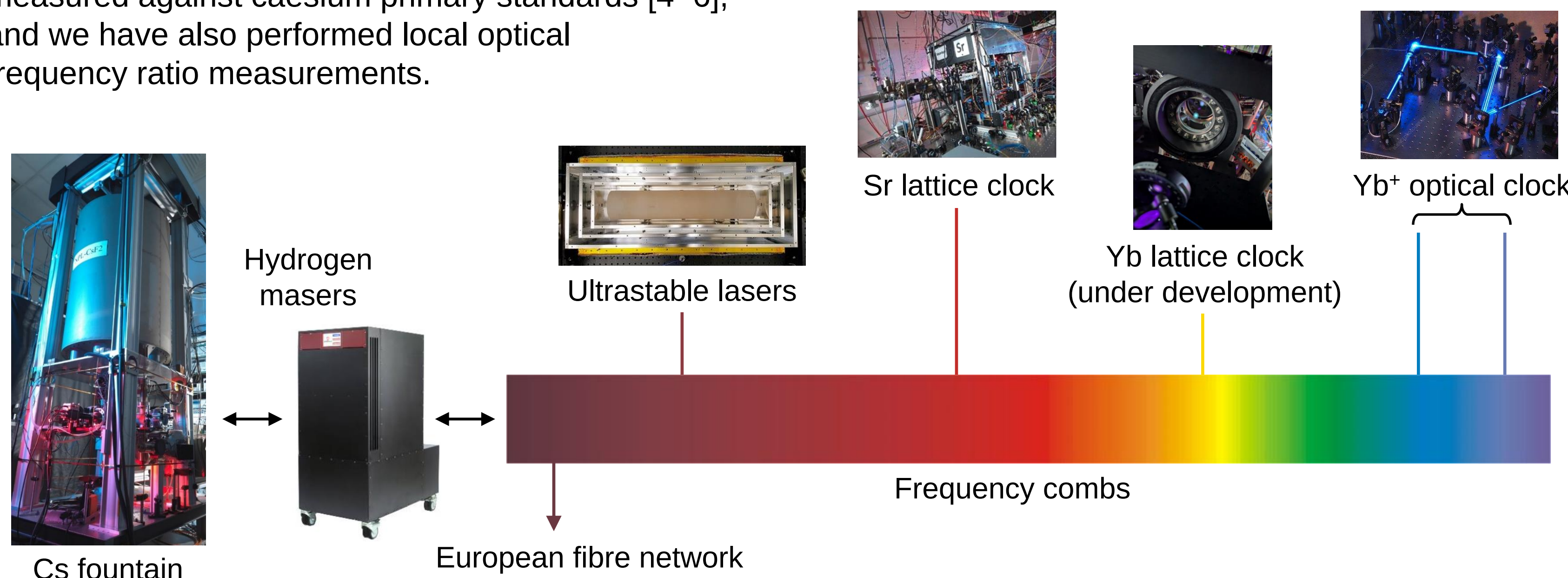
[1] N. Dimarcq *et al.*, Metrologia 61, 012001 (2024)



2. NPL's optical frequency metrology infrastructure

We operate two optical frequency standards (a strontium lattice clock and an ytterbium ion clock), the critical underpinning technologies of ultrastable lasers [2] and optical frequency combs [3], and an optical fibre link connecting NPL to other European National Metrology Institutes. We are also developing an ytterbium optical lattice clock.

- Our ytterbium ion optical clock recently reached an evaluated systematic uncertainty of 2.2×10^{-18} [4], very close to the target in the roadmap (2×10^{-18}).
- The best published uncertainty for our strontium optical lattice clock is 1.0×10^{-17} [5]. It is now within a factor of two of the roadmap target following a series of improvements to reduce leading sources of systematic uncertainty.
- The absolute frequency of both clocks has been measured against caesium primary standards [4–6], and we have also performed local optical frequency ratio measurements.



[2] M. Schioppo *et al.*, Nature Commun. 13, 212 (2022)
[3] L. A. M. Johnson *et al.*, Metrologia 52, 62 (2015)
[4] A. Tofful *et al.*, Metrologia 61, 045001 (2024)
[5] R. Hobson *et al.*, Metrologia 57, 065026 (2020)
[6] C. F. A. Baynham *et al.*, J. Mod. Opt. 65, 585 (2018)

3. Optical clock comparisons

We have participated in various international comparisons to check the uncertainty budgets of our optical clocks:

- A 26-day comparison involving 5 optical clocks and 6 fountains, using a broadband version of two-way satellite time and frequency transfer (TWSTFT) [7].
- A large-scale comparison of ten optical clocks in six countries, all linked by GPS integer precise point positioning (IPPP) and some also by optical fibre [8].
- The first intercontinental comparison using transportable optical clocks [9].

Larger scale intercontinental comparisons will be enabled by the Atomic Clock Ensemble in Space (ACES) mission, due to launch in April 2025. We are also investigating the possibility of intercontinental comparisons via optical fibre by adapting techniques originally conceived for seismic detection [10].

Comparisons between clocks must account for the relativistic redshift, which is proportional to the gravity potential difference between them. In collaboration with the University of Hannover, the gravity potential at NPL and other European NMIs is known to a level corresponding to clock uncertainties of $2\text{--}3 \times 10^{-18}$ [11].

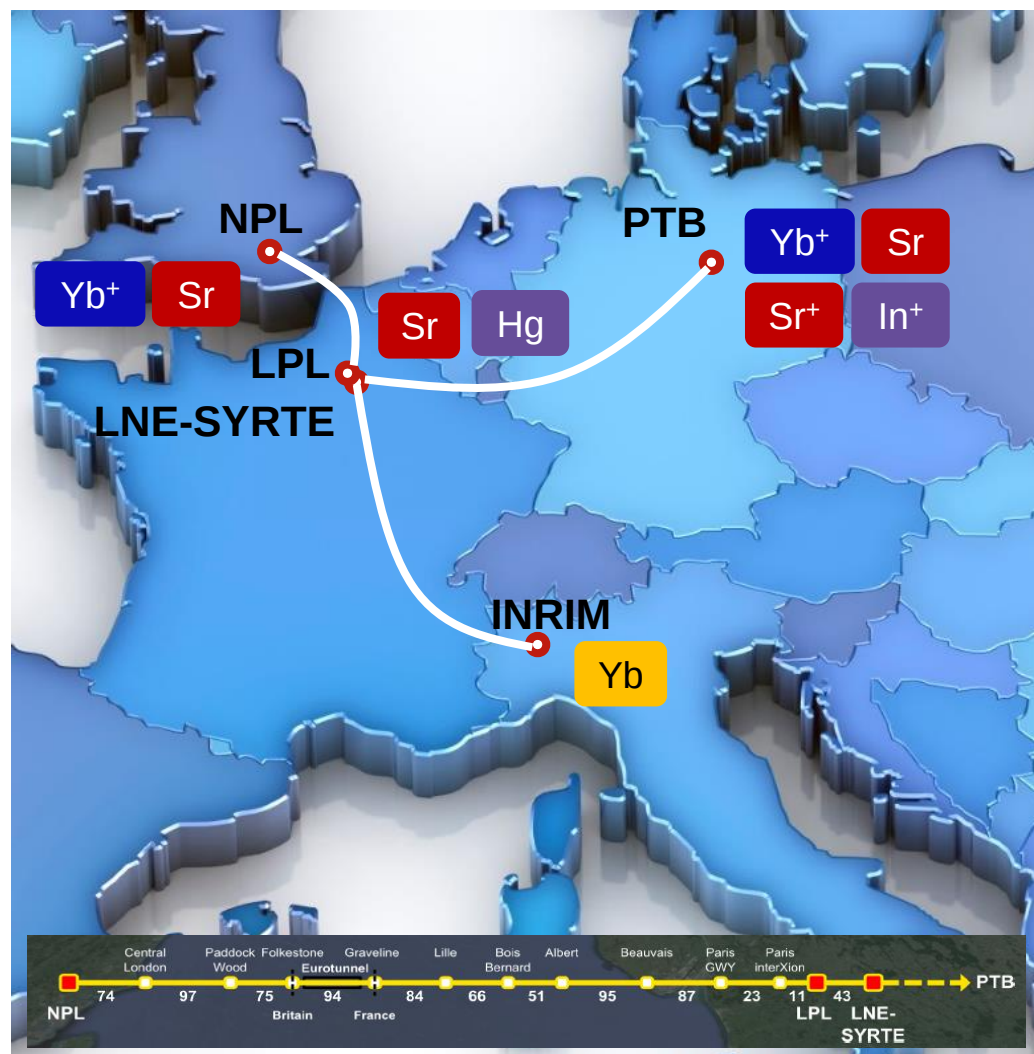
[7] F. Riedel *et al.*, Metrologia 57, 045005 (2020)

[8] H. S. Margolis *et al.*, J. Phys. Conf. Series 2889, 012022 (2024)

[9] International Clock Oscillator Networking (ICON) collaboration, arXiv:2410.22973 (2024)

[10] G. Marra *et al.*, Science 376, 874 (2022)

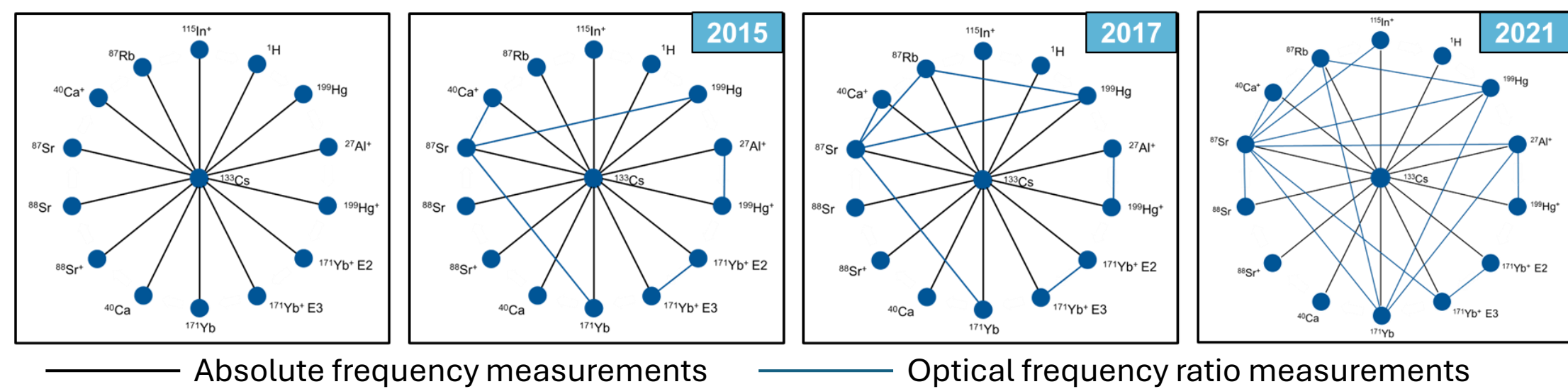
[11] H. Denker *et al.*, J. Geodesy 92, 487 (2018)



4. Analysis techniques

Since 2015, the worldwide body of clock comparison data has contained an increasing number of optical frequency ratio measurements, in addition to absolute frequency measurements relative to primary frequency standards.

NPL developed methods to handle such over-determined datasets, enabling optimized frequency values to be derived in a way that makes maximum use of the available data [12]. These methods have been used since 2015 to update the CIPM list of recommended frequency values [13], including the values used when optical clocks contribute to International Atomic Time (TAI) as secondary representations of the second.



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

[13] H. S. Margolis *et al.*, Metrologia 61, 035005 (2024)

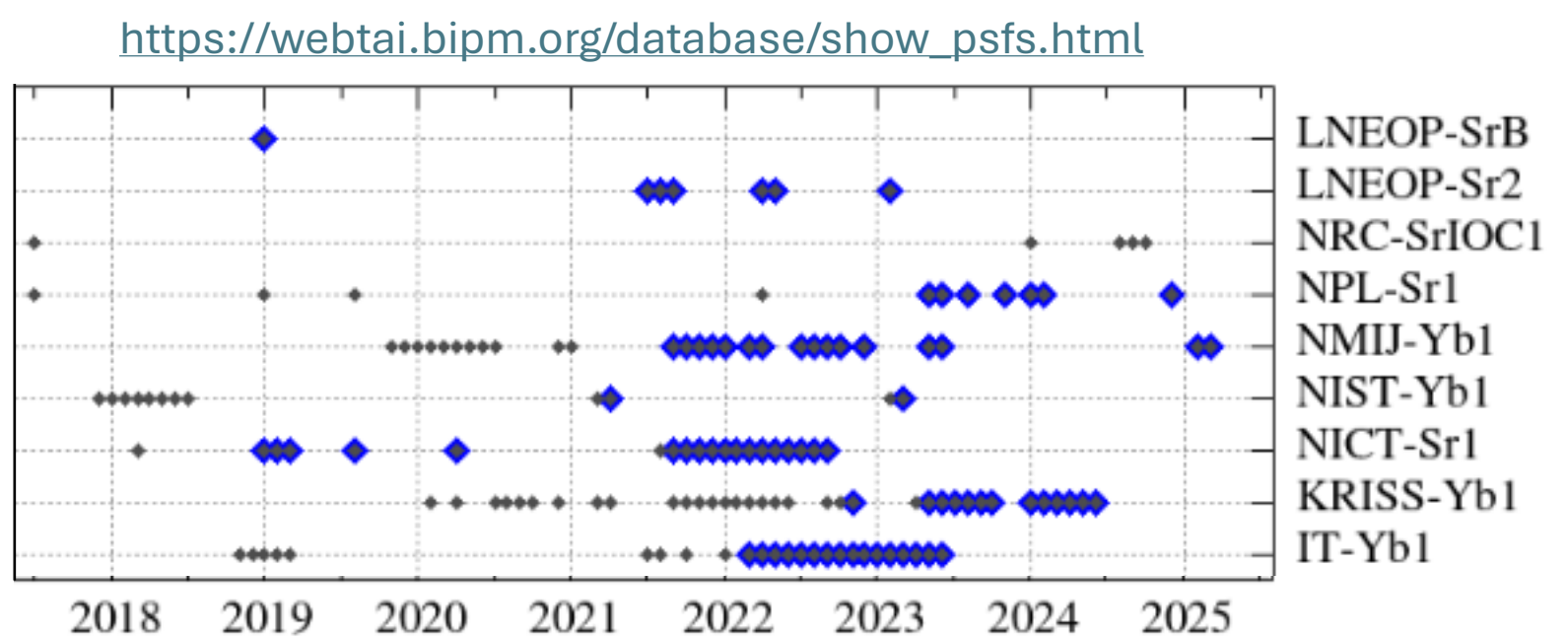
5. Contributions to time scales

Our strontium optical lattice clock NPL-Sr1 was approved for steering of International Atomic Time (TAI) in March 2023 and has so far contributed data in seven months since then.

A significant body of data has been gathered from our ¹⁷¹Yb⁺ optical clock and we are close to submitting this system to the BIPM for consideration for inclusion in TAI.

Locally to NPL we have also demonstrated a prototype real-time optically steered UTCx(k) time scale using our two optical clocks and compared this against a similar prototype time scale generated simultaneously at LNE-SYRTE [14].

The ytterbium optical lattice clock we are developing is targeted at routine contributions to TAI.



[14] M. Abgrall *et al.*, J. Phys. Conf. Series 2889, 012024 (2024)

