NPL

Optical clocks for a redefinition of the SI second

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Community Workshop on Cold Atoms in Space

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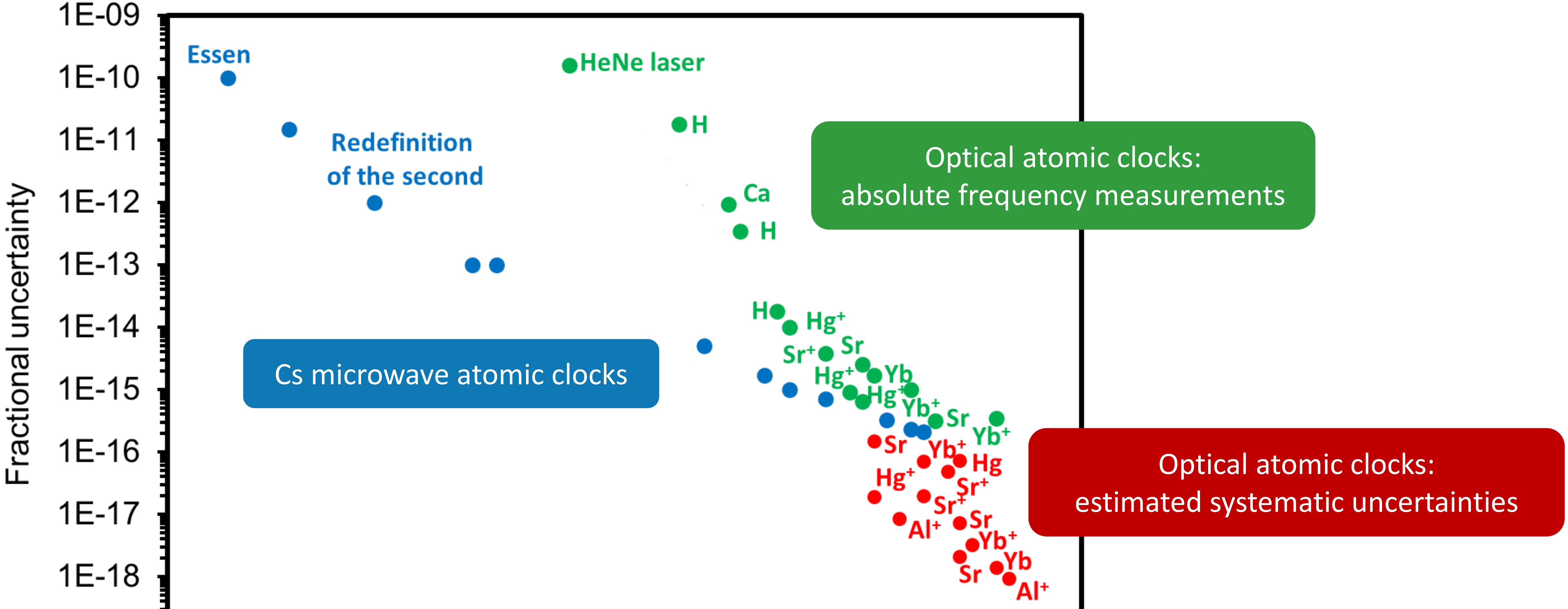
Improvements in atomic clocks



Optical redefinition of the SI second is anticipated

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Secondary representations of the second

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- Frequency standards that can be used to realise the SI second, and to contribution to TAI
- Uncertainty cannot be better than Cs primary standards
- List includes 1 microwave standard (Rb) and 8 optical standards

Atom or ion	Transition	Wavelength	Recommended fractional uncertainty (2017)
^{199}Hg	$^1S_0 - {}^3P_0$	266 nm	5×10^{-16}
$^{27}Al^+$	$^1S_0 - {}^3P_0$	267 nm	1.9×10^{-15}
$^{199}Hg^+$	$^2S_{1/2} - {}^2D_{5/2}$	282 nm	1.9×10^{-15}
$^{171}Yb^+$	$^2S_{1/2} - {}^2D_{3/2}$	436 nm	6×10^{-16}
$^{171}Yb^+$	$^2S_{1/2} - {}^2F_{7/2}$	467 nm	6×10^{-16}
^{171}Yb	$^1S_0 - {}^3P_0$	578 nm	5×10^{-16}
$^{88}Sr^+$	$^2S_{1/2} - {}^2D_{5/2}$	674 nm	1.5×10^{-15}
^{87}Sr	$^1S_0 - {}^3P_0$	698 nm	4×10^{-16}

March 2021 update: 6 secondary representations of the second now have uncertainties $\leq 2\times10^{-16}$

2 new secondary representations of the second (^{88}Sr and Ca^+)

Roadmap towards the redefinition

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CCTF

- Dedicated CCTF task force created, chaired by Noel Dimarcq and Patrizia Tavella
- Kick-off meeting held 24th June 2020
- 3 sub-groups bringing together 40 worldwide contributors

– What are the criteria for a redefinition?

Subgroup A:
– What benefits might arise from a redefinition?
– Consultation with end users
– Educational campaign

Subgroup B:
– What are our current and envisaged clock capabilities?
– What are the possible options for a redefinition?

Subgroup C:
– What is our regional / worldwide capacity to compare clocks and disseminate the second?
– What is our capacity to realise a time scale including optical clocks?

– Assessment of options against the criteria
– Are there other open issues that need to be resolved before a redefinition?

Goals of a new definition

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- Offer an **improvement by a factor of 10 – 100** in the realisation of the new definition in the short term after the definition (reaching 10^{-17} – 10^{-18} relative frequency uncertainty) and potentially a larger improvement in the longer term

- **Ensure continuity** with the current definition based on caesium

- Ensure continuity and sustainability of the **availability of the new SI second through TAI** (and UTC), and enable a **significant improvement of the quality of TAI** as soon as the definition is changed

- Enable the **dissemination of the unit** to a broad range of users

- **Be acceptable** to all NMIs and stakeholders

Redefinition options

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1) New definition based on a single optical reference frequency

- Similar to the present Cs-based definition
- Primary realisation using primary frequency standards based on this transition
- Secondary representations of the second provided by frequency standards based on other species (including Cs)

2) New definition based on an ensemble of optical reference frequencies

J. Lodewyck, Metrologia 56, 055009 (2019)

- Uses the weighted geometric mean of an ensemble of chosen transition frequencies
- Realisation using any frequency standard that is part of the defined ensemble, using a frequency ratio matrix updated by the CIPM
- List of chosen transitions and weights are periodically updated

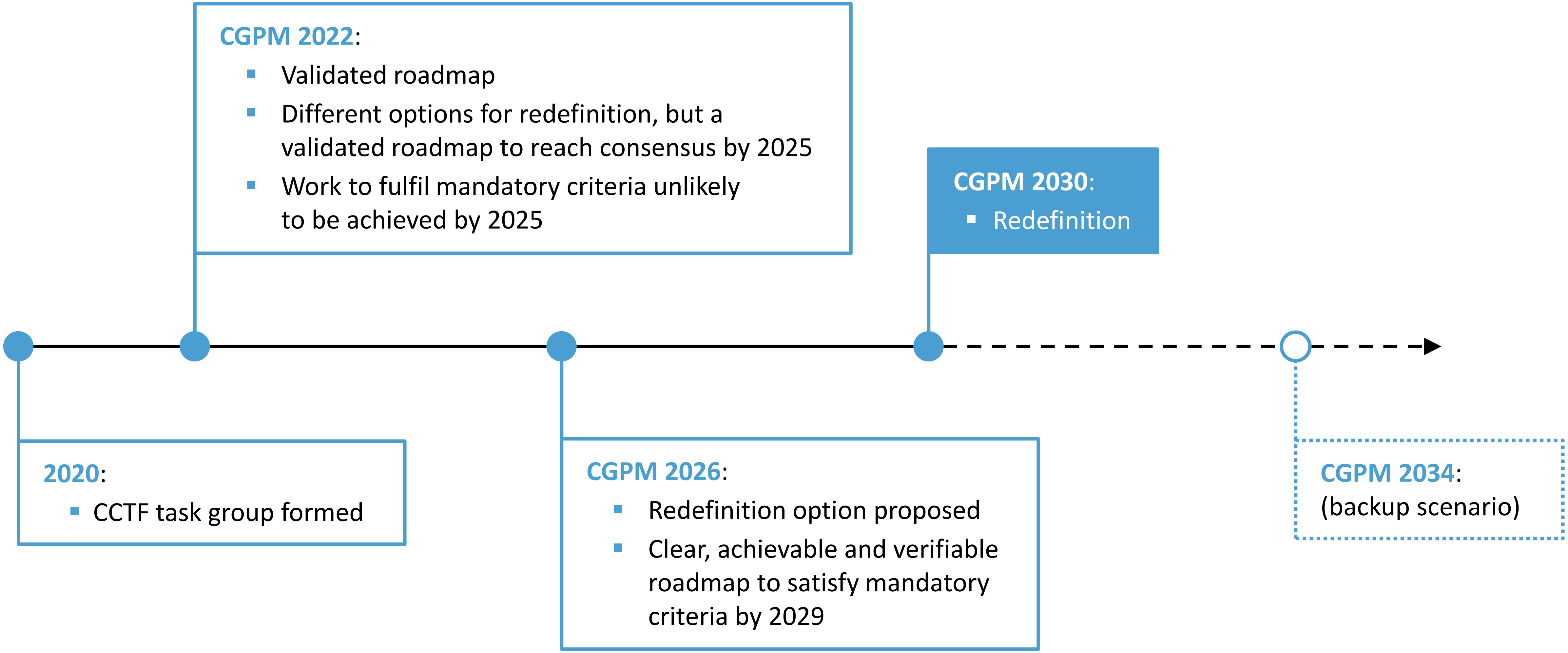
3) New definition based on fixing the value of another fundamental constant

- As done for other SI units by fixing c, h, k, e, N_A
- Not achievable at present (no fundamental constant known with sufficient accuracy)

Most favoured

Least favoured

Potential timeline



Mandatory criteria and ancillary conditions

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CCTF (Draft)

Achieved

Mandatory criteria

Must be achieved before changing the definition

- Validation that optical frequency standards (OFS) are at a level 100 times 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
- Definition allowing future more accurate realisations
- Access to the realisation of the new definition

Ancillary conditions

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

- 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

In progress

Mandatory criteria

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Validation that optical frequency standards (OFS) are at a level 100 times better than Cs

I.1 – Accuracy budgets of optical frequency standards

G At least 3 frequency evaluations of optical frequency standards based on **different reference transitions**, either **in the same institute or different institutes**, have demonstrated evaluated uncertainties $\leq 2\times10^{-18}$

NIST Al^+: 9.4×10^{-19}	S. M. Brewer *et al*, Phys. Rev. Lett. 123,033201 (2019)
NIST Yb: 1.4×10^{-18}	W. F. McGrew *et al*, Nature 564, 87 (2018)
JILA Sr: 2.0×10^{-18}	T. Bothwell *et al*, Metrologia 56, 065004 (2019)

A At least 3 optical frequency standards based on the **same reference transition**, in **different institutes**, have demonstrated evaluated relative frequency uncertainties $\leq 2\times10^{-18}$

JILA Sr:	2.0×10^{-18}	T. Bothwell *et al*, Metrologia 56, 065004 (2019)
Tokyo Sr:	5.5×10^{-18}	M. Takamoto *et al*, Nature Photonics 14, 411 (2020)

Mandatory criteria

Validation that optical frequency standards (OFS) are at a level 100 times better than Cs

I.2 – Validation of optical frequency standard uncertainty budgets – frequency ratios

R **Unit ratios**: at least 3 measurements between OFS in **different institutes** with an agreement $\leq 5\times10^{-18}$ (either by transportable clocks or advanced links)

Unit ratios have been measured at the required level of accuracy, but only between OFS in the **same** institute

NIST Yb: 9.4×10^{-19} W. F. McGrew *et al*, Nature 564, 87 (2018)

PTB Yb$^+$: 9.4×10^{-19} C. Sanner *et al*, Nature 567, 204 (2019)

Tokyo Sr: 4.7×10^{-18} M. Takamoto *et al*, Nature Photonics 14, 411 (2020)

R **Non-unit ratios**: at least 5 measurements, each ratio measured at least twice by **different institutes** with an agreement $\leq 5\times10^{-18}$

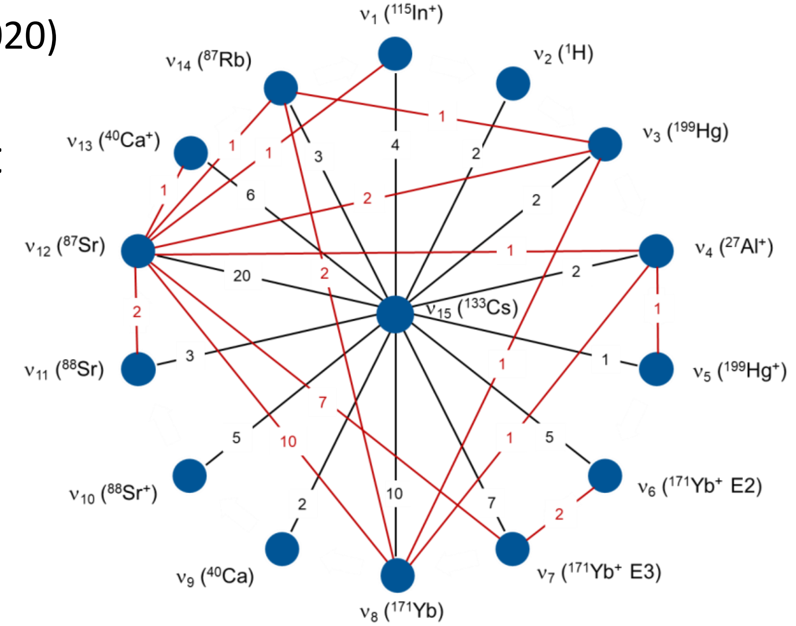
Increasing numbers of optical frequency ratio measurements, but none so far (quite) reach the target uncertainty:

NIST Al+ / NIST Yb: 5.9×10^{-18}

NIST Al+ / JILA Sr: 8.0×10^{-18}

NIST Yb / JILA Sr: 6.8×10^{-18}

K. Beloy *et al*, Nature 591, 564 (2021)



Mandatory criteria

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I.3 – Continuity with the definition based on Cs

G At least 3 independent frequency evaluations of OFS with TAI or with 3 independent Cs primary frequency standards (in different or the same institutes), with relative frequency uncertainties $\leq 3\times10^{-16}$

Sr:	LNE-SYRTE	2.8×10^{-16}	J. Lodewyck *et al*, Metrologia 53, 1123 (2016)
	PTB	1.5×10^{-16}	R. Schwarz *et al*, Phys. Rev. Research 2, 033242 (2020)
	NICT	1.8×10^{-16}	N. Nemitz *et al*, Metrologia 58, 025006 (2021)
Yb:	NIST	2.1×10^{-16}	W. F. McGrew *et al*, Optica 6, 448 (2019)
	INRIM	2.6×10^{-16}	M. Pizzocaro *et al*, Metrologia 57, 035007 (2020)
Yb^{+}:	PTB	1.3×10^{-16}	R. Lange *et al*, Phys. Rev. Lett. 126, 011102 (2021)

Mandatory criteria

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I.4 – Regular contributions of OFS to TAI as secondary representations of the second

R At least 3 state-of-the-art calibrations of TAI (uncertainty $\leq 2\times10^{-16}$, neglecting the recommended uncertainty of the secondary representation of the second) each month from a set of at least 5 optical frequency standards for at least one year

Check that there is no degradation of TAI if its calibrations were done by OFS considered as primary standards and Cs as secondary standards

6 OFS validated by the WGPSFS for use in TAI steering

OFS	First used in Circular T
SYRTE-Sr2	350 (February 2017)
SYRTE-SrB	350 (February 2017)
NICT-Sr1	371 (November 2018)
NIST-Yb1	374 (February 2019)
IT-Yb1	383 (November 2019)
NMIJ-Yb1	392 (August 2020)

Of 52 reports to date, only 13 involved operation of the OFS during the month of publication – important if they are to contribute in a significant way to estimation of the TAI frequency

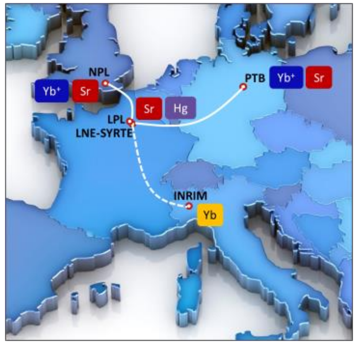
In August 2021, the number of optical clocks reporting reached 3 for the first time

None of the reports achieved the target uncertainty, though one reached below 3×10^{-16}

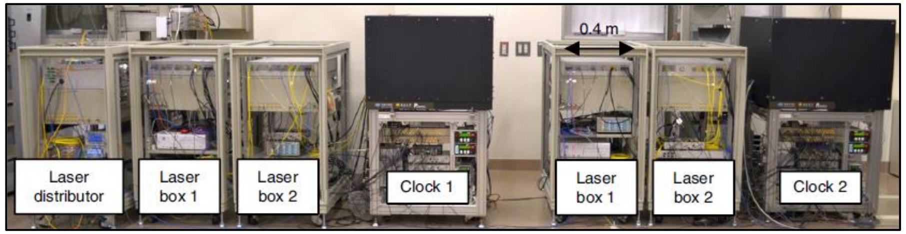
Mandatory criteria

II.1 – Availability of sustainable techniques for OFS comparisons

A Transportable clocks or T/F links with uncertainties < 5×10^{-18} for national / intracontinental comparisons



Uncertainties of fibre links < 5×10^{-18} (Europe, Japan)

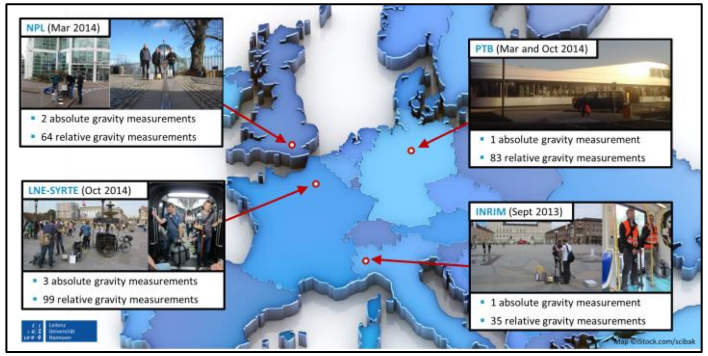


From M. Takamoto et al, Nature Photonics 14, 411 (2020)

Transportable Sr clock with uncertainty 5.5×10^{-18} (Tokyo)

II.2 – Knowledge of the local geopotential with a sufficient uncertainty level

A
- To support OFS comparisons using advanced links
- Corresponding to fractional frequency uncertainty $\leq10^{-17}$, for contributions to TAI



Europe: $2 – 4\times10^{-18}$

NIST: 6×10^{-18}
NICT: 2×10^{-17}
KRISS: 3×10^{-17}
NMIJ: 6×10^{-17}

Mandatory criteria

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III.1 – Definition allowing future more accurate realisations

G

To be confirmed, based on chosen option

- Must be long lasting
- Realisation should improve by a factor of 10 – 100 in the short term
- Must have potential for further improvement of the realisation to 10^{-18} and beyond

III.2 – Access to the realisation of the new definition

R

No document yet, depends on chosen option

- Realisation / “mise en pratique” must be easily understandable with a clear uncertainty evaluation process

G

To be confirmed, based on chosen option

- NMIs and high accuracy users must have access to primary or secondary realisations of the definition

G

To be confirmed, based on chosen option

- Cs frequency standards should provide a secondary realisation of the new definition

Ancillary conditions

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I.5 – High reliability of OFS

Reliable continuous operation capability of OFS over durations > 10 days, in a laboratory environment, with the appropriate level of uncertainty

A *Current status:* *Continuous operation for ~1 day (longer for a few OFS)*

II.3 – High reliability of ultra high stability T/F links

On-demand continuous operation capability of T/F links over sufficient durations that do not limit OFS comparisons and their regular contributions to TAI

A / R *Current status:* *A few months continuous unmanned operation of European fibre links*

No intercontinental link that does not limit OFS comparisons

III.3 – Continuous improvement of the realisation and of time scales after redefinition

Commitment of NMIs to make the best effort to

- Improve and operate OFS that provide primary or secondary realisations of the new definition
- Develop new OFS
- Maintain the operation of Cs fountain standards over the appropriate duration

G *Current status:* *11 Cs fountains in operation, 22 OFS (6 in operation, 16 under development)*

Ancillary conditions

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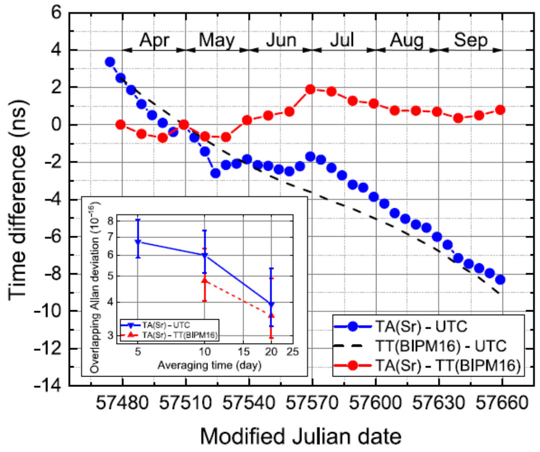
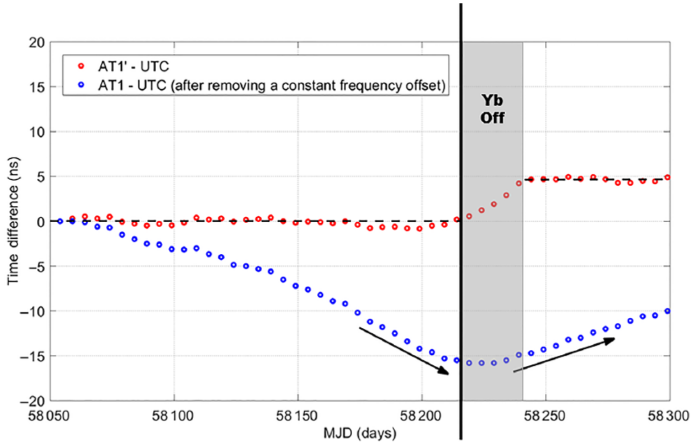
I.6 – Regular contributions of optical clocks to UTC(*k*)

A *Current status: Preliminary tests of UTC(k) steered by OFS reported*



From H. Hachisu et al,
Scientific Reports 8, 4243 (2018)



From J. Yao et al,
Phys. Rev. Applied 12, 044069 (2019)

III.4 – Availability of commercial optical clocks

R *Current status: No commercial optical clocks available*

III.5 – Improved quality of the dissemination towards users

A *Current status: Frequency stability 10^{-16} – 10^{-17} for satellite-based techniques, 10^{-20} for fibre links*

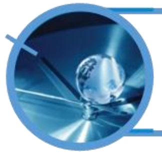
Time accuracy 1 ns for satellite-based techniques, 50 ps for fibre links

Robust Optical Clocks for International Timescales (ROCIT)

WP1: Robust optical clocks with on-the-fly correction of systematic frequency shifts

WP2: International optical clock comparisons (including traceability to the SI second)

WP3: Incorporating optical clocks into UTC(*k*) timescales (experimental prototypes)



WP4: Optical clocks as secondary representations of the second, regularly submitting data to BIPM

WP5: Creating impact, including an international workshop held in cooperation with the BIPM

I.5 – High reliability of OFS

I.2 – Validation of OFS uncertainty budgets

I.3 – Continuity with the definition based on Cs

I.6 – Regular contributions of optical clocks to UTC(*k*)

I.4 – Regular contributions of OFS to TAI as secondary representations of the second

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

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