Workshop Temps-Fréquence et Technologies Quantiques
Nice, 09/11/2023

Vers une redefinition de l'unité SI de temps

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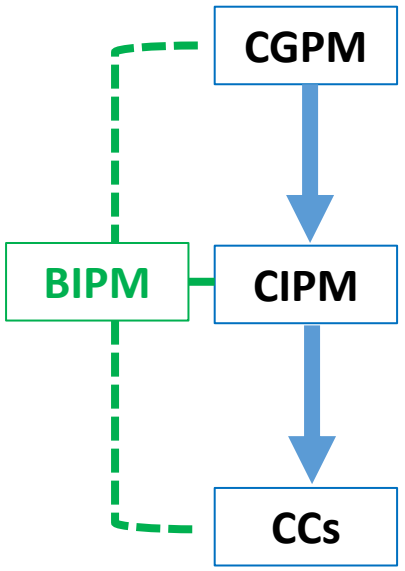
on behalf of
CCTF Strategic WG extended to co-chairs of dedicated CCTF WGs
CCTF Task Force on the Roadmap towards the redefinition of the second

Bureau International des Poids et Mesures

International Organization of Metrology



General Conference of Weights and Measures (60 Member States + 40 Associate/Observer States; meeting every 4 years): resolutions on the organization of Metrology, improvement and evolution of the SI

International Committee for Weights and Measures (18 members from different countries; meeting every year) : analysis of international work on metrology, preparation of recommendations for CGPM (especially the evolution of units)

10 **Consultative Committees** (meeting every 2 years) on specific metrology fields: organize the key-comparisons of the standards and discussions on important topics in relation to the definition of the corresponding unit in their field, its realization and its dissemination towards users

CCTF: Consultative Committee on Time & Frequency (26 members, 5 observers, 5 IO)

BIPM: Intergovernmental Organisation (Pavillon de Breteuil, Sèvres): in strong interaction with National Metrology Institutes, coordination of the international measurement system (compatibility and recognition of measurements) and of capacity building, writing of international reference documents

Roadmap towards the redefinition of the SI second

1) The special position of the second in the SI system

2) Definitions of the SI second, from past to future

3) Criteria and conditions to change the definition

4) Possible redefinition schedules

5) Conclusion

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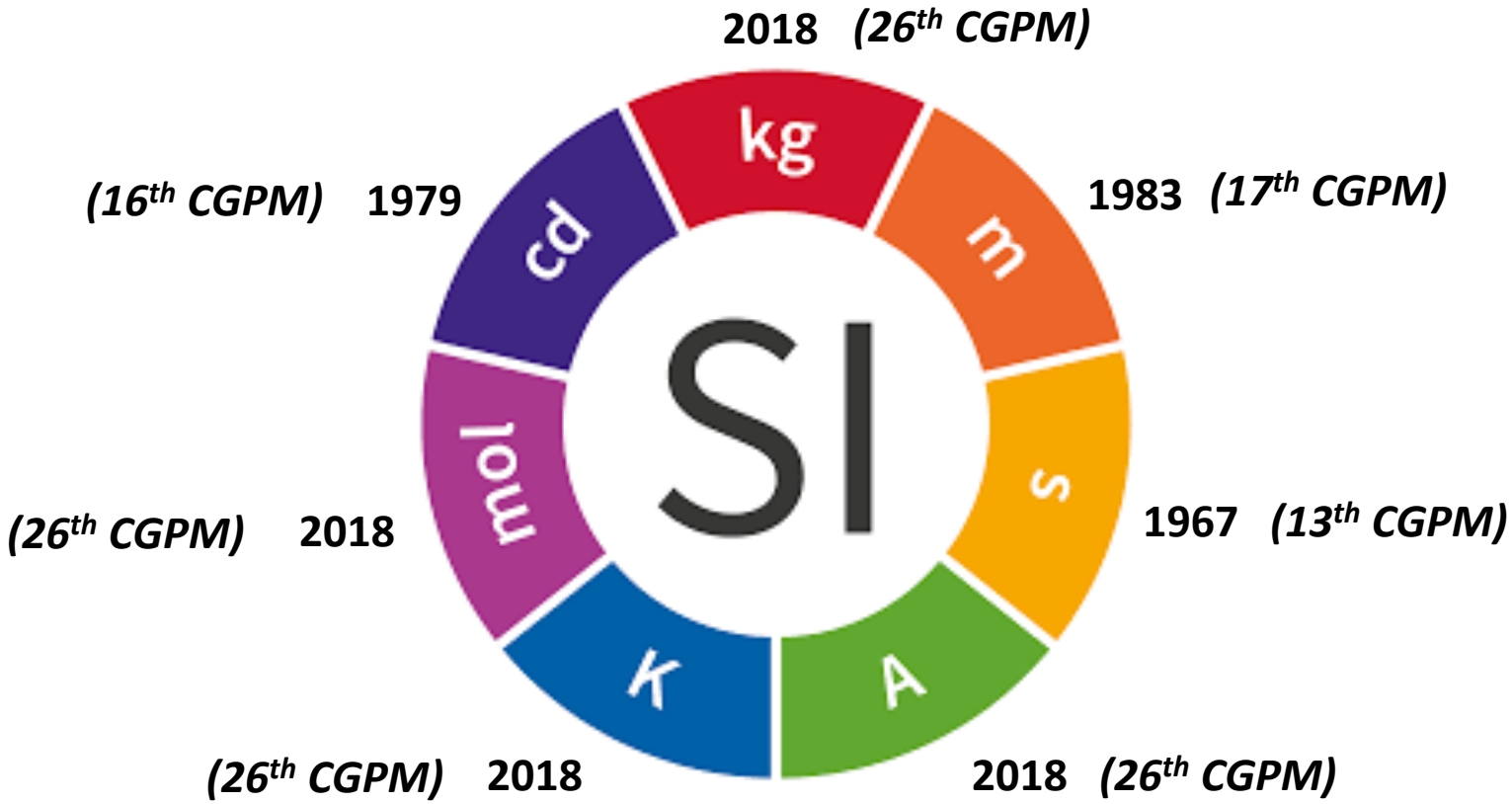
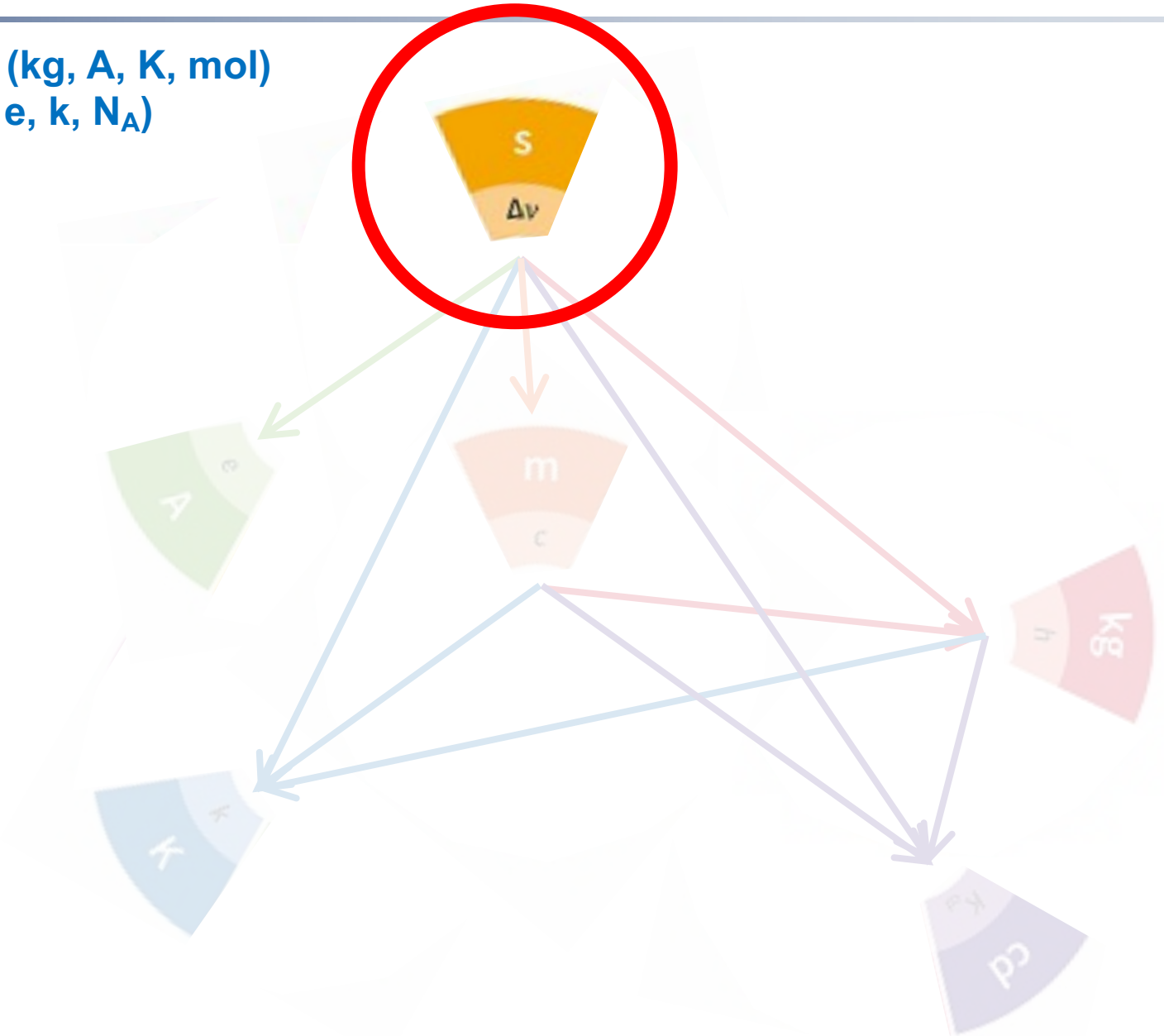
The International System of Units



The International System of Units

At CGPM 2018, redefinition of 4 units (kg, A, K, mol) relying on fondamental constants (h, e, k, N_A)
+ fixing the value of $\Delta\nu_{Cs}$



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Definitions of the SI unit of time

The SI unit of time – the second – is defined as:

Astronomy (angle/phase of a linear process)

→ **until 1956 : the fraction 1/86 400 of the mean solar day**

→ **1956 to 1967 : the fraction 1/31,556,925.9747 of the tropical year 1900**

1 tropical year = 365,2422 solar days = 366,2422 sideral days

Quantum physics (frequency of a periodic process)

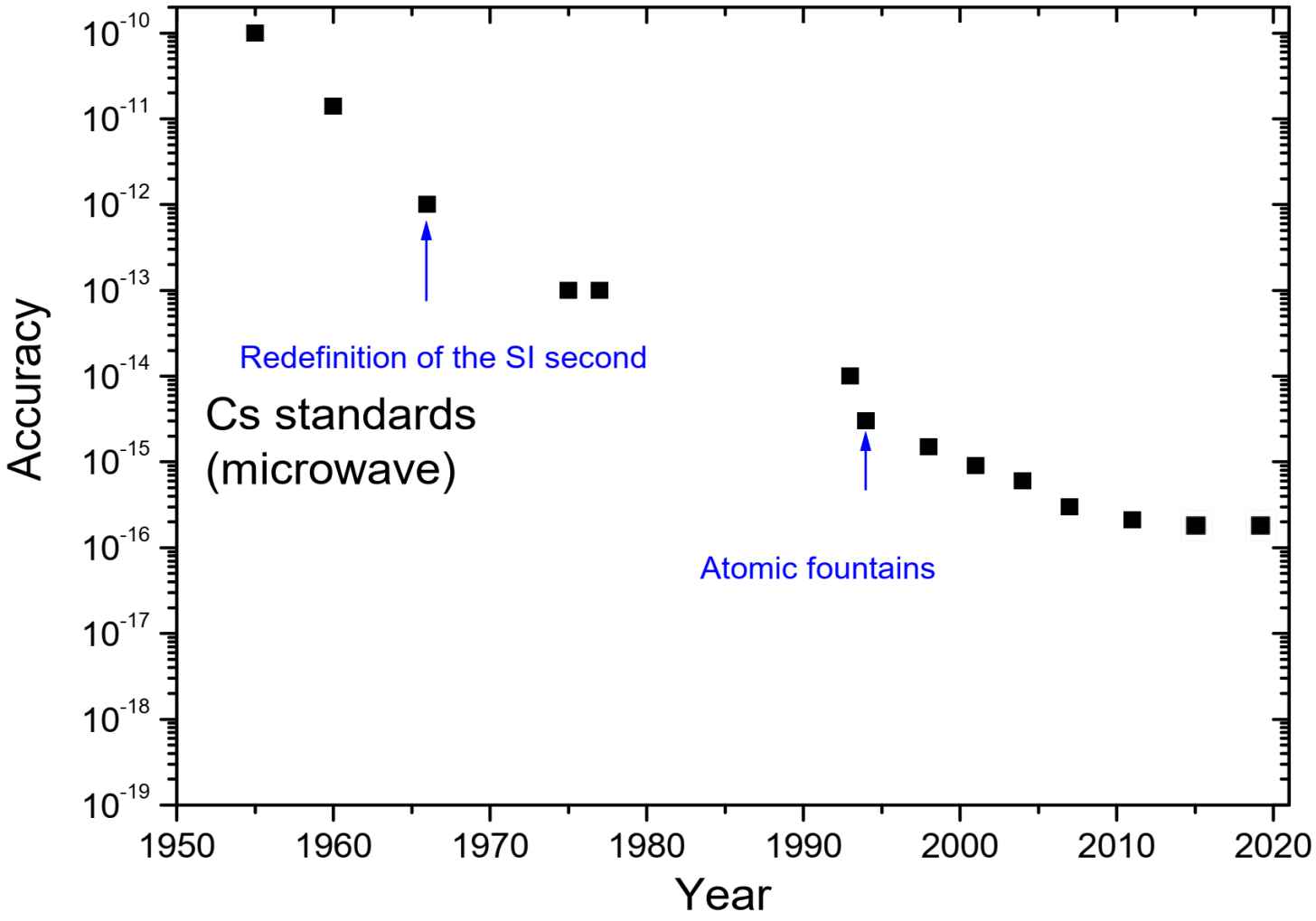
→ **1967 : the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom**

Added in 1999: This definition refers to a cesium atom at rest at a temperature of 0 K

New formulation in 2018:

The second, symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{Cs}$, the unperturbed ground-state hyperfine transition frequency of the caesium-133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1}.

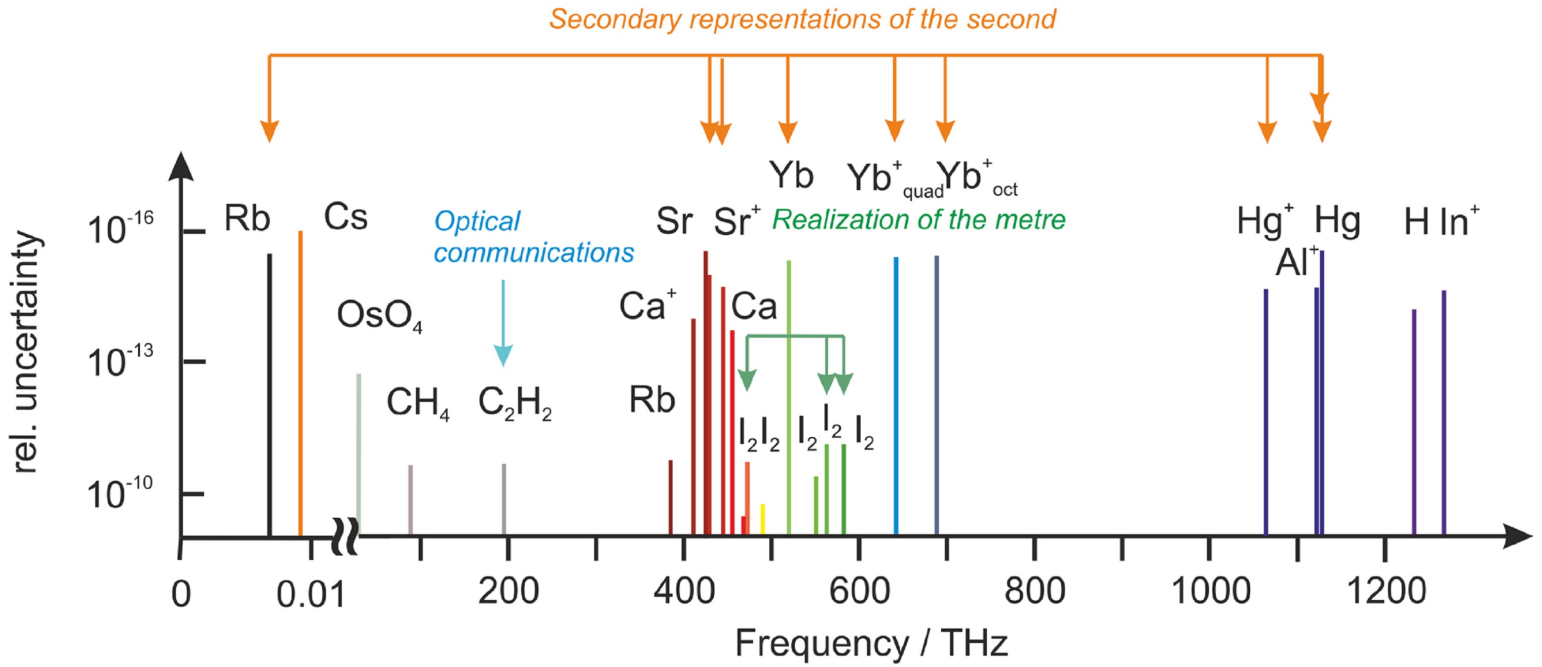
Realization of the SI second with primary Cs frequency standards



Cs fountain accuracy
$\sim 10^{-16}$

Secondary representations of the second

List of recommended standard frequencies (validated by CIPM, published on the BIPM website) recommended for applications including the practical realization of the metre and secondary representations of the second

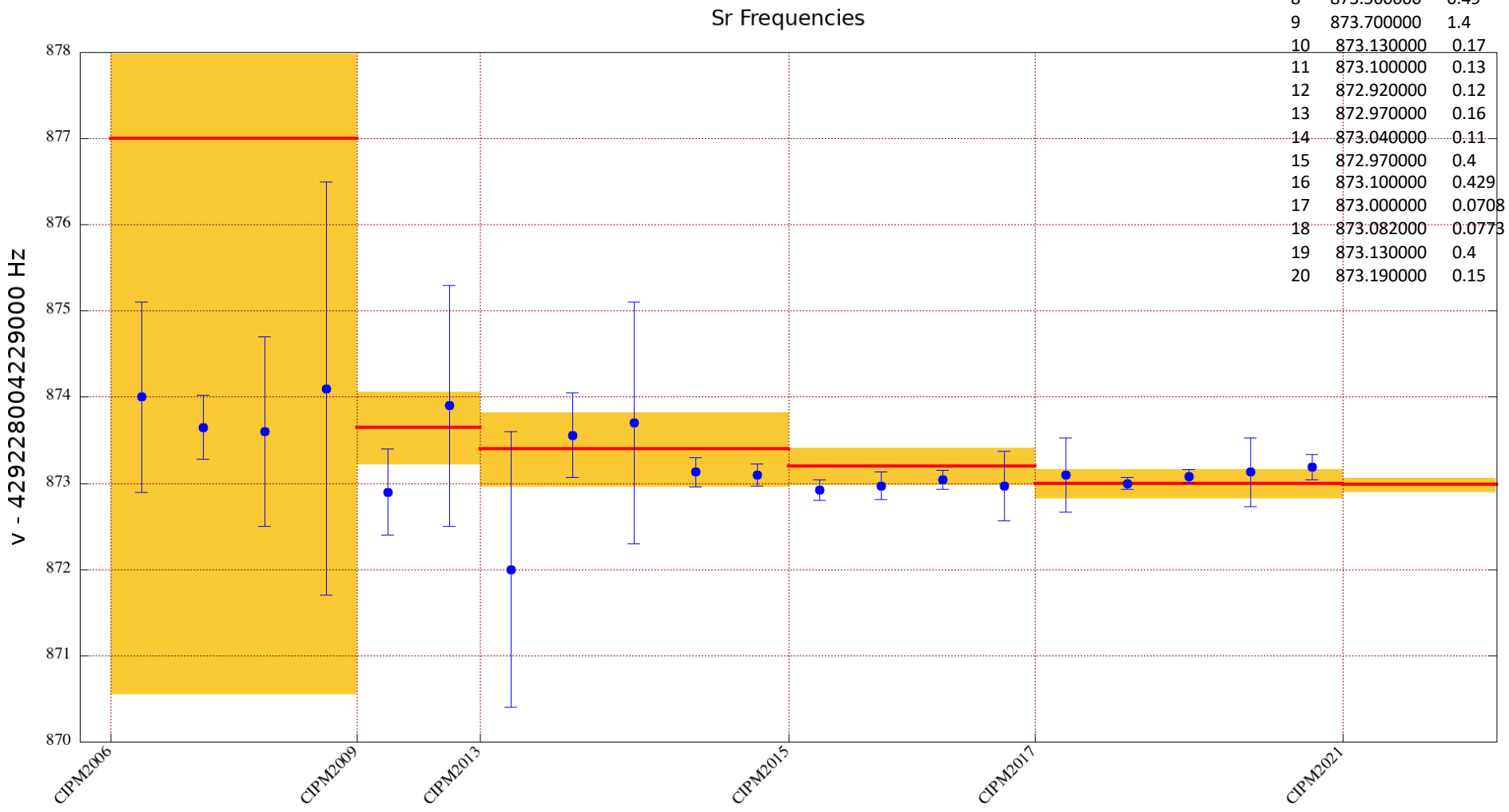


Uncertainty limited by the Cesium primary realization

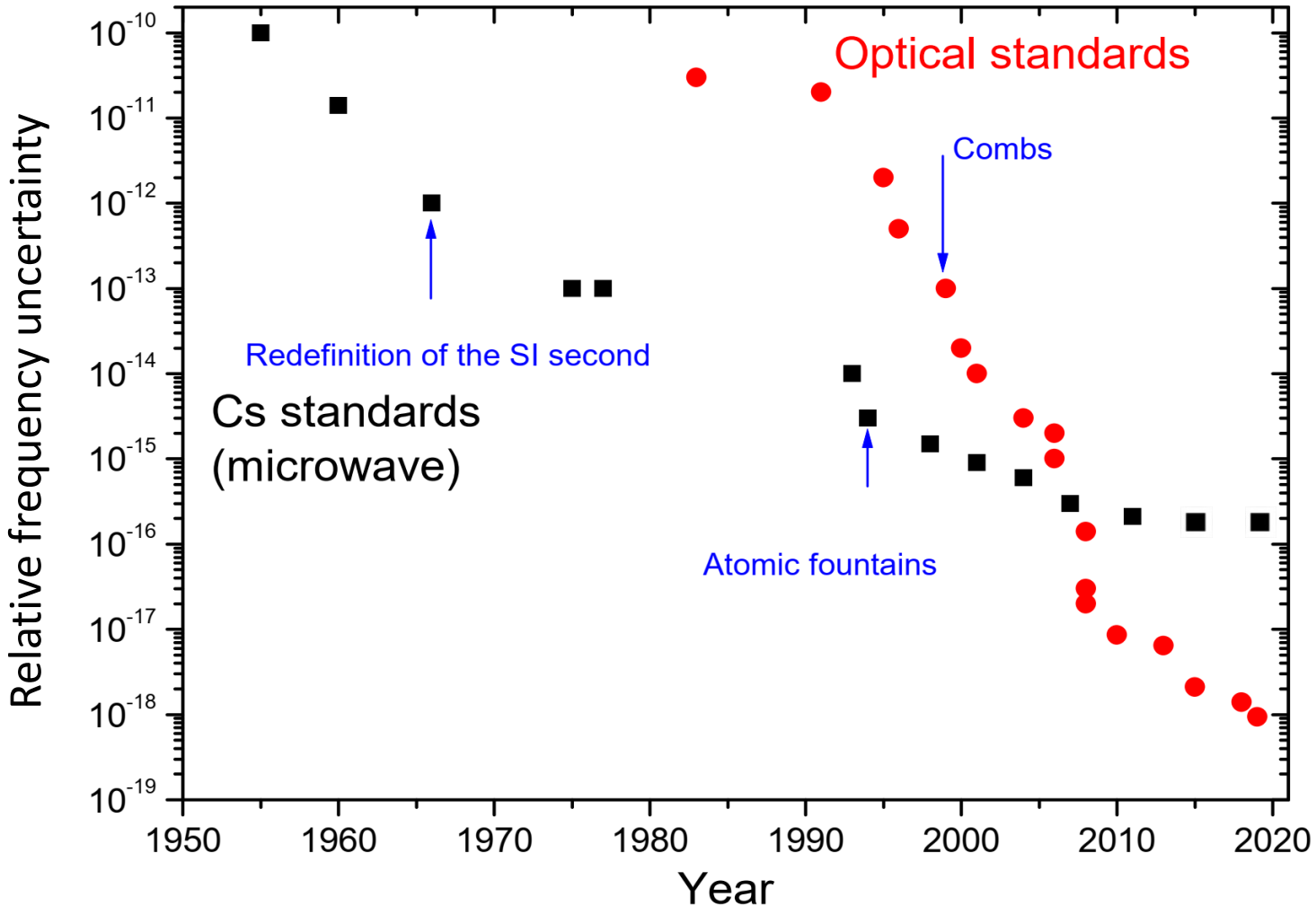
	2020 rec value	2020 rec unc
115In+	1267402452901041.3	4.3E-15
1H	1233030706593514	9.0E-15
199Hg	1128575290808154.32	2.4E-16
27Al+	1121015393207859.16	1.9E-16
199Hg+	1064721609899146.96	2.2E-16
171Yb+(E2)	688358979309308.24	2.0E-16
171Yb+(E3)	642121496772645.12	1.9E-16
171Yb	518295836590863.63	1.9E-16
40Ca	455986240494140	1.8E-14
88Sr+	444779044095486.3	1.3E-15
88Sr	429228066418007.01	2.0E-16
87Sr	429228004229872.99	1.9E-16
40Ca+	411042129776400.4	1.8E-15
87Rb	6834682610.9043126	3.4E-16

87Sr	429228004229872.99	1.9 E-16

1	874.000000	1.1	[Boyd2007]
2	873.650000	0.37	[Campbell2008]
3	873.600000	1.1	[Baillard2008]
4	874.100000	2.4	[Hong2009]
5	872.900000	0.5	[Falke2011]
6	873.900000	1.4	[Yamaguchi2012]
7	872.000000	1.6	[Akamatsu2014b]
8	873.560000	0.49	[Tanabe2015]
9	873.700000	1.4	[Lin2015]
10	873.130000	0.17	[Falke2014]
11	873.100000	0.13	[LeTargat2013]
12	872.920000	0.12	[Lodewyck2016]
13	872.970000	0.16	[Grebing2016(Oct14)]
14	873.040000	0.11	[Grebing2016(Jun15)]
15	872.970000	0.4	[Hachisu2017]
16	873.100000	0.429	[Hobson2020]
17	873.000000	0.0708	[Schwarz2020]
18	873.082000	0.0773	[Nemitz2020]
19	873.130000	0.4	[Grotti2018]
20	873.190000	0.15	[Leopardi2020]



The era of Optical Frequency metrology



Optical Frequency Standards (Sr, Yb, Yb+, Al+, Ca+, …) at 10^{-18} level

→ Time to change the definition?

Goals for a new definition

→ **Offer an improvement** by 10 to 100 of the realization of the new definition on short term after the redefinition (reaching 10^{-17} to 10^{-18} relative frequency accuracy) and a larger improvement on longer term

→ **Ensure continuity with the current definition**

→ **Ensure continuity and sustainability of the availability of the new SI second** through TAI, and a **significant improvement of the quality of TAI** as soon as the definition is changed (at least no degradation !)

→ **Enable the dissemination of the unit** towards wide categories of users

→ **Be acceptable** by all NMIs and stakeholders

Summary of options for the redefinition

— **Option 1:**

$$\nu_{\mathrm{Xy}} = N \ \mathrm{Hz}, c, h, e, k$$

- Example

$$\nu_{^{87}\mathrm{Sr}} = 429\ 228\ 004\ 229\ 872.99 \ \mathrm{Hz}, c, h, e, k$$

— **Option 2.1:**

$$\prod_i \nu_i^{w_i} = N \ \mathrm{Hz}, c, h, e, k \quad (\mathrm{with} \sum_i w_i = 1)$$

static definition

- Example

$$(\nu_{^{87}\mathrm{Sr}})^{0.25} (\nu_{^{171}\mathrm{Yb}})^{0.25} (\nu_{^{171}\mathrm{Yb}^+(\mathrm{E3})})^{0.2} (\nu_{^{27}\mathrm{Al}^+})^{0.3} = 650\ 464\ 137\ 090\ 812.53 \ \mathrm{Hz}, c, h, e, k$$

— **Option 2.2:**

$$\prod_i \nu_i^{w_i} = N \ \mathrm{Hz}, c, h, e, k \quad (\mathrm{with} \sum_i w_i = 1)$$

dynamic definition

CIPM can update w_i, N and the ensemble of chosen transitions following a set of predefined rules

Opt 2.2 is initially identical to opt 2.1, and include opt 1 as special case

— **Option 3:**

$$X, c, h, e, k$$

- Example:

$$m_e = 9.1093837015 \times 10^{-31} \ \mathrm{kg}, c, h, e, k$$

Options for the redefinition of the second

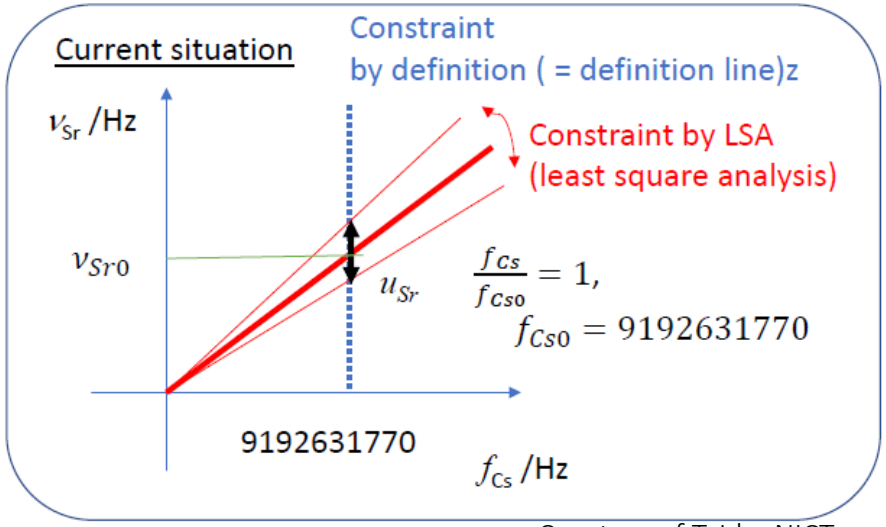
Option 1: Single atomic transition
Definition: fix the frequency of a single (optical) atomic transition

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

$$\Delta\nu_{\mathrm{Xy}} = 567\ 890\ 123\ 456\ 789.01\ \mathrm{Hz}$$

- Realization: with frequency standards based on Xy
- Continue to maintain and update a list of Second Representations of the Second (including Cs)
- To be redefined on the long term if major progress occurs in the uncertainty of frequency standards based on other transition(s)

→ **Classical approach similar to the current definition**
→ **Fix one frequency and measure all the others versus that one**
→ **Which one?** Currently, there are many promising transitions. The situation is highly dynamical, not settled. An obvious single best transition may or may not emerge



Courtesy of T. Ido, NICT

Options for the redefinition of the second

Option 2: Ensemble of transitions on an even basis
Definition: weighted geometric mean of an ensemble C of chosen transitions
Weight inversely proportional to the uncertainty of best standard using transition i

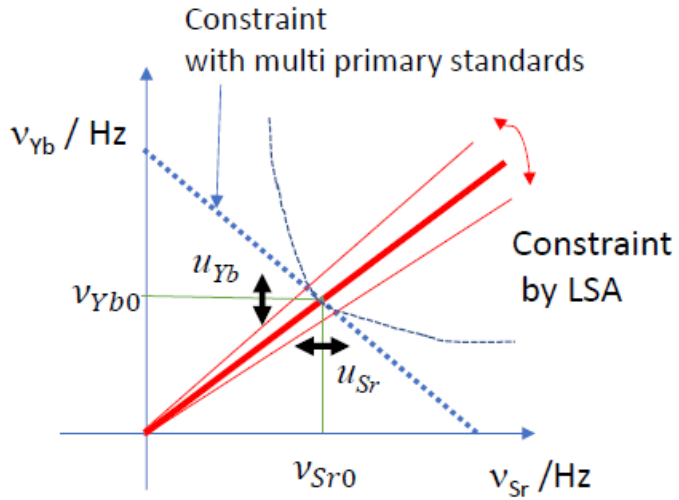
$$\Delta\nu_{\mathrm{Cs}} = 9\ 192\ 631\ 770\ \mathrm{Hz}$$

$$\nu = \frac{1}{N}\prod_{i\in C}\nu_i^{w_i}$$

See J. Lodewyck, Metrologia 56, 055009 (2019)

- Realization: with frequency standards based on transitions part of C (representations of the second) using frequency ratio matrix updated by the CIPM
- A single frequency standard i part of C realizes the unit
- 133Cs can (should) be part of C
- Including transitions in ensemble C and transitions not yet part of C
- Can follow the progress of frequency standards by updating the ensemble and the weights
- Merges the concept and use of primary and secondary representations of the second

→ **Fix a "mathematical constraint" and measure all frequencies versus that constraint**
→ **Frequency values are already interrelated**
→ **Species, weights and the constant N could be fixed at the time of the definition (Option 2) updated after the redefinition according to the OFS improvements (Option 2.2)**



Courtesy of T. Ido, NICT

Options for the redefinition of the second

Option 3: Fixing the value of another fundamental constant *X*

$$\Delta\nu_{\mathrm{Cs}}, c, h, e, k$$

$$X, c, h, e, k$$

- Directly connected to the underlying fundamental framework of general relativity and the standard model of particle physics
- Realization: would be based on atomic transition(s) (one of 2 previously discussed options)

Constant	Frac. Unc.
G	2.2×10^{-5}
m_e	3.0×10^{-10}
R_∞	1.9×10^{-12}
$\mathrm{H(1S-2S)}$	4.5×10^{-15}

→ **An ideal option that could complete the consistency of the SI system based on fundamental constants. But more futurist because to date, fundamental constants are known with a too large uncertainty**

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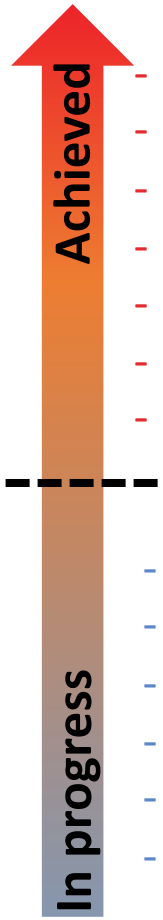
Priority setting of criteria / conditions to change definition



Mandatory criteria **To be achieved** before changing the definition

- Validation that Optical Frequency Standards 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 an adequate uncertainty level
- Definition allowing future more accurate realizations
- Access for NMIs to primary or secondary realizations of the new definition

Mandatory achievements frontier

Ancillary conditions corresponding to essential **Work still in progress** when the definition is changed

- 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

Priority setting of criteria / conditions to change definition

Frequency standards & contribution to atomic time scales

Mandatory criteria **To be achieved** before changing the definition

Achieved

- **Validation that Optical Frequency Standards 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 at the proper level
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Mandatory achievements frontier

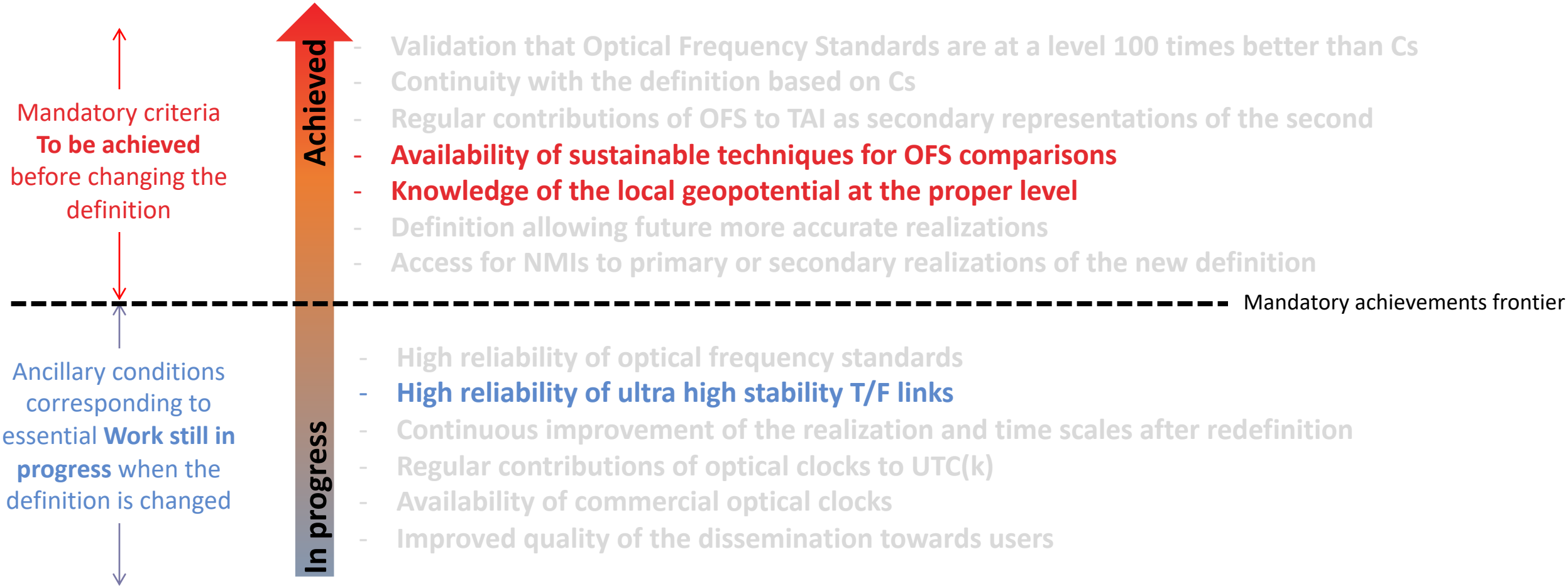
Ancillary conditions corresponding to essential **Work still in progress** when the definition is changed

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 (III.4)
- Improved quality of the dissemination towards users (III.5)

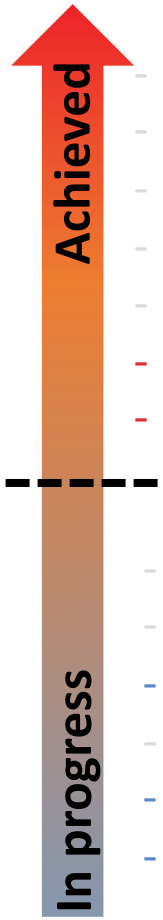
Priority setting of criteria / conditions to change definition

TF comparison and dissemination



Priority setting of criteria / conditions to change definition

Acceptability of the new definition



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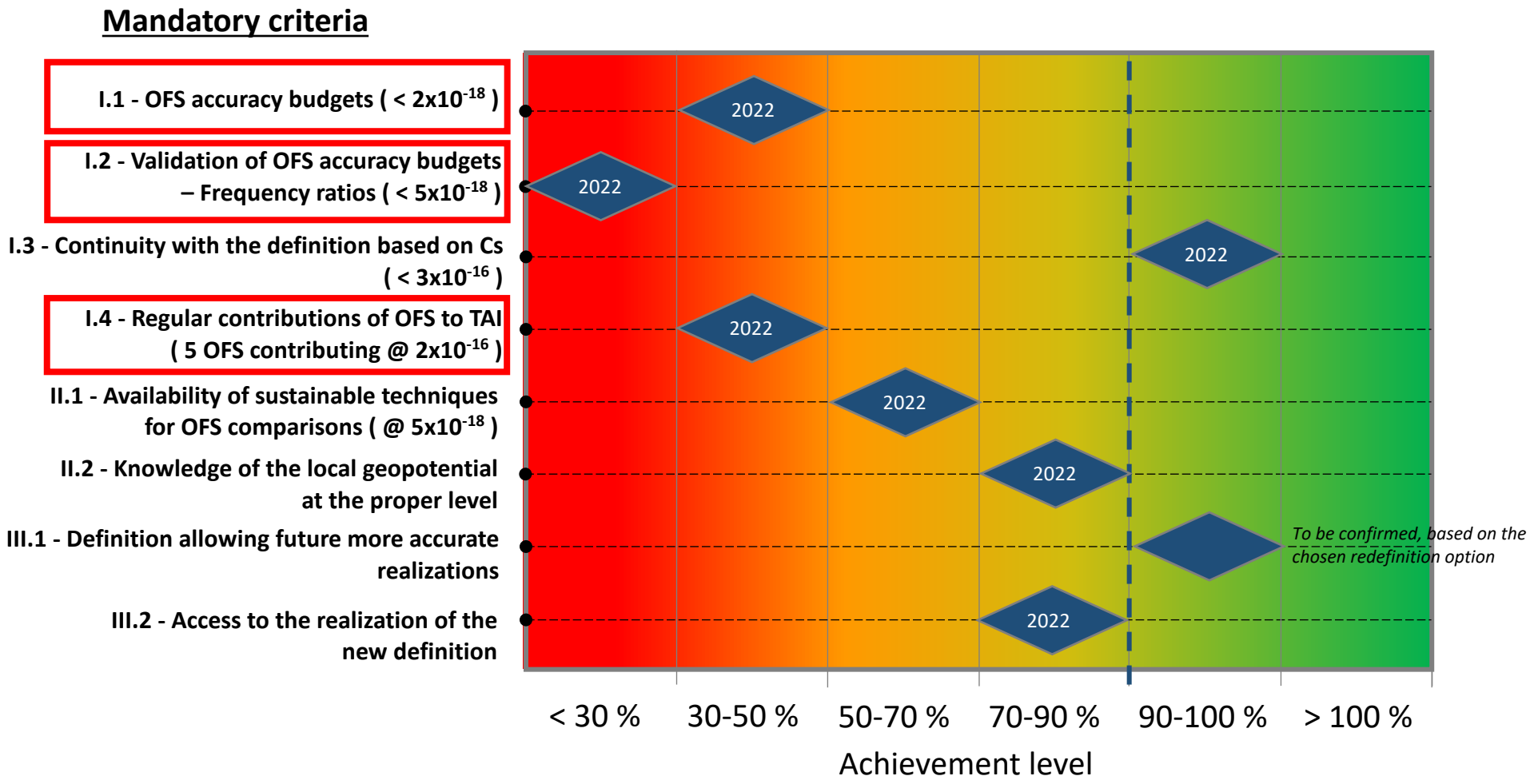
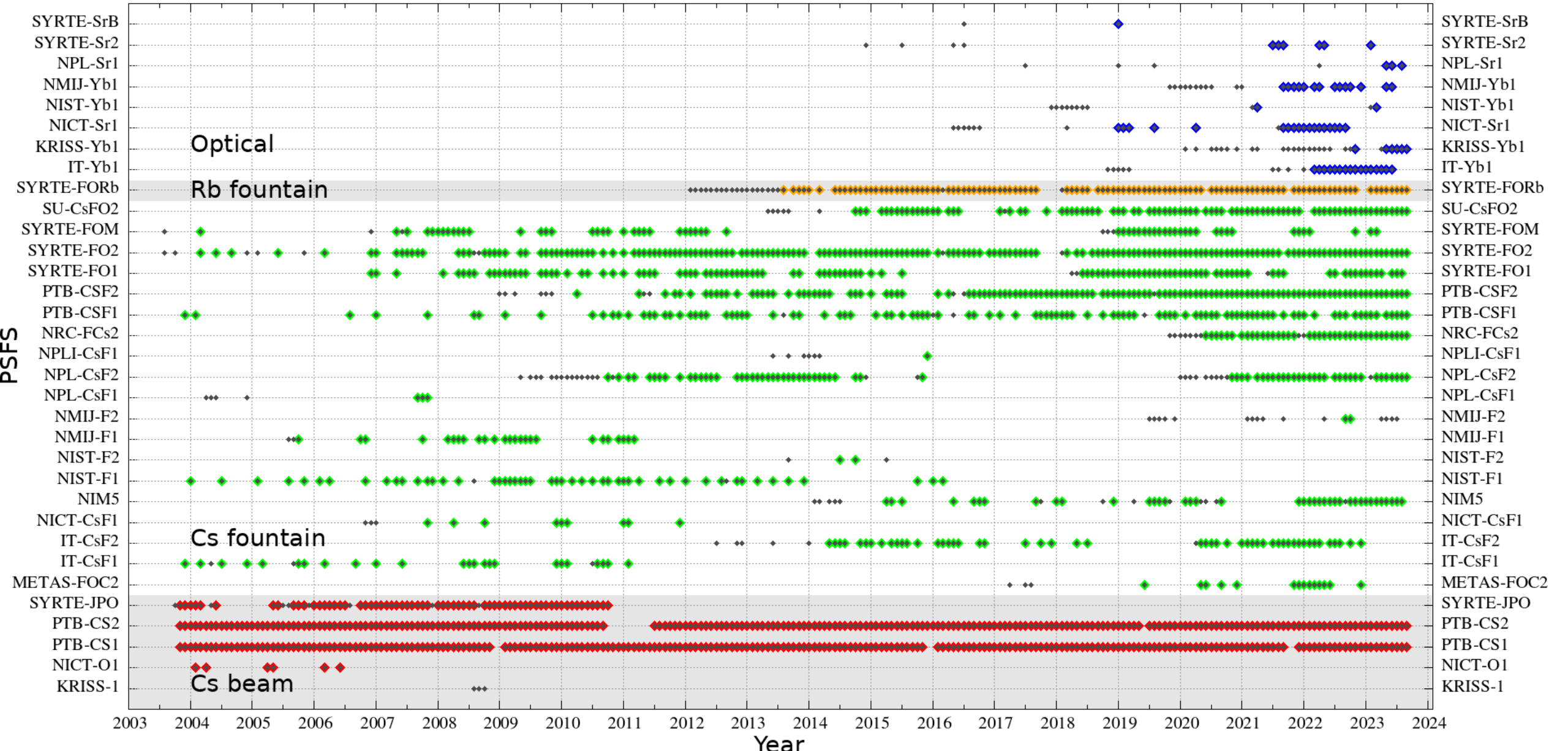
Fulfilment level of mandatory criteria (2022)

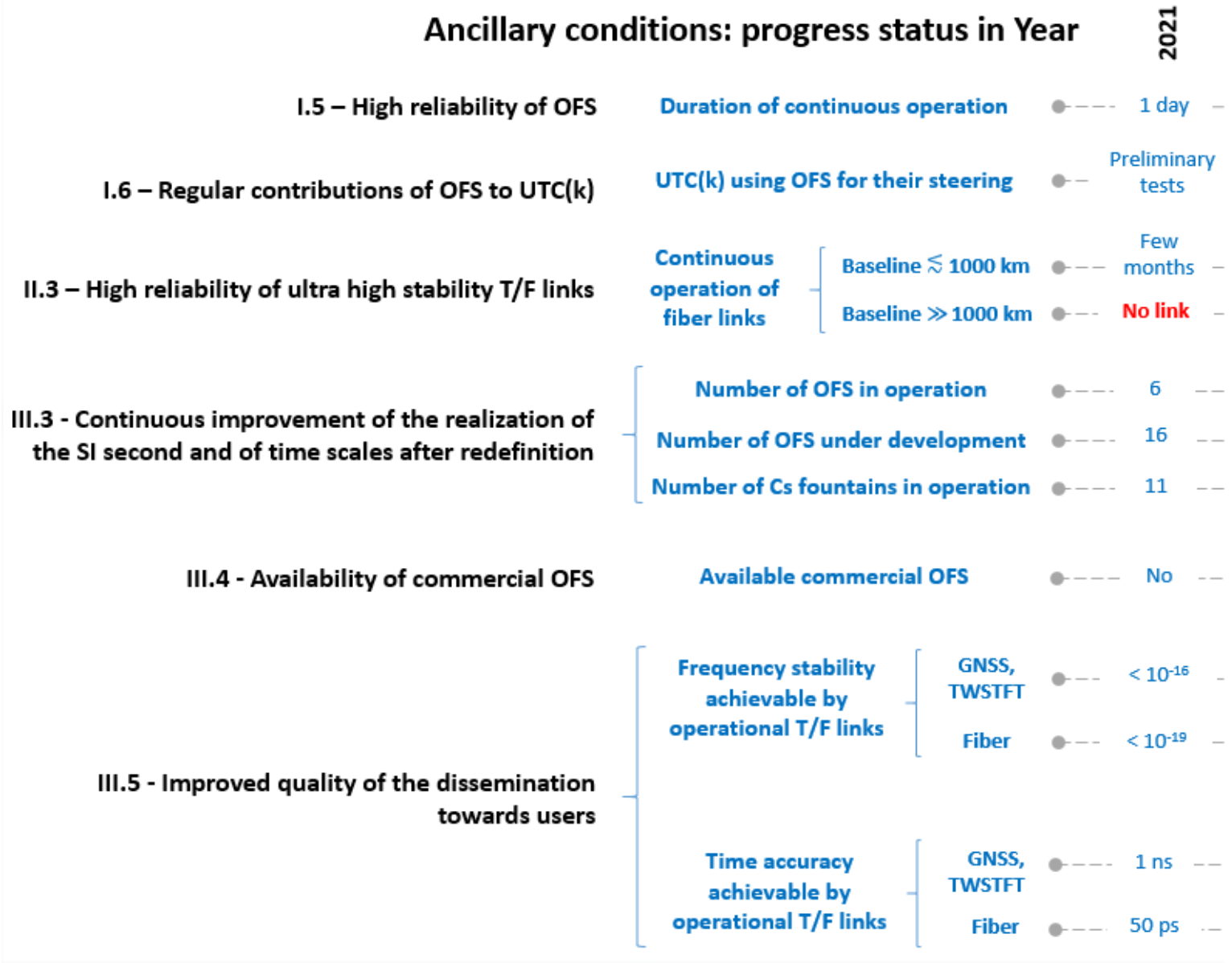


Contribution from Primary and Secondary Frequency Standards to UTC

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



Progress level of ancillary conditions



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Scenarios for the redefinition of the second

CGPM	2022	2026	2030	2034	….

A redefinition at CGPM 2026 is unrealistic since today there is no consensus on the preferred option and still some important work to do to fulfil all mandatory criteria.

Scenarios for the redefinition of the second

CGPM 2022 2026 2030 2034 ….

A redefinition at CGPM 2026 is unrealistic since today there is no consensus on the preferred option and still some important work to do to fulfil all mandatory criteria.

CGPM 2026 could validate a roadmap towards a redefinition in 2030 if, in 2026, there is a consensus on the redefinition option to be chosen and if the work to fulfil mandatory criteria is likely to be achievable by 2030.

Scenarios for the redefinition of the second

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CGPM 2026 could validate a roadmap towards a redefinition in 2030 if, in 2026, there is a consensus on the redefinition option to be chosen and if the work to fulfil mandatory criteria is likely to be achievable by 2030.

If it is not possible in 2030, the redefinition will have to be postponed, at CGPM 2034 or the following one… But it will require to maintain until the late 2030s the operation of Cs fountains primary frequency standards and their contributions to TAI calibration (a number of fountains have been built in the 1990s - 2000s).

CGPM 2022 Resolution 5 - On the future redefinition of the second

encourages the International Committee for Weights and Measures (CIPM)

- to promote the importance of achieving the objectives in the roadmap for the redefinition of the second,
- to bring proposals to the 28th meeting of the CGPM (2026) for the choice of the preferred species, or ensemble of species for a new definition of the second, and for the further steps that must be taken for a new definition to be adopted at the 29th meeting of the CGPM (2030),

and **invites** Member States to support research activities, and the development of national and international infrastructures, to allow progress towards the adoption of a new definition of the second.

Metrologia special focus

https://iopscience.iop.org/collections/0026-1394_challenges-in-time-and-frequency-metrology

1. **CCTF strategy *(in progress)***

2. **Roadmap towards the redefinition of the second *(accepted)***

   http://arxiv.org/abs/2307.14141

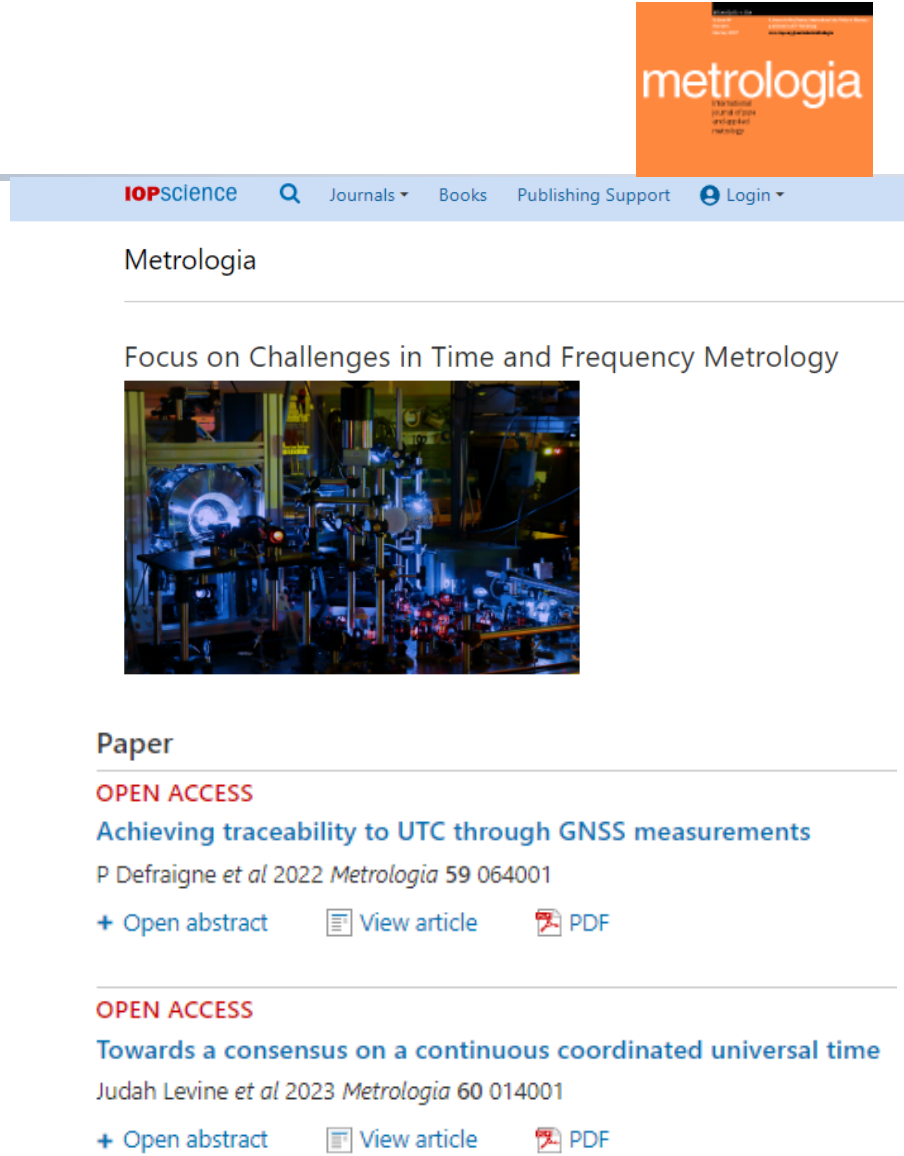
3. **Towards a consensus on a continuous UTC *(published)***

   https://iopscience.iop.org/article/10.1088/1681-7575/ac9da5

4. **Achieving traceability to UTC through GNSS measurements *(published)***

   https://iopscience.iop.org/article/10.1088/1681-7575/ac98cb

5. **Sharing Resources for Capacity Building *(included in paper 1)***



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Conclusion

→ Redefinition of the SI second:

- **Huge work done by the CCTF Task Force and T/F community to progress on the roadmap towards the redefinition of the second**
- **To be ready for a redefinition in 2030:**
  - ➢ reach a consensus on the preferred option for the new definition
  - ➢ have a good confidence in the capacity to fulfil the mandatory criteria before 2030 (on optical frequency standards and T/F links)
- **Decision at CGPM in 2026**

→ Reflections at the CIPM on the interface between Quantum Technologies and Metrology:

- Use of Quantum technologies in standards (frequency standards, electrical standards, …). What about quantum communication protocols for novel T/F transfer links?
- Identify National Metrology Institute capabilities that are relevant for quantum applications
- Identify and address industry's quantum measurement challenges and standardization needs.

Criteria and conditions
(Version 2021)

I - Criteria and conditions related to frequency standards and their contribution to time scales

To be achieved for redefinition

Criterion I.1 - Accuracy budgets of optical frequency standards

At least three optical frequency standards based on the same reference transition, in different institutes, have demonstrated evaluated relative frequency uncertainties $\lesssim 2 \times 10^{-18}$ (*).

At least three frequency evaluations of optical frequency standards based on different reference transitions, either in the same institute or different institutes, have demonstrated evaluated uncertainties $\lesssim 2 \times 10^{-18}$ (*).

(*) Based on comprehensive, comparable and published accuracy budgets.

Fulfilment Indexes:

- Number of OFS based on the same reference transition, in different institutes, with evaluated uncertainties $\lesssim 2 \times 10^{-18}$

Fulfilment level:

- Up to June 2021: 20-40 %

Sr: 2.0×10^{-18} [4], 5.5×10^{-18} [5]

Yb: 1.4×10^{-18} [6]

Yb+: 3.2×10^{-18} [7], 2.7×10^{-18} [9]

Al^+: 9.0×10^{-19} [8]

Ca^+: 3.0×10^{-18} [10]

- Number of frequency evaluations of OFS based on different reference transitions, either in the same institute or different institutes, with evaluated uncertainties $\lesssim 2 \times 10^{-18}$

Fulfilment level:

- June 2021: 80-100 %

Three different reference transitions (in different laboratories) have been evaluated at the required level:

Sr (2.0×10^{-18}) [4], Yb (1.4×10^{-18}) [6], Al^+ (9.0×10^{-19}) [8].

→ **June 2021: Overall Fulfilment Index for criterion I.1: 30-50 %**

Index monitored by CCTF-WGPSFS, CCL-CCTF-WGFS

I - Criteria and conditions related to frequency standards and their contribution to time scales

To be achieved for redefinition

Criterion I.2 - Validation of Optical Frequency Standard accuracy budgets – Frequency ratios

- Unit ratios (frequency comparison between standards with same clock transition): at least 3 measurements between OFS in different institutes with an agreement $\Delta\nu/\nu \lesssim 5\times10^{-18}$ (either by transportable clocks or advanced links). Applicable to at least one radiation of I.1.
- Non unit ratios (frequency comparison between standards with different clock transitions): at least 5 measurements between standards among I.1 or other, each ratio measured at least twice by different institutes with an agreement $\Delta\nu/\nu < 5\times10^{-18}$ (either by direct comparisons, transportable clocks or advanced links).

Fulfilment Indexes:

- Number of measurements of OFS with same clock transition in different institutes with an agreement $\Delta\nu/\nu \lesssim 5\times10^{-18}$

Fulfilment level:

- June 2021: 20-40 %

Unit ratios for three different reference transitions from I.1) have been measured once within the stated uncertainty: Yb (9×10^{-19}) [6], Yb^+ (4.2×10^{-18}) [9], Sr (4.7×10^{-18}) [5]

- Number of measurements of optical frequency ratios between standards of I.1 or other, each ratio measured at least twice by independent institutes with an agreement $\Delta\nu/\nu < 5\times10^{-18}$

Fulfilment level:

- June 2021: 0-20 %

Al+/Yb 4.8×10^{-18} [11]
Al+/Sr 7.0×10^{-18} [11]
Yb/Sr 6.4×10^{-18} [11]

→ **June 2021: Overall Fulfilment Index for Criterion I.2: < 30 %**

Indexes monitored by CCTF-WGPSFS, CCL-CCTF-WGFS

I - Criteria and conditions related to frequency standards and their contribution to time scales

To be achieved for redefinition

Criterion I.3 - Continuity with the definition based on Cs

There are at least three independent frequency evaluations of the optical frequency transitions utilized by the standards in I.1) with TAI or with three independent Cs primary frequency standards (in different or same institutes), possibly also via optical frequency ratio measurements, where the measurements are limited essentially by TAI or by the uncertainty of these Cs frequency standards ($\Delta\nu/\nu < 3 \times 10^{-16}$).

Fulfilment Index:

- Number of independent frequency evaluations of OFS listed in I.1) with uncertainty $\Delta\nu/\nu < 3 \times 10^{-16}$

Fulfilment level:

- June 2021: 90-110 %

Evaluations at the stated level:

Sr: 5 evaluations (published between 2013 and 2020) with an uncertainty in the range $1.5 - 3.1 \times 10^{-16}$ [12], [13], [14], [15], [16]

Yb: 2 evaluations (published in 2019 and 2020) with an uncertainty in the range $2.1 - 2.6 \times 10^{-16}$ [17], [18]

Yb+(E3): 1 frequency evaluation (published in 2021) with an uncertainty of 1.3×10^{-16} [19]

Indexes monitored by CCTF-WGPSFS, CCL-CCTF-WGFS

I - Criteria and conditions related to frequency standards and their contribution to time scales

To be achieved for redefinition

Criterion I.4 - Regular contributions of optical frequency standards to TAI (as secondary representations of the second)

At least 3 state-of-art calibrations of TAI (uncertainty $\lesssim 2\times10^{-16}$ without counting the recommended uncertainty of the secondary representation of the second u_rep) each month from a set of at least 5 Optical Frequency Standards for at least 1 year. Check that there is no degradation of TAI if its calibrations were done by OFS considered as primary standards and Cs frequency standards considered as secondary standards.

Fulfilment Index:

- Number of calibrations of TAI each month from a set of at least 5 Optical Frequency Standards for at least 1 year

Fulfilment level:

- June 2021: < 30 % (less than 0.5 report per month); 6 OFS (3 ^{87}Sr, 3 ^{171}Yb) have been validated by the WGPSFS for use in TAI steering (2 in 2017, 1 in 2018, 2 in 2019, 1 in 2020). 10 new reports in total have been submitted, seven of which at a time concerned the current month and three at a time the previous month. Excluding the initial submission which concerns measurements made months earlier, "regular" participation in 2020 is at most 0.5 per month, and all with uncertainty > 2×10^{-16}. None of the reports achieved the stated uncertainty, essentially because of Dead Time Uncertainty or because of Frequency Transfer Uncertainty or both.

Index monitored by CCTF-WGTAI

I - Criteria and conditions related to frequency standards and their contribution to time scales

Still in progress when redefinition

Condition 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.

Progress Index:

- Typical duration of OFS continuous operation

Progress status:

- June 2021: 1 day

Index monitored by CCTF-WGPSFS

Still in progress when redefinition

Condition I.6 - Regular contributions of optical frequency standards to UTC(k)

Progress Index:

- UTC(k) steered by OFS

Progress status:

- June 2021: Preliminary tests of UTC(k) steered by an OFS [20], [21], [22]

Index monitored by CCTF-WGTAI, CCTF-WGALGO

II - Criteria and conditions related to T/F links for comparison or dissemination

Criterion II.1 – Availability of sustainable techniques for Optical Frequency Standards comparisons

To be achieved for redefinition

Availability and sustainability of transportable clocks or T/F links with uncertainties < 5×10^{-18} for frequency comparisons between at least NMIs operating optical frequency standards of I.1), on a national / intracontinental basis (baseline up to about 1000 km). Capability of repeated uncertainty estimations of these links.

Fulfilment Index:

- Availability of transportable clocks approaching 5×10^{-18} or T/F links with uncertainties < 5×10^{-18} on a national / intracontinental basis

Fulfilment level:

- June 2021: 50-70 %

Uncertainties of fiber T/F links < 5×10^{-18} (in Europe , Japan, …)

Existence of transportable clocks approaching 5×10^{-18} [5]

Index monitored by CCTF-WGATFT, with contributions of CCTF-GNSS, CCTF-WGTWSTFT

II - Criteria and conditions related to T/F links for comparison or dissemination

To be achieved for redefinition

Criterion II.2 – Knowledge of the local geopotential with an adequate uncertainty level

Knowledge of geopotential differences for NMIs operating OFS of I.2) to be consistent with the uncertainty budget of a frequency comparison between OFS using advanced links, i.e. including the uncertainty budget of the two OFS and of the link.

Knowledge of local geopotential for NMIs operating OFS of I.4) with an uncertainty corresponding to a frequency uncertainty $\lesssim 10^{-17}$, for the calibration of TAI.

Fulfilment Index:

- For comparisons between OFS of I.2), uncertainty in the geopotential difference values sufficiently low with respect to the required uncertainty

-For NMIs operating OFS of I.4) for the calibration of TAI, uncertainty in the geopotential value $\lesssim 10^{-17}$

Fulfilment level:

- June 2021: 70-90 %

(Uncertainty of geopotential: NIST: 6×10^{-18}, INRIM: 3×10^{-18}, SYRTE: 4×10^{-18}, PTB: 2×10^{-18}, NICT: 2×10^{-17}, KRISS: 3×10^{-17}, NPL: 3×10^{-18}, NMIJ: 6×10^{-17})

[23], [24], [25], [26], [27], [28]

Index monitored by CCTF-WGPSFS, with contributions of CCTF-WGATFT, CCTF-WGTAI

II - Criteria and conditions related to T/F links for comparison or dissemination

Still in progress when redefinition

Condition 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.

Progress Index:

- Existence of reliable ultra-high stability T/F links

Progress status:

- June 2021: A few months continuous unmanned operation of fiber links for intracontinental comparisons [29], [30]
  No existing link that does not limit OFS intercontinental comparisons

Index monitored by CCTF-WGATFT, with contributions of CCTF-GNSS, CCTF-WGTWSTFT

III – Criteria and conditions related to the acceptability of the new definition

To be achieved for redefinition

Criterion III.1 - Definition allowing future more accurate realizations

The new definition must be long lasting. On the short term (just after the redefinition), it must ensure an improvement by 10/100 of its realization with OFS, i.e. reaching 10^{-17} / 10^{-18} relative frequency uncertainty. On the longer term, it must have the potential for further improvement of the realization of 10^{-18} and beyond in order to avoid any early obsolescence of the definition.

Fulfilment Index:

- No identified fundamental effect limiting OFS accuracy at 10^{-18} level

Fulfilment level:

- **June 2021: 100 %** (To be confirmed, based on the chosen option for the redefinition, but all species in I.1, and some newer systems have the potential to go beyond 10^{-18})

III – Criteria and conditions related to the acceptability of the new definition

To be achieved for redefinition

Criterion III.2 - Access to the realization of the new definition

- Realization / "mise en pratique" of the new definition must be easily understandable with a clear uncertainty evaluation process;
- Access for NMIs and high accuracy users to primary or secondary realizations of the new definition;
- Cs frequency standards ensure a secondary realization of the new definition.

Fulfilment Indexes:

- Existence of a document explaining the Mise en Pratique of the definition

Fulfilment level:

- June 2021: 0 % (No existing document; pending on the choice of the redefinition option)

- Access for NMIs and high accuracy users to primary or secondary realizations of the definition at least similar to the current situation

Fulfilment level:

- June 2021: 100 % (To be confirmed, based on the chosen option for the redefinition, but primary or secondary representations of the SI second will continue to be accessible via metrology institutes or TAI)

- Insurance of the capability of using Cs frequency standards as secondary realization of the new definition

Fulfilment level:

- June 2021: 100 % (existing TAI architecture will be maintained at current level or better and Cs will be a secondary representation of the second.

→ **June 2021: Overall Fulfilment Index for Criterion III.2: 70-90 %**

III – Criteria and conditions related to the acceptability of the new definition

Still in progress when redefinition

Condition III.3 - Continuous improvement of the realization and of time scales after redefinition

Commitment of NMIs to make the best effort to:

- improve and operate optical frequency standards that provide primary or secondary realizations of the new definition (reliable / continuous operation, regular contributions to TAI, …);
- develop new OFS;
- maintain the operation of Cs fountain standards over the appropriate duration.

Progress index:

- Number of operating OFS, number of OFS under development, number of operating Cs fountains

Progress status:

- June 2021: 11 Cs fountains in operation, 22 OFS (6 in operation, 16 under development) with the following species: Sr (9), Yb (5), Yb+ (4), Hg (1), Al+ (1), Sr+ (1), In+ (1)

Index monitored by CCTF-WGPSFS

III – Criteria and conditions related to the acceptability of the new definition

Still in progress when redefinition

Condition III.4 - Availability of commercial optical frequency standards

Progress index:

- Available commercial OFS

Progress status:

- June 2021: No available commercial OFS

Index monitored by CCTF-WGPSFS, CCTF-WGTAI

Still in progress when redefinition

Condition III.5 - Improved quality of the dissemination towards users

Progress index:

- Performance of T/F links (GNSS, TWSTFT, Fiber / Internet) for the dissemination of the definition towards users

Progress status:

- Frequency stability:
  - June 2021: 10^{-17} – 10^{-16} for satellite microwave techniques (GNSS, TWSTFT); 10^{-20} level for fiber links [31]
- Time accuracy:
  - June 2021: 1 ns for satellite microwave techniques (GNSS, TWSTFT); 50 ps for fiber links [32]

Index monitored by CCTF-WGTAI, CCTF-GNSS, CCTF-WGTWSTFT, CCTF-WGATFT, CCTF-WGMRA