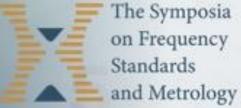
9th Symposium on Frequency Standards and Metrology 2023

Kingscliff, NSW, Australia 16–20 October 2023



Roadmap towards a redefinition of the SI second

Noel Dimarcq Patrizia Tavella CIPM Member, CCTF President BIPM, CCTF Executive secretary

with the

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

Bureau
International des
Poids et
Mesures



††**| CCTF**

Definitions of the SI unit of time



Astronomy (from the configurations of a dynamical system)

Quantum physics (frequency of a periodic process)



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

→ until 1960 : the fraction 1/86 400 of the mean solar day

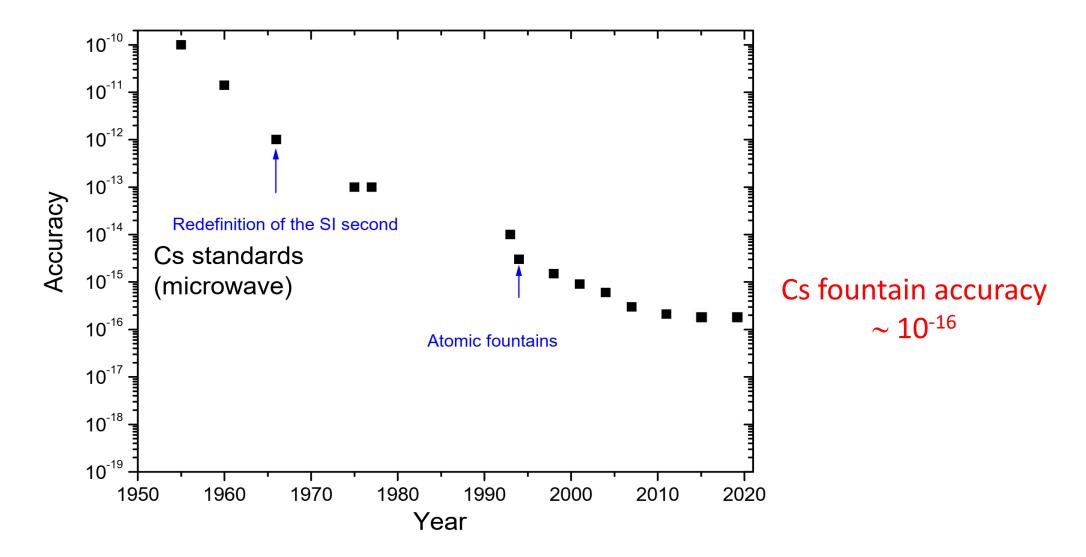
→ 1960 to 1967 : the fraction 1/31,556,925.9747 of the tropical year 1900 1 tropical year = 365,2422 solar days = 366,2422 sideral days

→ 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 Δv_{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



13th General Conference on Weights and Measures CGPM (1967)

Resolution 1

The second is 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 caesium 133 atom.

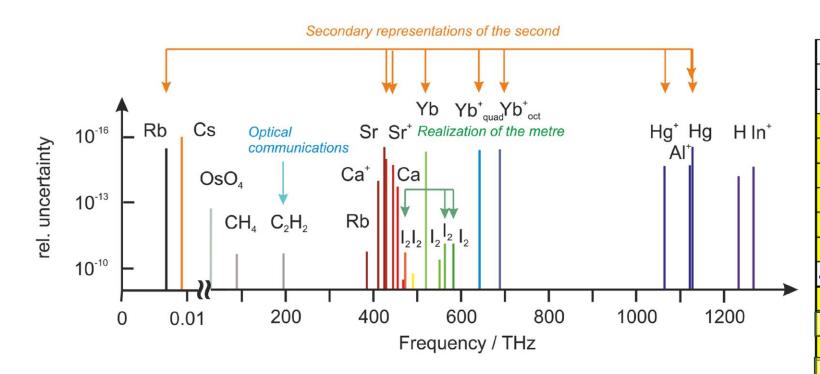
Resolution 2

Considering that the cesium frequency standard is still perfectible and current experiments allow the hope of producing other standards with even better qualities to define the second, invites laboratories in the field of atomic frequency standards to actively pursue their studies.

Since 2001 CCL-CCTF working group on Frequency Standards:

produces and maintains a single list of *Recommended frequency standard values for applications including the practical realization of the metre and 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



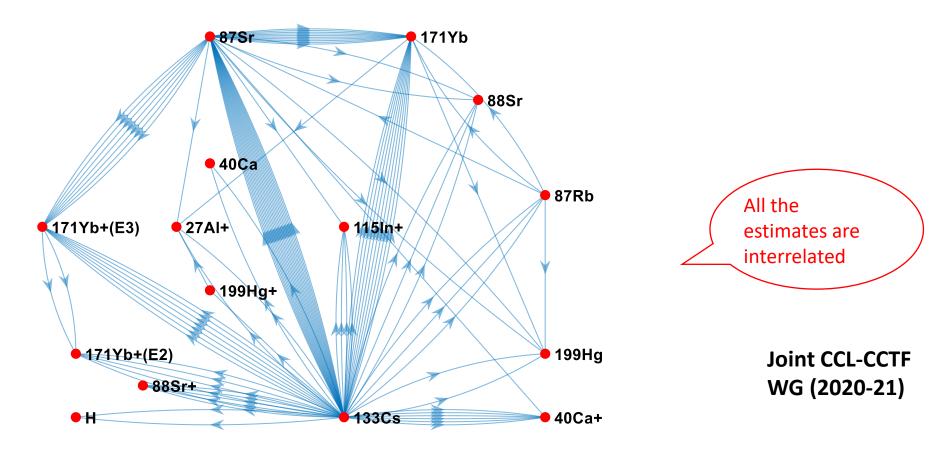
	2020 rec value	2020 rec uno		
115In+	1267402452901041.3	4.3E-15		
1H	1233030706593514	9.0E-15		
199Hg	1128575290808154.32	2.4E-16		
27Al+	1121015393207859.16	1.9E-16		
199Hg+	1064721609899146.96	2.2E-16		
171Yb+(E2)	688358979309308.24	2.0E-16		
171Yb+(E3)	642121496772645.12	1.9E-16		
171Yb	518295836590863.63	1.9E-16		
40Ca	455986240494140	1.8E-14		
885r+	444779044095486.3	1.3E-15		
885r	429228066418007.01	2.0E-16		
875r	429228004229872.99	1.9E-16		
40Ca+	411042129776400.4	1.8E-15		
87Rb	6834682610.9043126	3.4E-16		

Uncertainty limited by the Cesium primary realization

Values of the secondary representations of the second from a multisystem of frequency ratio measures

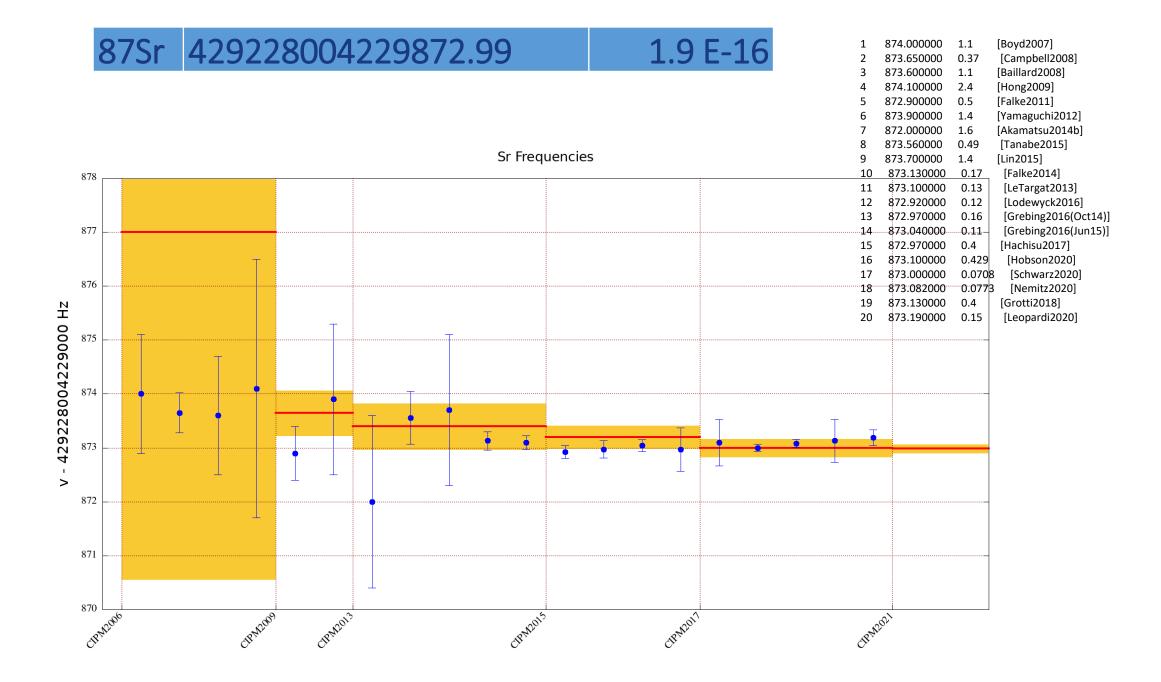
Estimation by 3 independent methods and software

Take into account the correlation between measurements (e.g. due to their comparison to the same Cs standards

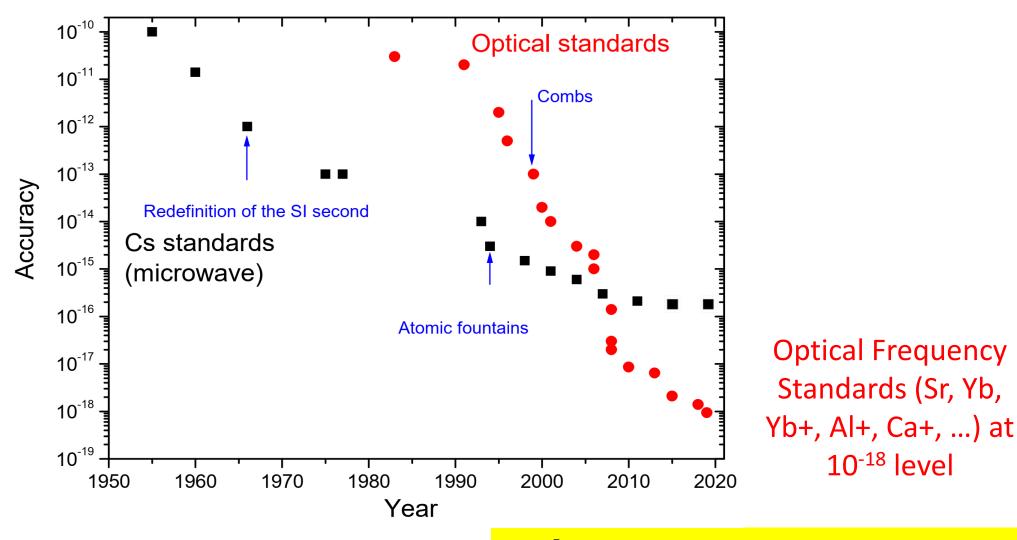


Graphical representation of 105 frequency measures (33 optical frequency ratios and 72 absolute frequency measures vs Cesium) used for the calculation of 14 frequency values.

The new computational mode has been able to take into account 483 correlations



The era of optical frequency metrology



→ Time to change the 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

\rightarrow Ensure continuity with the current definition

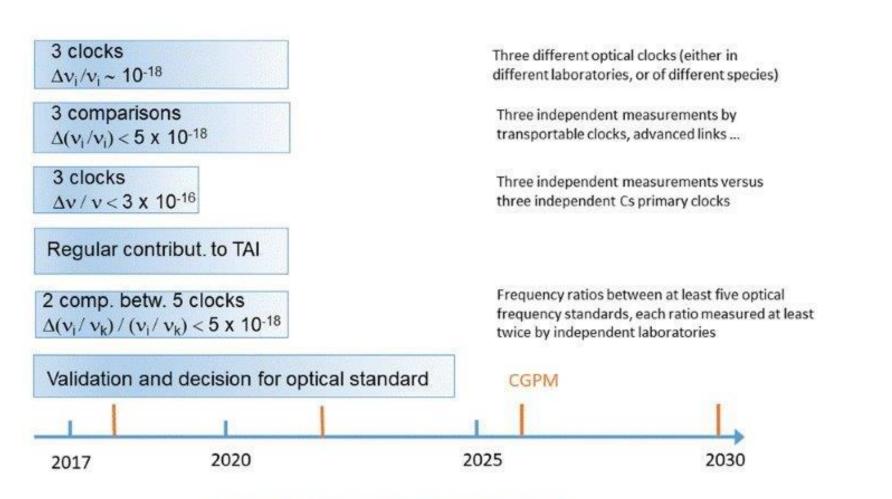
→ Ensure continuity and sustainability of the availability of the new SI second through TAI, and a significant improvement of the quality of TAI as soon as the definition is changed (at least no degradation !)

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

 \rightarrow **Be acceptable** by all NMIs and stakeholders

Criteria fixed in 2016 for a change of the definition

Roadmap towards a redefinition of the SI second (CCTF 2016)



CCTF Task Force Updating the roadmap towards the redefinition of the SI second

Roadmap and mandatory criteria

- A. Request from user communities, NMIs and Liaisons
- B. Atomic frequency standards, and redefinition approaches
- C. TF Dissemination and time scales

(N. Dimarcq CIPM, P. Tavella BIPM)

(M. Gertsvolf, NRC; G. Mileti, Uni Neuchatel)

(S. Bize, SYRTE; E. Peik, PTB; C. Oates, NIST)

(D Calonico, INRIM; T. Ido NICT)

More than 40 people from all the RMOs, all CCTF members at work

=> Started in 2020, presented the objectives to the CCTF 22-1 in October 2020, updates on the work to the CCTF 22-2 in March 2021, and CCTF 23rd in June 2022,

- Launched a questionnaire online and stimulated > 200 answers
- Defined the mandatory criteria and the ancillary conditions for the redefinition readiness
- Evaluated the status of criteria fulfilment in 2021 and 2022
- Evaluated the impact on the user communities
- Proposed 3 possible options for the redefinitions and organized two related workshops online
- Published a Metrologia paper (accepted, under revision, <u>http://arxiv.org/abs/2307.14141</u>), and several posters/papers in international fora



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

n progress

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

- 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 a sufficient uncertainty level
- Definition allowing future more accurate realizations
- Access for NMIs to primary or secondary realizations of the new definition

Mandatory achievements frontier

- 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

Frequency standards & contribution to atomic time scales

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
- Definition allowing future more accurate realizations
- Access for NMIs to primary or secondary realizations of the new definition

Mandatory achievements frontier

- 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)

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

progress

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

TF comparison and dissemination

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

progress

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

- 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
- Definition allowing future more accurate realizations
- Access for NMIs to primary or secondary realizations of the new definition

Mandatory achievements frontier

- 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

Acceptability of the new definition

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

n progress

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

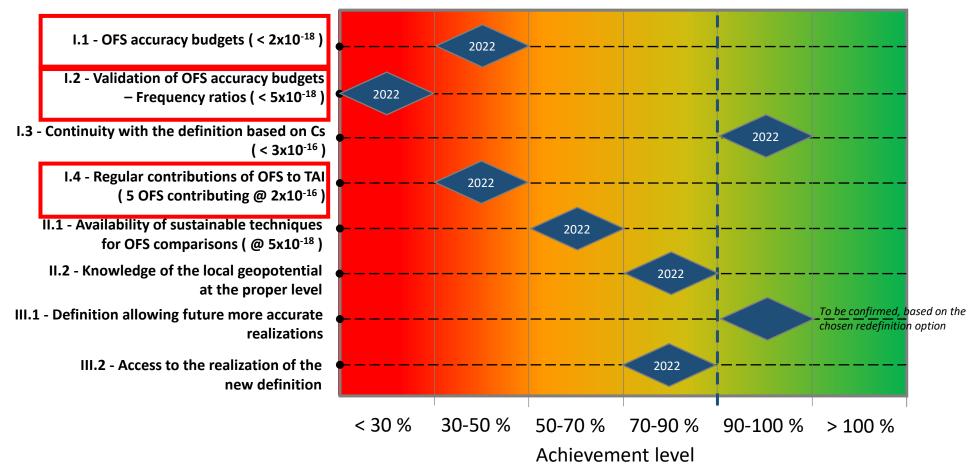
- Validation that Optical Frequency Standards are at a level 100 times better than Cs
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-- Mandatory achievements frontier

- 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

Fulfilment level of mandatory criteria (2022)

Mandatory criteria



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

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

To be achieved for redefinition

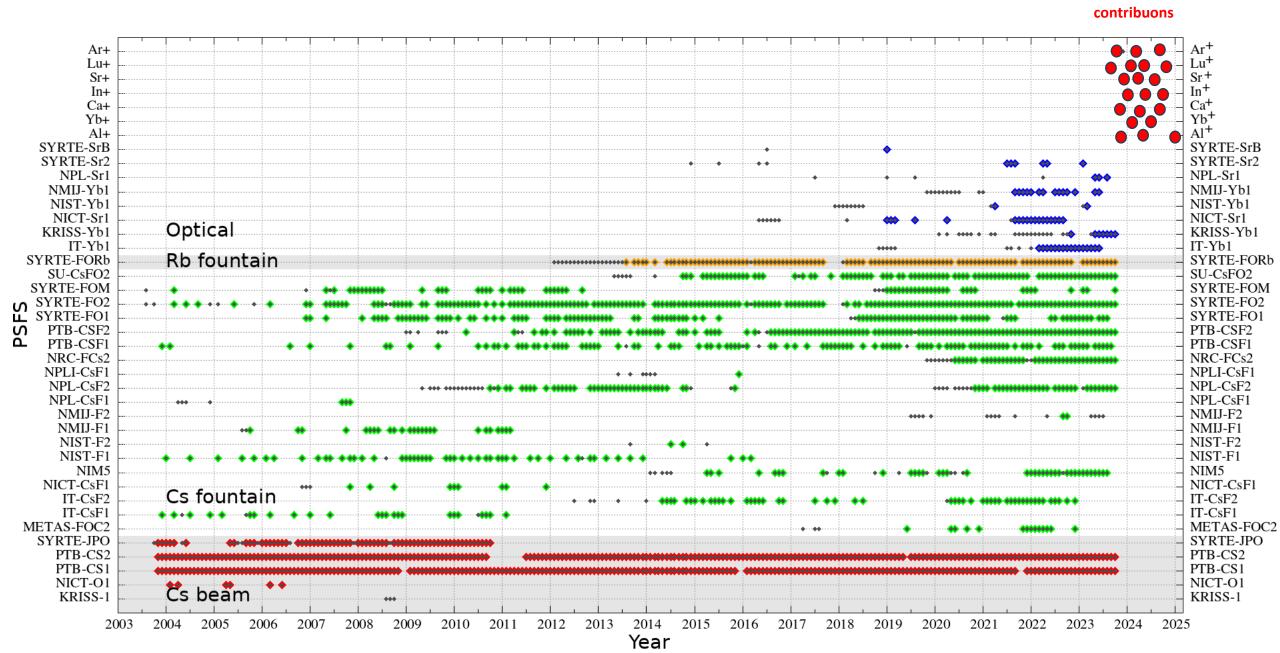
At least 3 state-of-art calibrations of TAI (uncertainty $\leq 2x10^{-16}$ without counting the recommended uncertainty of the secondary representation of the second usrep) each month from a set of at least 5 Optical Frequency Standards for at least 1 year. Check that there is no degradation of TAI if 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

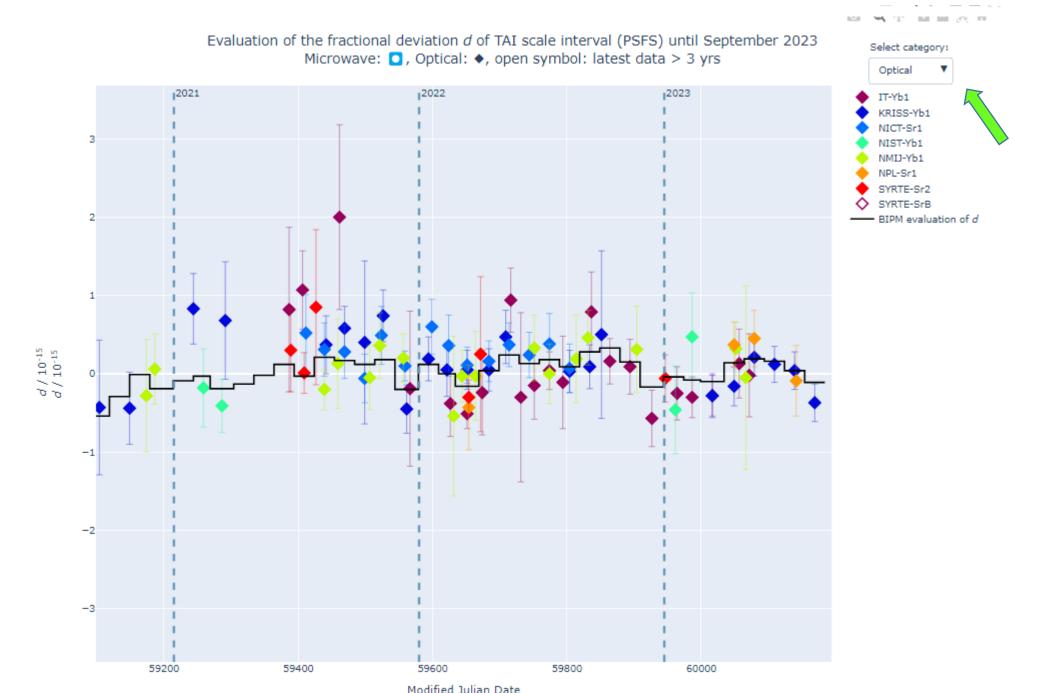
Contribution from Primary and Secondary Frequency Standards to UTC

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



Next ion standard

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



Progress level of ancillary conditions

Ancillary con	ditions: progress status in Ye	ear	2021	2023	2025	2027	2029	2030
I.5 – High reliability of OFS	Duration of continuous operation	•	1 day					>
I.6 – Regular contributions of OFS to UTC(k)	UTC(k) using OFS for their steering	•	Preliminar tests	У				>
II.3 – High reliability of ultra high stability T/F links	Continuous operation of fiber linksBaseline \lesssim 1000 km						-	-
III.3 - Continuous improvement of the realization of the SI second and of time scales after redefinition	Number of OFS in operation Number of OFS under development Number of Cs fountains in operation	•	. 16 .					\geq
III.4 - Availability of commercial OFS	Available commercial OFS	•	No -				>	≥
	Frequency stability GNSS, achievable by TWSTFT	•	< 10 ⁻¹⁶					>
III.5 - Improved quality of the dissemination towards users	operational T/F links Fiber	•	< 10 ⁻¹⁹					≥
	Time accuracy GNSS, achievable by - TWSTFT	•	- 1 ns -				>	≥
	operational T/F links Fiber	•	50 ps				>	≥

Summary of options for the redefinition

$$\begin{array}{ll} - & \underline{\mathsf{Option 1:}} \\ \nu_{\mathrm{Xy}} = N \; \mathrm{Hz}, c, h, e, k \\ \bullet \; \mathrm{Example} \\ - & \underline{\mathsf{Option 2.1:}} \\ \bullet \; \mathrm{Example} \\ - & \underline{\mathsf{Option 2.1:}} \\ \bullet \; \mathrm{Example} \\ - & \underline{\mathsf{Option 2.2:}} \\ & \prod_{i} \nu_{i}^{w_{i}} = N \; \mathrm{Hz}, c, h, e, k \quad (\mathrm{with} \sum_{i} w_{i} = 1) \\ & \prod_{i} \nu_{i}^{w_{i}} = N \; \mathrm{Hz}, c, h, e, k \quad (\mathrm{with} \sum_{i} w_{i} = 1) \\ & \prod_{i} \nu_{i}^{w_{i}} = N \; \mathrm{Hz}, c, h, e, k \quad (\mathrm{with} \sum_{i} w_{i} = 1) \\ & \prod_{i} \nu_{i}^{w_{i}} = N \; \mathrm{Hz}, c, h, e, k \quad (\mathrm{with} \sum_{i} w_{i} = 1) \\ & \prod_{i} \nu_{i}^{w_{i}} = N \; \mathrm{Hz}, c, h, e, k \quad (\mathrm{with} \sum_{i} w_{i} = 1) \\ & \mathrm{CIPM} \; \mathrm{can update} \; w_{\mu} \; N \; \mathrm{and the ensemble of chosen transitions following a set of } \underbrace{\mathrm{predefined rules} \\ & \mathrm{Opt 2.2 \; is initially identical to opt 2.1, and include opt 1 \; \mathrm{as special case} \end{array}$$

– Option 3:

1

• Example:

www.bipm.org

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

21

Strengths, Weaknesses, Opportunities and Threats

- Based on the many inputs from CCTF workshop participants
 - A Git page was used
 - One SWOT analysis for each option 1, 2 & 3.
 - 3 discussion tracks: "understanding the options", "Fundamental issues of the definition" and "Primary/secondary realizations"

					💭 🛆 TheBIPM / cctf-tf-redef > Projec	jects 👌 🔒 SWOT analysis for option 3	Q Filter cards	+ Add cards 🗧 Exit fullsc	
		* * * * •	· · · · · ·		+ 2 Strengths	+ ··· (3) Weaknesses	+ ··· 0 Opportunities	es + …	4 Threats +
General O	· · · · · · · · · · · · · · · · · · ·		+ + + + + General + + + +	+ + + + + + + + + General + +	Matched to the approach adopted by CGPM 2018 with c, h, e, k	in frequency metrology and related applications.	ed		E Breaks the metrological principle that any new definition of a measurement unit should be consistent with the old
Understanding the	e options Fundame	nental issues of t <u> </u> 🗛 🏎	'heBIPM / cctf-tf-redef > Projects > 🔒 SWC	SWOT analysis for option 2	Q Filter cards	+ Add cards 🐈 Exit fullscr			definition to within the uncertainty with which the old definition can be realised.
🖶 ndimarcq 💡 💊	o o o 🔛 🕘 patriziat	iatavella + + + 📝 🖲 Strength	ngths + ···	14 Weaknesses + ···	3 Opportunities + ···	• 5 Threats + •••			Added by HelenMargolis
C A TheBIPM / cctl-tf-redet > Projects > A :	SWOT analysis for option 1	present	ent situation with several optical itions are outperforming Cs	The definition of the unit of time is adopted in a number of national laws on legal time. It may become difficult to the tailor and the transitional lawnskers to accept a time definition where potential area not under their control.	[From INRiM] strong stimulus to explore *** new frequency standards options. Added by fmeynadier Schemes and rules can be adopted (by ***	optical frequency standards.	resent *** t):		[From INRIM] Possibility to jeopardize *** critical technologies, like e.g. satellite navigation (frequency inaccuracy is reflected to position inaccuracy). Added by fmeynadier
8 Strengths +	4 Weaknesses + ···	·	6 Threats	+ ···· i by epeik	CGPM/CIPM) such that the definition will adapt more easily to the fast continuing	Added by HelenMargolis	orse		If option 3 is chosen, future change(s) of***
E Familiar and practical, using primary and *** secondary realisations just as we do today.	[from INRiM] No clear best transition is "" currently identified, based neither on metrological (best transition), nor on geo-	Many advantages of the many-species Approach (option 2) could be realized with a single primary and many-SR	A Image of the accuracy of frequency standards, by biasing future developments towards ("evolves") which is essentially a	A lefinition of the unit changes over ("evolves") which is essentially a	adapt more easily to the last commany progress of optical frequency standards. Added by fmeynadier understanding.				~1E-12 or more (1E-10 for m_e) of the realization of the second (including the scale interval of TAI) and of the entire
Added by HelenMargolis	political reasons (most widespread clock). Added by fmeynadier	approach with more aggressive uncertainty determination of the SRs. If a re-definition occurs based on a single	the atomic transition selected as the primary standard.	inition by another name. In the ition of other base units the imental constant is fixed.	E All short term and long term benefits associated to an improvement by 100 of	Added by HelenMargolis			system of units. Added by fmeynadier
 Consistent with the current SI base unit *** definitions. 	Secondary representations of the second required to achieve sufficient dissemination	optical transition, high accuracy measurements between the optical	Added by HelenMargolis	i by HelenMargolis	the realization of the unit of time.	 [From INRiM] Need of more radical redefinition, realigned with the present 			Poor accuracy of realization in the
Added by HelenMargolis	(at least at the beginning) Added by fmeynadier	clocks could help keep the uncertainties for the SRs small in the future. Added by elizabeth-donley	practice, the main high-level disseminations (including TAI) will be done by or dominated by secondary	defining constant" has no physical ***		one based on Cs, in case one species will emerge as the most accurate one. Added by fmeynadier			present and foreseeable future (1E-12 at best): more than 4 order of magnitude worse than present definition and 6
will emerge as the most accurate one, the path toward a new redefinition will be straightforward and in continuity	Need to tradeoff best standard against broad enough use of this standard	[From INRIM] Clear path forward for all *** who are willing to develop a primary	representations. Added by fmeynadier	ant or an atomic property. Hence it not have the same qualities as the six defining constants.		Development of commercial systems *** become ricks or or discoursed uplace			orders of magnitude than optical frequency standards uncertainties.
with the history of the second definition changes decided in the past.	Added by fmeynadier	clock. Added by fmeynadier	That the chosen transition will be	i by HelenMargolis		becomes risky or are discouraged unless one or two transitions become			
Added by fmeynadier	Difficulty to reach a consensus for the single transition given the diversity of		surpassed fast, pushing toward another redefinition after 1 or 2 decades only.	ms unlikely that any individual		dominant. Added by fmeynadier			
[from INRiM] The present situation "" where we rely on primary clocks and	transition used Added by fmeynadier	Stimulate the development of commercial standards	Added by fmeynadier	atory would be able to realise the ition in isolation - it seems similar onsensus value, which is exactly		Difficulty to sustain calibrations of TAI			
secondary representations of the second will be maintained.	Address of interference	Added by fmeynadier	Project based on other transitions hampered or stopped, due to	tuation that is currently trying to		by optical standards in quality and			
Added by fmeynadier		All short term and long term benefits associated to an improvement by 100 of the militation o	reallocation of resources and delays to develop standards based on the chosen				4		22
[from INRIM] : No limit to the intrinsic *** accuracy of the definition of the second. In principle we can perform accurate		the realization of the unit of time. Added by fmeynadier	transition (for NMIs that are not developing already standards with the chosen transition).		ç	see presentation	n hy laron		

Scenarios for the redefinition of the second

2022

2026

CGPM

A redefinition at CGPM 2026 is unrealistic since in 2022 there was no consensus on the preferred option and still some important work to fulfil all mandatory criteria.

2030

2034

....

Scenarios for the redefinition of the second

2022

CGPM

2026

A redefinition at CGPM 2026 is unrealistic since in 2022 there was no consensus on the preferred option and still some important work to fulfil all mandatory criteria.

2030

2034

....

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

CGPM 2022 2026 2030 2034

A redefinition at CGPM 2026 is unrealistic since in 2022 there was no consensus on the preferred option and still some important work 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.

If it is not possible in 2030, the redefinition will be postponed, to CGPM 2034 or the following one... But what about maintaining until 2040 and later the operation of Cs fountains that have been built in the 1990s - 2000s?



https://www.bipm.org/documents/20126/64811223/Resolutions-2022.pdf

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. in preparation to CGPM 2026, we need a consensus on

- which definition option, which radiation(s) (or a few possibilities)
- 2. have a good confidence in the capacity to fulfil the mandatory criteria before 2030

Re-organization of the Task Force for the redefinition of the second

Coordination: Dimarcq, Tavella

SG 1 - Redef options (Bize, Peik, Fang, Panfilo with members to ensure an international/all countries point of view) Provide analysis of concrete proposals focused on options 1 and 2

SG 2 - Criteria (Calonico, Ido, Weyers, Tagliaferro with Chairs CCTF WG FS, PSFS, ATFT, TAI, ALGO, GNSS, TWSTFT) Monitor fulfilment index and promotion of progress and achievements

SG 3 - Education (Gertsvolf and Mileti, Meynadier with dedicated members) Educational activities and communication

	TF Actions and deliverables	KO all TF members Sept 26, 2023	CCTF Information meeting, Nov 16, 2023	24 th CCTF Session 1 Nov 2024	24 th CCTF Session 2 Sept. 2025	CGPM 2026
TF	Action Plan	Almost finalized	Finalized			
	Updated roadmap towards the redefinition of the second, criteria, conditions, and Indicators to discriminate among redef possibilities			Draft Preliminary redef possibilities	Updated roadmap with chosen redefinition option and species (or a few possibilities) and planned fulfilment of mandatory criteria by 2029	
	Draft resolution to the CGPM			draft Submitted to		CGPM
SG1	 Option documents 1. Description of options describing opt 1, opt 2 (a and b), (opt 3), 2. practical implementation of opt 1 and 2 (comparative table?) 3. Pros/cons 	ToC and draft version	First version	Final version		
	Eactsheets on most promising atomic species	Template/ Preliminary version	First version	Updated version - Categorize candidates (mostly ready, intermediate, not ready)	Final version	
	Factsheet for each criterion fulfilment status	Template/ Preliminary version	First version	Updated version – Pointing out criticalities and achievements	Updated version	
	On CCTF web page: criteria fulfilment presentation	Announce	2023 version	2024 version	2025 version	2026 version
	Ideas for recognition of the activities in NMIs and for valorisation of achievements and progress. Monitor projects and possible delay in achievements with the Sg3 and all sg Chairs	Preliminary list of ideas	Proposed list of ideas	Updated status	Updated status	
SG3	Shared repository for educational, reference and supporting material (including attribution and copyright rules)	Announce	Draft plan	Updated status	Updated status	
	FAQ page on the CCTF web page (with possibility to raise additional questions)	Announce	Template	First update	Updated status	
	Develop tools for recognizing and acknowledging achievements at Nivils and progress status of the criteria fulfilment (with SG2)	Announce	Draft plan	Updated status	Updated status	
	Develop long-term plan for education and communication to wider audience (with SG1 and SG2)	Announce	Draft plan	Updated status	Updated status	

Discussion on the redefinition of the second at Consultative Committee for the Definition of the Second (now CCTF) (1963)



Topics discussed:

- Conditions for a change of the definition
- Choice of the atom (Cs, H) or molecule ?
- Radio techniques for comparisons

RECOMMANDATIONS

1) the SI second be defined as the duration of a specified number of periods of a specified transition between two energy levels of an atom or a molecule

2) the definition of the second (when it will be time to choose the transition) be in accordance with the value of 9 192 631 770 Hz attributed to the radiation corresponding to the transition between the two hyperfine levels of the unperturbed ground state of the ¹³³Cs atom.

To review the long process to measure the Cs frequency in terms of Ephemerids second see Metrologia 42 (2005) S10–S19 "The definition of the 'atomic' second" by S. Leschiutta

Thanks to CCTF, its WGs, the Task Force for the "roadmap to redefinition of the second", National Metrology Institutes, academic experts, and concerned bodies for their constructive contribution and dedication



Thanks for your attention

