H CGPM

Draft Resolution E

"On the future redefinition of the second"

Noël Dimarcq, CCTF President Patrizia Tavella, BIPM Time Dept. Director Working together to promote and advance the global comparability of measurements

November 2022

th CGPM

Projet de résolution E

« Sur la future redéfinition de la seconde »

Noël Dimarcq, Président du CCTF Patrizia Tavella, Directrice BIPM Time Dept 27^e réunion de la Conférence générale des poids et mesures

November 2022

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 Δv_{cs}





Definitions of the SI unit of time

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



Astronomy



→ 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

→ 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



The era of Optical Frequency metrology



Optical Frequency Standards (Sr, Yb, Yb+, Al+, Ca+, ...) uncertainty at 10⁻¹⁸ level →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 the International Atomic Time (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

Updated CCTF Roadmap towards the redefinition of the SI second

→ Dedicated CCTF Task Force with 40 people in 4 specific Working Groups :

- Roadmap and mandatory criteria
- Request from user communities, NMIs and Liaisons
- Atomic frequency standards, and possible redefinition approaches
- Time & Frequency dissemination and time scales

SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis of the possible options for the new definition:

Option 1: Single atomic transition Option 2: Ensemble of atomic transitions Option 3: Fixing the value of another fundamental constant

→Definition of an ensemble of criteria and conditions to change the definition, with associated indicators to evaluate fulfilment levels

→ Analyse of possible schedule scenarios for the redefinition of the second

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 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

- 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

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)**
- n progress Availability of commercial optical clocks
 - Improved quality of the dissemination towards users

Fulfilment level of mandatory criteria (2022)



Mandatory criteria

OFS accuracy budgets ($< 2x10^{-18}$) Validation of OFS accuracy budgets – Frequency ratios (< 5x10⁻¹⁸) Continuity with the definition based on Cs ($< 3x10^{-16}$) Regular contributions of OFS to TAI (5 OFS contributing @ 2x10⁻¹⁶) Availability of sustainable techniques for OFS comparisons (@ 5x10⁻¹⁸) Knowledge of the local geopotential at the proper level Definition allowing future more accurate realizations Access to the realization of the new definition

Scenarios for the redefinition of the second

2022

CGPM

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.

2030

2034

....

2026

Scenarios for the redefinition of the second

2022

CGPM

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.

2030

2026

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 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.

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 that have been built in the 1990s - 2000s.

Dratf Resolution E - 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.

th CGPM

Special thanks to the CCTF WGs, the Task Force, external experts, the BIPM Time Department for fruitful discussions, support and contribution 27th meeting of the General Conference on Weights and Measures

27^e réunion de la Conférence générale des poids et mesures

Thanks for your attention

Extra slides

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



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

- 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

<u>Option 2</u>: Ensemble of transitions on an even basis $\Delta \nu_0$ Definition: weighted geometric mean of an ensemble C of chosen transitions Weight inversely proportional to the uncertainty of best standard using transition i

- 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

\rightarrow Novel approach providing a dynamic definition





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

Option 3: Fixing the value of another fundamental constant Definition: fix the value of one more fundamental constant

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

ightarrow 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

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



First ensemble of criteria fixed in 2016 for a change of the definition

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



Contribution from Primary and Secondary Frequency Standards to TAI



Contribution from Primary and Secondary Frequency Standards to TAI







Record number of frequency standards contribute to International Atomic Time

International Atomic Time (TAI) achieves its stability from more than 450 atomic clocks world-wide and its accuracy from a small number of primary and secondary frequency standards which aim at realizing the SI second with the smallest uncertainty. Each month the BIPM publishes, in section 3 of *Circular T* [1], an estimation of the TM frequency accuracy as measured by those individual nequency, standards, as there as an ensemble average computed by the BIPM. In November 2021, sixteen different frequency standards operated in eleven laboratories contributed to this estimation, including ten Cs fountains, one Rb fountain, one Sr optical lattice and two Yb optical lattice clocks, in addition to the two legacy Cs beams operated by the PTB. This constitutes a record level of participation, both in terms of the number of different standards and the number of different laboratories.

Optical clocks have an check a proven accuracy of order 10⁻¹⁸ in relative frequency sur-

present Cs fountains by two orders of magnitude and driving the Consultative Committee for Time and Frequency (CCTF) to initiate work towards a redefinition of the second [2]. The CCTF has set-up a wide-ranging task force of experts, which worked to define a number of mandatory criteria to be achieved before changing the definition. One of the mandatory criteria states that optical standards should regularly contribute to TAI, with a goal of at least three contributions per month, with a total uncertainty not larger than 2×10^{-16} . This criterion is intended to ensure that the accuracy of TAI is at least maintained and hopefully improved when the redefinition takes place and that it will be based on a robust set of optical frequency standards. Indeed after redefinition Cs fountains will become secondary standards with enlarged uncertainty while the uncertainty of optical standards will be reduced and it is important to ensure that the overall effect of the change is beneficial to TAI.

In 2021, 13 evaluations of optical frequency standards could be used to calibrate TAI, this is more than twice as many as the total number in the preceding three years (PSFS chart). Furthermore, two of them had a total uncertainty around 2.5×10^{-16} , which is close to the requirement set in the criterion for redefinition. While this is only a first step towards achieving one of the mandatory criteria, this shows the strong impetus from NMIs and DIs to operate optical frequency standards and move towards the redefinition. The results show significant progress in the operational capabilities, with optical clock uptime exceeding 90 % in some cases. This allows longer operating period and reduced frequency transfer uncertainty, key factors to achieve contributions of optical standards to TAI with a total uncertainty not larger than 2×10^{-16} as required. Looking at the past history of Cs fountain development (PSFS chart) we expect that a similar trend will occur for optical standards, so that the redefinition of the second could take place in 2030 as in the current CCTF plans.

Nov 2021





Yo optical lattice clock (image courtery of (RISS)



We optical lattice clock (image coursely of NMI)

Progress level of ancillary conditions

Ancillary conditions: progress status in Year					2023	2024	2025	2026	2027	2029	2030
1.5 – High reliability of OFS	Duration of continuous operation	n •	1 day	day							>
I.6 – Regular contributions of OFS to UTC(k)	UTC(k) using OFS for their steeri	Pre ng ●	eliminary tests	/							>
II.3 – High reliability of ultra high stability T/F links	Continuous operation of fiber links Baseline ≈ 100 Baseline ≫ 100	km ● n)km ● N	Few nonths Io link								> >
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 developm Number of Cs fountains in opera	• ent •	6 – 16 – 11 –								> >
III.4 - Availability of commercial OFS	Available commercial OFS	•	No -								>
	Frequency stability GN achievable by TWS operational T/F links	S, IFT ● <	< 10 ⁻¹⁶								>
III.5 - Improved quality of the dissemination towards users	Fib	er • <	< 10-19								>
	Time accuracy GI achievable by – TWS operational T/F links Fi	SS, IFT per	1 ns 50 ps								>

Uncertainty limited by the Cesium primary realization

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 und			
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			
88Sr	429228066418007.01	2.0E-16			
87Sr	429228004229872.99	1.9E-16			
40Ca+	411042129776400.4	1.8E-15			
87Rb	6834682610.9043126	3.4E-16			

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

Estimation by 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

Option 1: Single atomic transition Definition: fix the frequency of a single (optical) atomic transition $\Delta\nu_{\rm Cs} = 9 \ 192 \ 631 \ 770 \ {\rm Hz}$

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

- 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)

- ightarrow Classical approach similar to the current definition
- \rightarrow 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

<u>Option 2</u>: Ensemble of transitions on an even basis $\Delta \nu_0$ Definition: weighted geometric mean of an ensemble C of chosen transitions Weight inversely proportional to the uncertainty of best standard using transition i

- 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
- \rightarrow Fix a "mathematical constraint" and measure all frequencies versus that constraint
- \rightarrow frequency values are already interrelated
- ightarrow weights and the constant N could be updated









Courtesy of T. Ido, NICT

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

- 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)

→ 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



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

Strengths, Weaknesses, Opportunities and Threats

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

					C A TheBIPM / cctf-tf-redef > Proje	ects > SWOT analysis for option 3		 Filter cards 	+ Add cards 52 Exit fullscre
		• • • • • • • • • • • • • • • • • • •			2 Strengths	+ ··· 3 Weaknesses	+ ··· 0 Opportunities	+ ④ Thre	ats +
General O	• • • Ge		General + + + +	+ + + + + + + + + + + + + + + + + + +	Matched to the approach adopted by CGPM 2018 with c, h, e, k	 From INRiM] A substantial step backw in frequency metrology and related applications. 	rard ***	E Breat any unit	ks the metrological principle that new definition of a measurement should be consistent with the old
Understanding the	e options 💦 🛛 🗛	undamental issues of t	💭 🛆 TheBIPM / cctf-tf-redef > Projects > 🛆 SWOT a	nalysis for option 2		+ Add cards the Exit fullscre		defin whic	ition to within the uncertainty with the old definition can be realised.
🕀 ndimarcq 💡 💡		patriziatavella	7 Strengths + 14	Weaknesses + ···	3 Opportunities + ···	5 Threats + ··· th	ie ***	Adde	ed by HelenMargolis
A TheBIPM / cct/st/redet > Projects > A	SWOT analysis for option 1		Form INRIM] Well suited for the present situation with several optical transitions are outperforming Cs Filter cards + Add cards C bot	The definition of the unit of time is A adopted in a number of national laws on legal time. It may become difficult to united the national lawmakers to accept a mic definition where potential pes are not under their control.	[From INRiM] strong stimulus to explore "" new frequency standards options. Added by fmeynadier Schemes and rules can be adopted (by ""	Industrial clock manufacturers are likely *** to have difficulty in deciding which standard to develop. The same would be true for NMIs not currently operating optical frequency standards.	sent ***	E (Fron critic navig refle Adde	n INRiM) Possibility to jeopardize *** al technologies, like e.g. satellite gation (frequency inaccuracy is cted to position inaccuracy). ad by fmeynadier
Strengths + ··· Familiar and practical, using primary and*** secondary realisations just as we do today.	4 Weaknesses If from INRiM] No clear best transitic currently identified, based neither metrological (best transition), nor opolitical reasons (most widespread)	+ ··· ransition is ··· either on 0, nor on geo-	+ ··· 6 Threats + pecies ··· slized SR biasing future developments towards the atomic transition selected as the	by epeik efinition of the unit changes over '' ''evolves'') which is essentially a inition by another name. In the	CGPM/CIPM) such that the definition will adapt more easily to the fast continuing progress of optical frequency standards. Added by fmeynadier	Complexity of definition could lead to misuse due to limitations in understanding.	e	If op: ~1E- real: scale sset	tion 3 is chosen, future change(s) of *** 12 or more (1E-10 for m_e) of the zation of the second (including the i interval of TAI) and of the entire en of units
Consistent with the current SI base unit *** definitions. Added by HelenMargolis	Added by fmeynadier Secondary representations of the s required to achieve sufficient disse	econd uncertainty determination of the a re-definition occurs based on a optical transition, high accuracy measurements between the opti mination clocks could help keep the uncer	SRs. If primary standard. single Added by HelenMargolis cal tainties ID o evolve toward a situation where, in ····	ition of other base units the imental constant is fixed. i by HelenMargolis	[E] All short term and long term benefits associated to an improvement by 100 of the realization of the unit of time. Added by fmeynadier	 From INRIM] Need of more radical redefinition, realigned with the present one based on Cs, in case one species 		Adde	d by fmeynadier
[from INRiM] In the case a new species	(at least at the beginning) Added by fmeynadier	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 *** ing - it is neither a fundamental		will emerge as the most accurate one. Added by fmeynadier		best) wor): more than 4 order of magnitude se than present definition and 6
will emerge as the most accurate one, the path toward a new redefinition will be straightforward and in continuity with the history of the second definition changes decided in the past.	Need to tradeoff best standard age broad enough use of this standard Added by fmeynadier	ainst [From INRiM] Clear path forward who are willing to develop a prin clock.	I for all · · · Added by fmeynadier any That the chosen transition will be · · · ·	ant or an atomic property. Hence it not have the same qualities as the six defining constants. i by HelenMargolis		Development of commercial systems *** becomes risky or are discouraged unless one or two transitions become		orde frequ	rs of magnitude than optical uency standards uncertainties.
Added by fmeynadier	Difficulty to reach a consensus for	Added by fmeynadier	surpassed fast, pushing toward another redefinition after 1 or 2 decades only.	ms unlikely that any individual		dominant.			
[from INRiM] The present situation where we rely on primary clocks and	single transition given the diversity transition used Added by fmeynadier	of E 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. Added by fmeynadler		All short term and long term ben associated to an improvement by the realization of the unit of time	Appropriate tasks on other transitions the hampered or stopped, due to reallocation of resources and delays to develop standards based on the chosen transition (for NMIs that are not transition to NMIs that are not transition to the transition to the transit	tuation that is currently trying to		by optical standards in quality and			33
accuracy of the definition of the second.		Added by fmeynadier	developing already standards with the chosen transition).	~					