Defining the SI Second via “Option 1”: Change and Continuity

Ekkehard Peik

CCTF Task Group „Options“

Department Time and Frequency, Physikalisch-Technische Bundesanstalt, Germany
ekkehard.peik@ptb.de

Previous definitions of the second

1960: Ephemeris second

"The second is the fraction 1/31 556 925.9747 of the tropical year for 1900 January 0 at 12 hours ephemeris time."

1967: SI definition of the atomic second:

"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."

NB: This is **proper time**, assuming the atom to be observed under idealized conditions: at rest and in the absence of external electromagnetic fields.

Relativistic corrections are applied to clocks when the SI second is used for time scales (like UTC, TAI) in specific reference systems.

SI redefinition from 2019:

For the unit second, the wording of the definition has been changed, not the content.

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 1/s.

(SI Brochure, 9th Edition, 2019)

In 2019, a uniform structure of the definitions for the seven base units has been aimed for.

Definition of the SI

As for any quantity, the value of a fundamental constant can be expressed as the product of a number and a unit.

The definitions below specify the exact numerical value of each constant when its value is expressed in the corresponding SI unit. By fixing the exact numerical value, the unit becomes defined, since the product of the ***numerical value*** and the ***unit*** has to equal the ***value*** of the constant, which is postulated to be invariant.

SI Brochure, 9th Edition, 2019

The numerical values of the seven defining constants have no uncertainty.

Table 1. The seven defining constants of the SI and the seven corresponding units they define

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta \nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	m s^{-1}
Planck constant	h	$6.626\ 070\ 15 \times 10^{-34}$	J s
elementary charge	e	$1.602\ 176\ 634 \times 10^{-19}$	C
Boltzmann constant	k	$1.380\ 649 \times 10^{-23}$	J K^{-1}
Avogadro constant	N_A	$6.022\ 140\ 76 \times 10^{23}$	mol^{-1}
luminous efficacy	K_{cd}	683	lm W^{-1}

Preserving continuity, as far as possible, has always been an essential feature of any changes to the International System of Units. The numerical values of the defining constants have been chosen to be consistent with the earlier definitions in so far as advances in science and knowledge allow.

SI Brochure, 9th Edition, 2019

Comparison of astronomic and atomic time scales 1955-58

FREQUENCY OF CESIUM IN TERMS OF EPHEMERIS TIME

W. Markowitz and R. Glenn Hall,
United States Naval Observatory, Washington, D. C.

and
L. Essen and J.V. L. Parry,

National Physical Laboratory, Teddington, England
(Received July 7, 1958)

We find, thus, the transition frequency of cesium $(4, 0) \rightarrow (3, 0)$ at zero magnetic field is

$$\nu_E = 9\,192\,631\,770 \pm 20 \text{ cycles}$$

per second (of E.T.) at 1957.0.

Phys. Rev. Lett. **1**, 105 (1958)

W. Markowitz with dual-rate moon camera for the measurement of occultations of stars by the moon. Photo: USNO

Uncertainty: about 0.1 s per day ($\approx 10^{-6}$)
(earth rotation: 1 arc second ≡ 0.0667 s of solar time)

The defining constant for the SI second is the result of this measurement, setting the uncertainty to zero.
The measurement has not been repeated, as the dominant causes of uncertainty persist (irregularities in earth rotation rate, historic ephemerides, etc.).

A redefinition of the second should achieve:

- exploit the advantages of optical atomic clocks relative to Cs clocks
- enable improvements in the realisation of the unit of time and of time scales
- ensure the continuity of frequency measurements and time scales
- fit into the structure of the 2019 SI system

2019 Definition:
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 1/s.

Option 1 for redefinition

- Selection of an optical reference transition in a suitable atom or ion, instead of the ground-state hyperfine transition in Cs-133
- New determination of the numerical value in Hz (now 9 192 631 770) while maintaining the continuity of the duration of the second

Steps for implementing this option:

1: Selection of the new reference transition from the ≈10 candidates of the current Secondary Representations of the Second (SRS)

- Initially based on objectifiable criteria that are generally considered for the redefinition:
  - Lowest possible systematic uncertainty
  - Consistent uncertainty budgets from different laboratories verified in comparative measurements
  - Over several (1-3) years accumulated weights of TAI contributions with frequency standards based on the transition (includes the number of laboratories involved, the systematic and statistical uncertainty and the availability (reliability in operation, duty cycle over 30 days).
  - and others …

In case of several candidates with similar status in these figures: Discussion and voting in CCTF, CGPM

2: Determination of the numerical value of the defining constant:

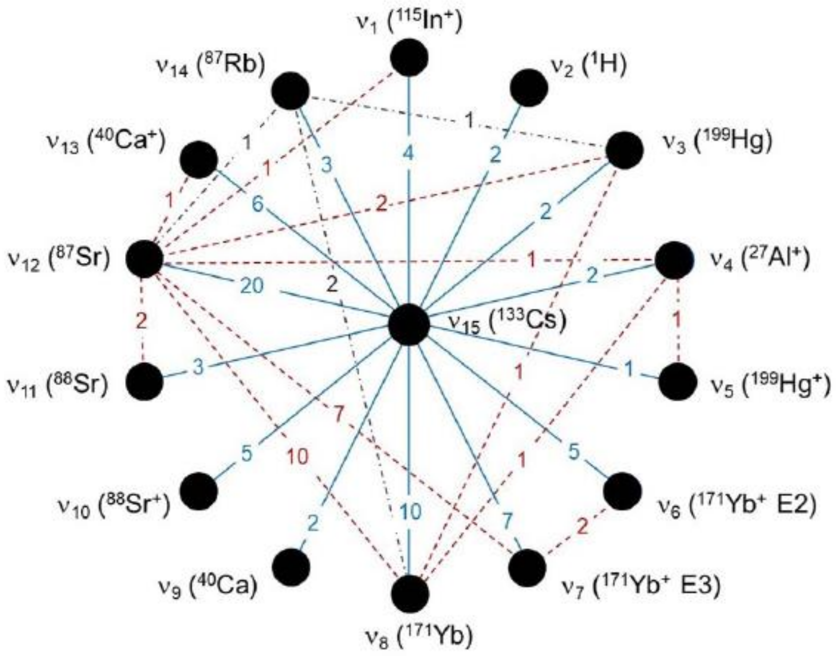
- From the CCL-CCTF evaluation of absolute frequency and ratio measurements.
- Expected uncertainty: $\approx 1\times10^{-16}$ corresponding to ≈0.1 Hz; is set to zero for the definition.
- The procedure is unique and does not need to be repeated later, as the causes of the uncertainty (in the Cs clocks) persist.

What about the other candidates that are not selected for the definition?

These will continue to be used as SRS, e.g. for TAI calibrations.
Uncertainty for this now: $>1.9\times10^{-16}$, then possibly $\approx10^{-18}$ (about $\sqrt{2}\times$ higher than for the primary standard).
The recommended frequencies are obtained from the adjustment of the measured optical frequency ratios (CCL-CCTF).
The metrological value of all these SRS therefore increases with the redefinition!

Table 5. List of secondary representations of the second adopted by the 22nd CCTF (Ma

Transition	Approximate wavelength/nm	Recommended frequency/Hz	Recommended relative uncertainty
^{199}Hg	265	1128 575 290 808 154.32	2.4×10^{-16}
^{27}Al$^+$	267	1121 015 393 207 859.16	1.9×10^{-16}
^{199}Hg$^+$	282	1064 721 609 899 146.96	2.2×10^{-16}
^{171}Yb$^+$(E2)	436	688 358 979 309 308.24	2.0×10^{-16}
^{171}Yb$^+$(E3)	467	642 121 496 772 645.12	1.9×10^{-16}
^{171}Yb	578	518 295 836 590 863.63	1.9×10^{-16}
^{88}Sr$^+$	674	444 779 044 095 486.3	1.3×10^{-15}
^{88}Sr	698	429 228 066 418 007.01	2.0×10^{-16}
^{87}Sr	698	429 228 004 229 872.99	1.9×10^{-16}
^{40}Ca$^+$	729	411 042 129 776 400.4	1.8×10^{-15}
^{87}Rb		6834 682 610.904 3126	3.4×10^{-16}



N. Dimarcq et al., „Roadmap…“, Metrologia **61**, 012001 (2024)

H. S. Margolis et al., “Recommended values...”, Metrologia **61** 035005 (2024)

What happens to Cs clocks and the existing global microwave infrastructure?

Cs loses its status as PS, becomes SRS with a frequency of 9 192 631 770 Hz and can continue to be used in all systems - including for the realisation of the second - with an uncertainty of $\approx 2 \times 10^{-16}$ or higher.

Won't a lot of work and knowledge with other systems be uselessly lost by selecting a single transition as primary standard?

Let's look at the situation before and after the selection of caesium in 1967:

- Work with ammonia and thallium was gradually discontinued as it showed little progress and fell behind Cs.
- Work with H-masers and Rb clocks has been continued to this day, as they were superior to Cs in terms of short-term stability, price and size, respectively.

TABLE I. NUMBER OF REPORTED ATOMIC FREQUENCY STANDARDS ACCORDING TO THE 1961 CCDS MEEETING [4]

Type of standard	*In operation*	*Under development*
Cesium beam	54[a]	4
Ammonia masers	8	9
Hydrogen masers	-	2
Thallium beam	-	3
Rubidium beam	-	1
Rubidium cell	1	1

a. including commercial Atomichrons

G. Mileti et al., in prep.

Discussion of the CCDS 1963: N. Ramsey, L. Essen, …

How will the system of PS and SRS develop after the redefinition, if...

- ...a previously unknown problem is recognized with the primary standard (such as BBR with Cs in the 1990s), or no laboratory operates this standard any more?

→ the definition clearly refers to the unperturbed atom, indicating in which way the problem should be addressed.

In the worst case, a switch to a different primary standard could be required.

- ...one of the SRS has a previously unknown problem or no laboratory operates such a standard any more?

→ CCTF/CGPM will either adjust the recommended frequency of the SRS or withdraw the SRS.

This has no effect on the definition.

- ...a new, previously unknown system with promising or superior properties appears?

→ CCTF/CGPM will recommend a frequency measured in relation to the PS and place it on the list of SRS, and the system can contribute to time scales and frequency measurements.

This has no effect on the definition.

A redefinition of the second should achieve:

- exploit the advantages of optical atomic clocks relative to Cs clocks
→ higher accuracy and stability of a primary optical frequency standard

- enable improvements in the realization of the unit of time and of time scales
→ make use of the availability of a variety of primary and secondary frequency standards

- ensure the continuity of frequency measurements and time scales
→ ensure seamless integration with existing microwave infrastructure

- fit into the structure of the 2019 SI system
→ present a definition that is familiar to the whole community of metrologists

A redefinition following Option 1 would achieve these goals
and remain adaptive to future developments via the established tools of SRS.