

## CCTF preparation for the CGPM 2022

### Draft Resolution E – On the future redefinition of the second

#### 1 Context: current situation, needs, and future evolution

Since 1967, the definition of the SI second has relied on the caesium atom hyperfine transition frequency. Caesium primary frequency standards currently realize this unit with a relative uncertainty at the  $10^{-16}$  level. This value is today the ultimate uncertainty level that is reachable for the Mise en Pratique of the current definition. On the other hand, in recent years Caesium frequency standards have been surpassed by optical frequency standards (OFS) with much lower uncertainties, typically 2 orders of magnitude better (Fig 1). Thus, it is time to envisage a redefinition of the second.

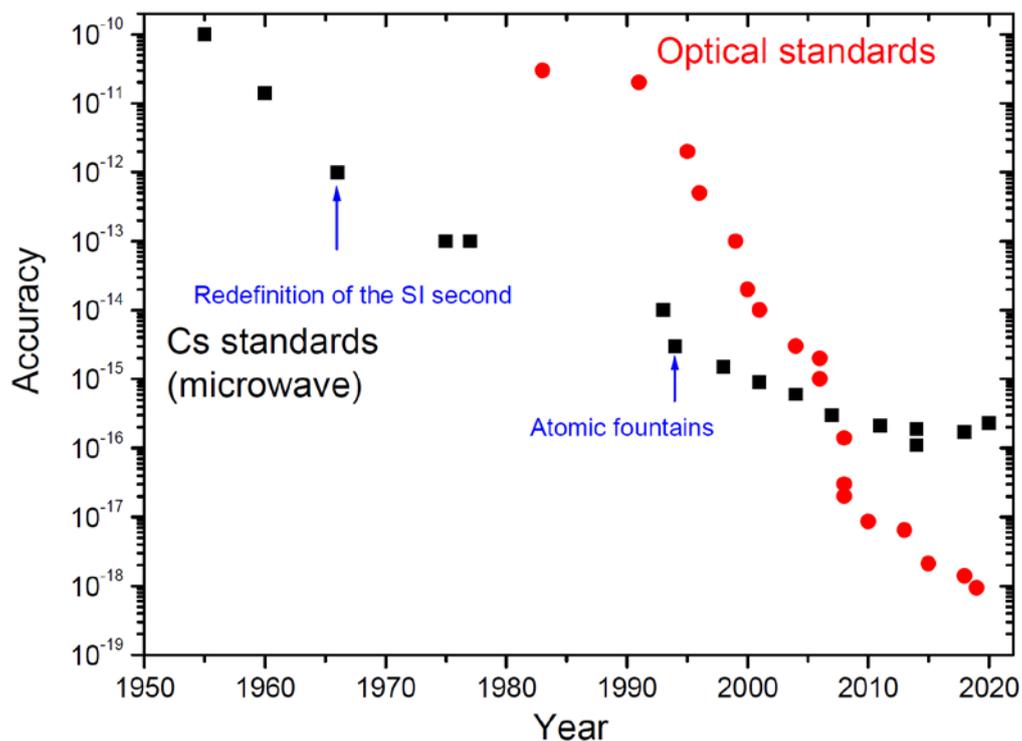


Figure 1: evolution of the relative frequency uncertainty of frequency standards

A new definition relying on optical frequency transitions will offer a full benefit for the exploitation of the outstanding OFS current and future performances. As it has been already demonstrated with the current definition over the past five decades, a new definition and its continuously improving realisation are very likely to foster the dynamics in the fields of fundamental metrology and

fundamental science with the emergence of new exploration fields for time and frequency metrology (search for dark matter, chronometric geodesy, ...). A positive impact on socio-economic sectors is also expected with improved capabilities for critical systems (positioning, navigation, telecoms, energy, ...) thanks to more stable and accurate industrial clocks that will be developed and to a more stable and accurate international time reference UTC.

In order to prepare for a future redefinition of the SI second, the Consultative Committee for Time and Frequency (CCTF) has investigated possible options and their impacts on concerned communities and applications, not just scientific and technological, but also regulatory and legislative. This was carried out through an online survey from December 2020 to January 2021. In addition, a dedicated CCTF Task Force has been created, which is divided into three subgroups related to:

- A. Requests from user communities, National Metrology Institutes (NMIs) and liaisons
- B. Atomic frequency standards, and possible redefinition approaches
- C. Time and frequency dissemination and time scales.

The survey found that in terms of awareness and interest of the user communities in the possible new definition, overall, the time and frequency (T/F) community is well informed about the redefinition efforts and is supportive of the initiative. Several of the survey's responders from NMIs, academia and industry indicated that they would benefit from access to optical frequency standards and more accurate T/F signals associated with the redefinition. The survey responses also revealed that many industrial users have current and future T/F needs that can be addressed by the current definition and dissemination methods. The redefinition campaign presents an opportunity for CCTF members and timing laboratories to improve and enhance their efforts in education and knowledge transfer of the T/F metrology principles and techniques. The survey responses also indicated that limited effort, if any, would be required to adapt existing laws and regulations to the new definition. This aspect would require additional consultation and validation to ensure that formal administrative and legal processes are launched in a timely manner so as not to hinder the redefinition schedule.

In order to choose the best new definition and its implementation timeline, and to provide the CGPM with all the required information to make its decision, criteria and conditions have been defined to assure that the following goals of the redefinition are reached:

- Offer an improvement by 10 to 100 of the realization of the new definition in the short term after the redefinition (reaching  $10^{-17}$  to  $10^{-18}$  relative frequency uncertainty) and potentially a larger improvement in the longer term;
- Ensure continuity with the current definition based on caesium;
- Ensure continuity and sustainability of the availability of the new SI second through TAI/UTC, and enable a significant improvement of the quality of TAI as soon as the definition is changed;
- Enable the dissemination of the unit to a broad category of users;
- Be acceptable by all NMIs and stakeholders.

The possible redefinition scenarios depend on the capabilities of optical frequency standards and their envisaged evolution, considering their performance, their readiness for sustainable contributions to the realization of time scales, especially UTC, and also their potential for commercial availability and space qualification. A roadmap will address T/F transfer techniques required for the comparison of atomic clocks, for the construction of international time scales, and for the dissemination of reference signals to users, with an adequate uncertainty level.

To quantify the status of the developments and their maturity for a redefinition, the CCTF has defined a list of mandatory criteria, that need to be fulfilled before redefinition, and a list of ancillary conditions, that need to achieve an advanced status, even if not yet completely fulfilled at the time of the redefinition. These criteria and conditions are detailed in the CCTF document “Roadmap to the redefinition of the second” (to be published soon) and briefly illustrated in Fig 2.

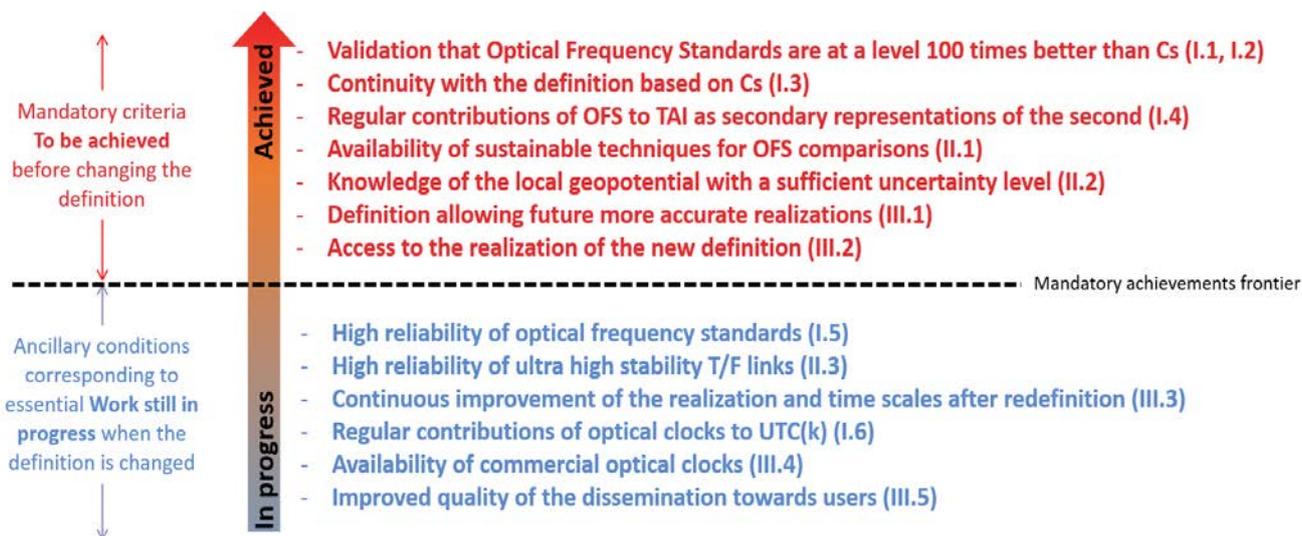


Figure 2: *criteria and conditions for redefinition of the SI second*

## 2 Issues and possible solutions

The fulfilment of the criteria and conditions are continuously monitored by the CCTF through its WGs, and are periodically assessed by the CCTF WG on Strategic Planning by the use of “fulfilment indexes” that help to:

- evaluate the current status of fulfilment and progress,
- be aware of the remaining work to fulfil all mandatory criteria,
- be able to quantitatively follow the improvements,
- to decide if it is time to change the definition.

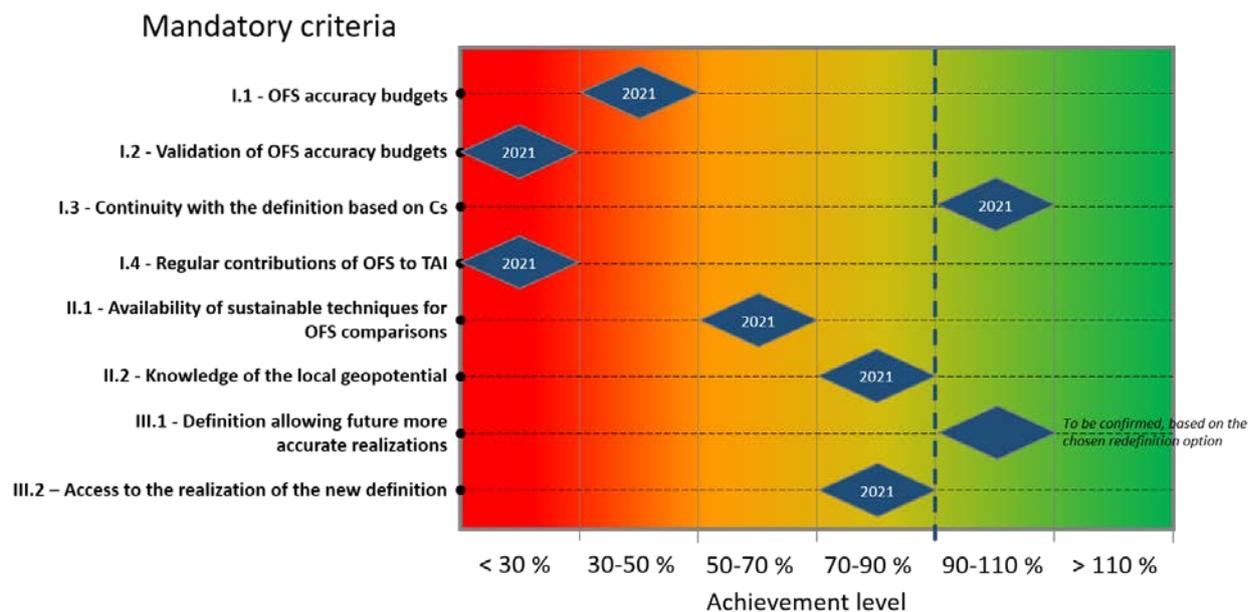


Figure 3: *Fulfilment levels of mandatory conditions*

While for certain criteria the fulfilment seems to have been almost achieved, for others fulfilment is more challenging.

Due to the considerable number of optical frequency standards under development, good progress has been made on OFS performance Criteria I.1 and I.3 (fulfilment indices close to 50 % and 100 %, respectively) as well as on their realization viability Criteria III.1 and III.2 (fulfilment near 100 % for both, to be confirmed since they are based on the chosen redefinition option). However, the challenges associated with limited resources for developing multiple standards in one institute (along with limitations in long-distance time transfer) have led to a low fulfilment index for the optical frequency standards' comparison Criterion I.2 (fulfilment < 30 %), while demands associated with long measurement runs at high duty cycle and prioritizing the work on other criteria have slowed progress on the OFS contributions to TAI Criterion I.4 (fulfilment < 30 %).

The fulfilment of the criterion II.2 related to knowledge of the geopotential is achieved in the majority of NMIs operating an OFS.

For Criterion II.1, a sustainable technique for OFS comparison at the proper uncertainty level is more challenging. Over an intracontinental scale (baselines of about 1000 km), the requirement is fulfilled by optical fibre links, even if a significant effort for regular comparison campaigns should be addressed. Comparisons over intercontinental scales (baselines much longer than 1000 km) at the required uncertainty are not presently demonstrated. Optical fibre links and transportable OFS are viable means, but to date no intercontinental OFS comparisons with fibre links or with transportable OFS have been demonstrated. Only one single intercontinental fibre link has been demonstrated so far (without an OFS comparison). Hence, significant efforts should be addressed

- i) to ensure regular comparisons of OFS at the continental scale, where current possibilities fulfil the requirements;
- ii) to provide realistic and reliable methods to compare OFS at the intercontinental scale.

Research is progressing on novel T/F transfer techniques (VLBI, optical TW communication link on satellites, ...). The necessary level of accuracy and reliability has not yet been achieved, but the anticipated evolution over the next few years is promising and additionally is under investigation for

commercial purposes in other communities. Nevertheless, this achievement may be possible only over the long term, possibly a few decades.

An important issue in the debate on a redefinition of the second is whether to choose a new definition based on:

1. the current approach by choosing a radiation corresponding to a single atomic reference transition in the optical frequency range from among the several promising candidates under investigation,
2. adopting a new approach based on an “ensemble” definition, which would include more than one radiation in a dynamic and evolving average,
3. a redefinition based on fixing the value of another fundamental constant.

At present, the third option is not achievable as there is no known fundamental physical constant with the necessary accuracy. However, there is still no clear consensus on

- i) the choice between the first option (single transition) and the second option (ensemble of transitions), even though the majority of participants in the survey favoured the first option;
- ii) the identification of the preferable atomic radiation(s) for the definition.

Progress toward consensus will come from the following actions:

- The CCTF will clarify and make explicit the practical aspects of the new definition under every proposed option. The CCTF will increase the level of awareness of these practical aspects among CCTF members, the Consultative Committee for Units (CCU), International Committee for Weights and Measures (CIPM), General Conference on Weights and Measures (CGPM) and within a broader audience.
- Further development of optical frequency standards by NMIs and other institutes; achievements in terms of their operability; as well as further evaluation of specific redefinition alternatives, may provide a clearer choice of the redefinition option.

Depending on the development and achievement of these activities, the CCTF envisages three possible schedule options for the redefinition (Fig 4).

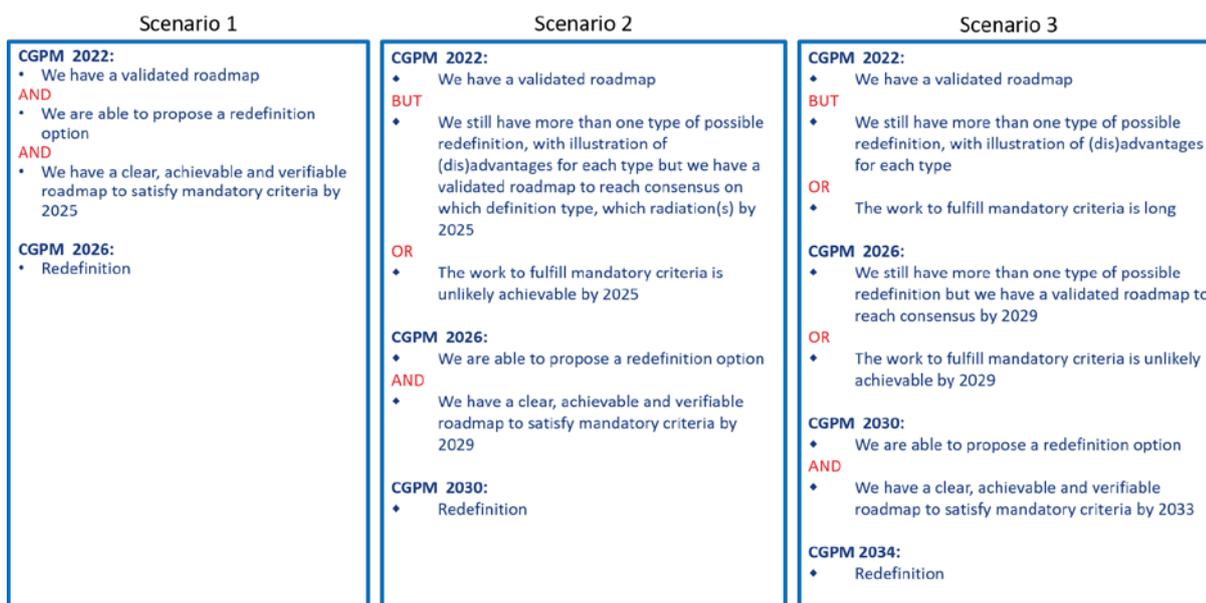


Figure 4: schedule options for the redefinition of the second

### 3 Conclusion and way forward

The goal to achieve a better definition and realization of the SI second is intended to serve current and future needs in metrology and to foster scientific and technological applications at the highest accuracy.

The CCTF, having examined the necessary criteria to be achieved before changing a definition, having consulted the users and stakeholders, and particularly having thoroughly studied the necessary achievements in the development of frequency standards, their comparison techniques, and their capacity to contribute to time scales, considers the schedule scenario aiming at a redefinition in 2026 to be unrealistic.

The maturity of optical frequency standards, T/F transfer, and time scale formation is growing impressively and there is a clear way forward to choose between the two options for the new definition: a single atomic reference transition in the optical frequency range or an ensemble of reference transitions.

Therefore, the CCTF recommends adopting a roadmap to the redefinition of the second according to the criteria and ancillary conditions listed in this document, and preferably according to the schedule scenario aiming at a redefinition in 2030, with a back-up schedule scenario leading to a redefinition in 2034.

**Annex: Draft Resolution E – On the future redefinition of the second**  
<https://www.bipm.org/en/cgpm-2022>, February 2022

Draft Resolution E

**On the future redefinition of the second**

The General Conference on Weights and Measures (CGPM), at its 27th meeting,

**recalling** that

- the CGPM at its 13th meeting (1967) defined the second as “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”,
- the CGPM at its 26th meeting (2018) revised the definitions of the base units of the SI including the second, which it defined by taking the fixed numerical value of the caesium frequency  $\Delta\nu_{\text{Cs}}$ , which is 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  $\text{s}^{-1}$ ,

**noting** that

- optical frequency standards based on different species and transitions in many National Metrology Institutes (NMIs) have surpassed the accuracy achievable by the realization of the current definition by a factor of up to 100,
- the reliability and uncertainty of the related time and frequency transfers are improving significantly,
- some institutes have demonstrated that time scales based on one or more optical frequency standards have the potential to be more accurate than the time scale based on the current definition of the second,
- these advances will allow further improvements in the realization and dissemination of time scales, particularly Coordinated Universal Time (UTC),

**further noting** that the Consultative Committee for Time and Frequency (CCTF) in its work to serve current and future needs in time metrology

- has carried out an extensive survey amongst metrological, scientific and technology institutions, and other stakeholders, which has confirmed world-wide interest in more accurate time and frequency services enabled by a new definition of the second,
- is working to identify the best candidate species or ensemble of species that could serve as the basis for a new definition,
- has prepared a roadmap of the actions and timings needed to decide on a new definition of the second and has established criteria and appropriate indicators to monitor progress towards such a new definition,

**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.