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The measurement of time / La mesure du temps

International atomic time: Status and future challenges

Le temps atomique international : état de l'art et perspectives

Gérard Petit *, Felicitas Arias, Gianna Panfilo

Time Department, Bureau international des poids et mesures, Pavillon de Breteuil, 92312 Sèvres, France

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A B S T R A C T

We present the time scales elaborated at the International Bureau of Weights and Measures (BIPM), review their present status, and discuss the transition in frequency performance from the present 10^{-16} to the future 10^{-17}–10^{-18}, and its impact on time and frequency metrology. We focus our attention on future developments in the calculation of Coordinated Universal Time (UTC), on the evolution of time links and algorithms, on improving the access to the time reference and on possible changes in the definition of the timescales.

R É S U M É

Nous présentons les échelles de temps élaborées par le Bureau international des poids et mesures (BIPM) et évaluons leurs performances présentes. Nous discutons la transition en cours pour passer du niveau actuel de 10^{-16} sur l'incertitude de fréquence au niveau futur de 10^{-17}–10^{-18}, et de l'impact de ce changement sur la métrologie temps–fréquence. Nous concentrons notre attention sur les développements futurs pour le calcul du temps universel coordonné (UTC), sur l'évolution des techniques de comparaisons d'horloges et des algorithmes, sur l'amélioration de l'accès à la référence de temps et sur les changements possibles dans la définition des échelles de temps.

1. Introduction

The BIPM Time Department has the responsibility to maintain and disseminate UTC, the world time reference. UTC gets its stability from several hundred atomic clocks spread in more than 70 laboratories worldwide and its accuracy from primary and secondary frequency standards (PFS and SFS) constructed and operated in some ten laboratories to realize the second of the International System of units (SI). The calculation of UTC relies on two main ingredients, the methods used to compare atomic clocks and the algorithms used to generate the timescale. The quality of UTC is somewhat limited by the methods used for clock comparison; therefore coordinated efforts are undertaken by the BIPM and the contributing laboratories for their improvement. The algorithms are designed to optimize the UTC long-term stability and accuracy and they are updated whenever necessary for dealing with the improved performance of clocks and new time transfer techniques.

* Corresponding author.

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New applications at time laboratories result in an increasing need of rapid accessibility to UTC. For satisfying their requests, the BIPM started implementing rapid solutions. This article reviews the present status and future development of the time scales computed at the BIPM: Section 2 presents general definitions and describes the timescales; Section 3 discusses the use of the PFS in the calculation of UTC and TT(BIPM), BIPM's realization of Terrestrial Time. Future developments related to UTC are discussed in Section 4, including frequency standards, algorithms, time links, real time prediction, and the possible need for new definitions.

2. International atomic time: definitions and realizations

2.1. Institutional role

The General Conference on Weights and Measures (CGPM) decided in 1968 [1] that "*the second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the cesium 133 atom*". It was later clarified that this definition refers to an atom at rest at a thermodynamic temperature of 0 K. The recommendation of this transition for the definition of the time unit called for the adoption of a time scale built by cumulating atomic seconds. The unification of time on the basis of the atomic time scale already computed at the Bureau international de l'heure (BIH) was recommended by the International Astronomical Union (IAU, 1967), the International Union of Radio Sciences (URSI, 1969) and the International Radio Consultative Committee of the International Telecommunication Union (CCIR, 1970, predecessor of the Radiocommunication Sector of the International Telecommunication Union, ITU-R). Ultimate consecration came from the official recognition by the 14th CGPM in 1971 [2], which introduced the designation *International Atomic Time* and the universal acronym TAI.

TAI was then defined as "*the time reference established by the BIH on the basis of the readings of atomic clocks operating in various establishments in accordance with the definition of the second*". In 1980, the definition of TAI was completed by the Consultative Committee for the Definition of the Second (renamed Consultative Committee for Time and Frequency, CCTF in 1997), adding "*TAI is a coordinate time scale defined in a geocentric reference frame with the SI second as realized on the rotating geoid as the scale unit*." This definition explicitly refers to TAI as a coordinate time, recognizing the need for a relativistic approach. TAI is the basis of realization of time scales used in dynamics, for modeling the motions of artificial and natural celestial bodies, with applications in the exploration of the solar system, tests of theories, geodesy, geophysics, and studies of the environment.

Nevertheless, TAI was never disseminated directly, and UTC, which was designed to approximate UT1 (a timescale derived from the rotation of the Earth), was chosen as the practical world time reference. At the time of its definition, UTC was the unique means of having real time access to UT1, as needed for some specific applications including astronomical navigation, geodesy, telescope settings, space navigation, satellite tracking, etc. The definition of UTC is based on the atomic second, but the time scale is synchronized to UT1 to maintain $|UT1 - UTC| < 0.9$ s. Since 1972, UTC differs from TAI by an integral number of seconds, changed when necessary by insertion of a *leap second*, as predicted and announced by the International Earth Rotation and Reference System Service (IERS). Since June 2012 and until 30 June 2015, the offset between TAI and UTC is 35 s, then it will be 36 s until further notice.

Since 1988 the BIPM is responsible for the computation of TAI and UTC. An algorithm developed at the BIPM Time Department treats clock data submitted by worldwide-spread institutes to give traceability to the SI second to the local realizations of UTC, named UTC(k) where k refers to a laboratory. The dissemination of the international time UTC by time and frequency signals is regulated by the ITU-R; in parallel, Global Navigation Satellite Systems (GPS and GLONASS at present) provide the broadest dissemination of UTC.

UTC is calculated with one-month data batches, and is available monthly in the *BIPM Circular T* [3] under the form of values $[UTC - UTC(k)]$ at five-day intervals. Extrapolation of values over 10 to 45 days based on prediction models is necessary to many applications. UTC, as published today, is not adapted for real and quasi-real time applications, and it was recognized that a more rapid realization would benefit, e.g., to the following:

- UTC contributing laboratories would have more frequent assessing of the UTC(k) steering, and consequently better stability and accuracy of UTC(k) and enhanced traceability to UTC;
- users of UTC(k) would access to a better "local" reference, and indirectly, better traceability to the UTC "global" reference;
- users of Global Navigation Satellite Systems (GNSS) would get a better synchronization of GNSS times to UTC, through improved UTC and UTC(k) predictions: this is the case of UTC(USNO) for GPS, UTC(SU) for GLONASS, and of the UTC(k) to be used in the generation of the system times of the new satellite systems Galileo, BeiDou, and IRNSS/Gagan.

These reasons moved the BIPM to implement UTCr ("rapid" UTC) [4], a new realization of UTC available with a shorter delay than *Circular T*. After a phase of pilot experiment started in 2012, and with the approval of the CCTF, UTCr has become a regular product of the BIPM since July 2013. UTCr is a weekly solution based on daily data covering four consecutive weeks, reported daily by contributing laboratories. It is disseminated through daily values of $[UTCr - UTC(k)]$ published at one-week intervals on the Wednesday afternoon, providing access to results up to the preceding Sunday.