C. R. Physique 16 (2015) 480–488

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

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

A R T I C L E I N F O

Article history:
Available online 1 April 2015

Keywords:
International timescales
Frequency standards
Time links
Algorithms

Mots-clés :
Échelles de temps internationales
Etalons de fréquence
Horloges
Algorithmes

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.

http://dx.doi.org/10.1016/j.crhy.2015.03.002
1631-0705/

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.

2.2. Realization of the timescales

The BIPM Time Department computes each month the international reference UTC. The calculation of UTC is carried out in three successive steps [5]:

1) the free atomic time scale EAL (*échelle atomique libre*) is computed as a weighted average of the free-running atomic clocks spread world-wide. The number of participating clock amounts today about 450;
2) the frequency of EAL is steered to maintain agreement with the definition of the SI second, and the resulting time scale is TAI. The steering correction is determined by comparing the EAL frequency with that of PFS and SFS. Primary standards directly realize the Cs transition defining the SI second, while secondary standards realize other transitions that have been recommended as secondary representations of the second [6]. The number of these standards maintained in laboratories and contributing to the accuracy of TAI amounts to 18 in the last five years: 17 PFS among them 14 are cesium fountains, and one rubidium fountain SFS;
3) leap seconds are inserted to maintain agreement with UT1, thus with the rotation of the Earth. The timescale resulting from the application of the integral number of leap seconds is then UTC. The dates of leap second insertion are decided and announced by the IERS.

In step 1, the algorithm used for defining EAL gives the difference between EAL and each participant clock:

$$x_j(t) = EAL(t) - h_j(t) = \sum_{i=1}^{N} w_i \left[h'_i(t) - x_{i,j}(t)\right] \tag{1}$$

where N is the number of participating clocks during the interval of calculation (one month), w_i the relative weight of clock H_i, $h_i(t)$ is the reading of clock H_i at time t, and $h'_i(t)$ is the prediction of the reading of clock H_i that serves to guarantee the continuity of the time scale. Clock readings in (1) actually take the form of time differences between readings of clocks, written as:

$$x_{i,j}(t) = h_j(t) - h_i(t) \tag{2}$$

Two algorithms are used in applying (1) to calculate the free atomic time scale (EAL): the prediction algorithm [7] that provides $h'_i(t)$ and the weighting algorithm [8] that provides w_i.

- The prediction algorithm is designed to avoid time and frequency jumps due to different clock ensembles being used in consecutive calculation periods; a quadratic model is used to describe the atomic clocks behavior and the frequency drift of the clocks is taken constant on a monthly period. This approach takes into account the frequency drift affecting most of the atomic clocks and has an impact on the EAL long term performance.
- The weighting algorithm is designed to optimize the long-term stability of EAL (thus of TAI) and to distribute in a correct way the weight of the different atomic clocks. The principle of the weighting algorithm in use since January 2014 is to rely on the clocks whose frequency is predictable, i.e. a clock with strong signatures such as frequency drift or aging can nevertheless be correctly used in the timescale ensemble if its behavior is well predicted. This is an evolution with respect to the algorithm used previously, which relied on clocks whose frequency is stable. In the new weighting algorithm, the difference between the predicted and the real frequencies of the atomic clocks is evaluated. A filter over one year of these data is applied to evaluate the weights and to guarantee the long-term stability of the clock ensemble. A maximum weight is fixed to avoid some of the clocks to become predominant in the ensemble.

In step 2, the frequency of EAL is computed by comparison to all available primary and secondary frequency standards using an estimation algorithm [9,10], and a frequency shift (frequency steering correction) is applied to EAL to ensure that the frequency of TAI conforms to its definition. Changes to the steering correction are expected to ensure accuracy without degrading the long-term (several months) stability of TAI, and these changes are announced in advance in the *BIPM Circular T*. The accuracy of TAI therefore depends on PFS and SFS measurements and on their regular report to the BIPM.

From (1), access to the time scale is provided by each participant H_j, which may be a clock or a local realization UTC(k). In the latter case, $x_j(t)$ can also be interpreted as:

$$x_j = EAL - UTC(k) \tag{3}$$

where for simplicity we have dropped the time instant t from the notation. From Eq. (1), and following the steps described in TAI and UTC generation, the differences [UTC − UTC(k)] are evaluated.

The instability of TAI is provided by the EAL ensemble and is estimated today at about three parts in 10^{16} for averaging time of 30 days. Its frequency accuracy is also presently estimated at the same level, thanks to the regular report of PFS and SFS evaluations. In the very long term, the stability and accuracy of TAI is maintained by PFS: over the decade 2000–2010, it may be estimated at the level of 1–2 parts in 10^{15} [11], limited by the reported performance of PFS and by the steering strategy.

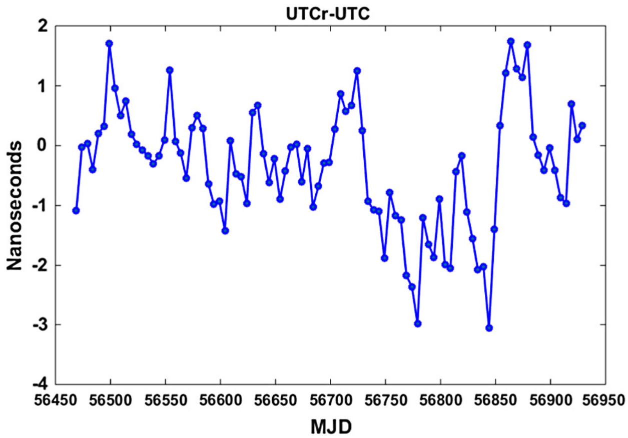

Fig. 1. Comparison of UTCr to UTC from MJD56467 to MJD56929.

UTCr was designed to be a realization of UTC, i.e. in practice the goal is to minimize the time difference $|UTCr - UTC|$. The number of clocks eligible for weighting in UTCr is typically between 280 and 300, so that we can infer that UTCr is about 20% less stable than UTC, considering that it is based on 60% to 70% of the clocks with similar characteristics. We estimate the one-month instability of UTC to be in the order of $3 \cdot 10^{-16}$ to $3.5 \cdot 10^{-16}$ over 2012–2014, so that the one-month instability of UTCr is in the order of $4 \cdot 10^{-16}$. UTCr is based on the same clock frequency prediction algorithm as UTC. However, the clock weighting algorithm is different; while clocks in UTC are weighted according to their predictability, clocks in UTCr are weighted in function of their stabilities.

To compare UTCr to UTC, we compute a weighted average of the individual differences of the solutions UTC and UTCr for each laboratory k, expressed at date t_j as:

$$D(t_j) = \sum_{k=1}^{N} W_{kj}\left(\left[UTCr - UTC(k)\right](t_j) - \left[UTC - UTC(k)\right](t_j)\right)$$

where W_{kj} is the total weight of the laboratory k in the UTCr calculation at the publication date t_j. Fig. 1 shows this comparison from July 2013 (MJD 56467) when UTCr started to be an official product; the agreement between UTCr and UTC is at a level of 1 ns RMS. Over the interval MJD 56467–56929, the difference $UTCr - UTC$ remains in the interval $[-3.06$ ns; 1.75 ns$]$, with a mean of -0.35 ns and a RMS of 1.06 ns.

3. Frequency standards and TT(BIPM)

Because TAI is computed in "real-time", each month, and has operational constraints, it does not provide the best timescale that could be generated in post-processing. The BIPM therefore computes in deferred time another realization TT(BIPM) [10], which is based on a weighted average of the evaluations of TAI frequency by the PFS and SFS. Here we briefly review the presently available frequency standards and the performance of TT(BIPM).

Primary frequency standards aim at realizing the SI second. Over the last decades of the 20th century, beam frequency standards had been steadily improved to attain $1 \cdot 10^{-14}$ accuracy at the end of the 1980s/the early 1990s. For example, the primary standard PTB Cs1 of the Physikalisch-Technischen Bundesanstalt in Braunschweig (Germany) was operated continuously over the 1978–1995 period (accuracy $\sim 3 \cdot 10^{-14}$) and since 1998 (present accuracy $0.8 \cdot 10^{-14}$), and PTB Cs2 started continuous operation in 1986 (present accuracy $1.2 \cdot 10^{-14}$), while other standards operated discontinuously. Then the first Cs fountain to be used as a PFS in the calculation of TAI was reported to the BIPM in 1995 [12], but the situation changed radically when regular submissions of fountain data started in 1999. Since year 2000, the number of Cs fountains contributing to TAI has increased regularly: from only two over the period 2000–2002, their number has reached fourteen since 2010, see [13] and references therein for more details on the different Cs fountains in operation. In addition, their evaluations have been carried out on a more regular basis, and, since 2009, more than four fountain evaluations are reported each month on average and this number will continue to increase as several new Cs fountains are currently under development. Finally the uncertainty assigned to each evaluation has also decreased over one decade from the low 10^{-15} to the low 10^{-16} in the best cases. As an example, Table 1 provides information on the PFS contributing to the BIPM in 2013.

In addition, a secondary frequency standard based on the ^{87}Rb transition was reported for the first time in 2012: SYRTE-FO2(Rb) has a stated uncertainty $u_B = 3.3 \cdot 10^{-16}$ [14] and some 40 evaluations, going back to the end of 2009, have been reported as of October 2014.

The present procedure for computing TT(BIPM) is described in [10] and a yearly computation is performed each January, the latest being TT(BIPM13) available in January 2014 at ftp://tai.bipm.org/TFG/TT(BIPM)/TTBIPM.13. In addition, an extrap-

Table 1
Primary and secondary frequency standards contributing to TAI in 2013. Extract from *BIPM Annual Report on Time Activities*, see http://www.bipm.org/en/bipm/tai/annual-report.html for details on the standards and on the laboratories operating them.

Primary standard	Type/selection	Type B std. uncertainty (10^{-15})	u_B (Ref.) (10^{-15})	Comparison with	Number/typical duration of comp.
NIST-F1	Fountain	0.31	0.35	H maser	4/15–45 d
NPL-CSF2	Fountain	0.23	0.23	H maser	12/15–35 d
PTB-CS1	Beam/Mag.	8	8.	TAI	12/30 d
PTB-CS2	Beam/Mag.	12	12.	TAI	12/30 d
PTB-CSF1	Fountain	(0.70 to 0.72)	1.4	H maser	4/15–30 d
PTB-CSF2	Fountain	(0.29 to 0.38)	0.41	H maser	9/15–30 d
SYRTE-FO1	Fountain	(0.35 to 0.41)	0.37	H maser	5/10–30 d
SYRTE-FO2	Fountain	(0.23 to 0.31)	0.23	H maser	13/10–35 d
Secondary standard	**Type**	**Type B std. uncertainty (10^{-15})**	**u_B (Ref.) (10^{-15})**	**Comparison with**	**Number/typical duration of comp.**
SYRTE-FORb	Fountain	(0.28 to 0.34)	0.33	H maser	14/10–35 d

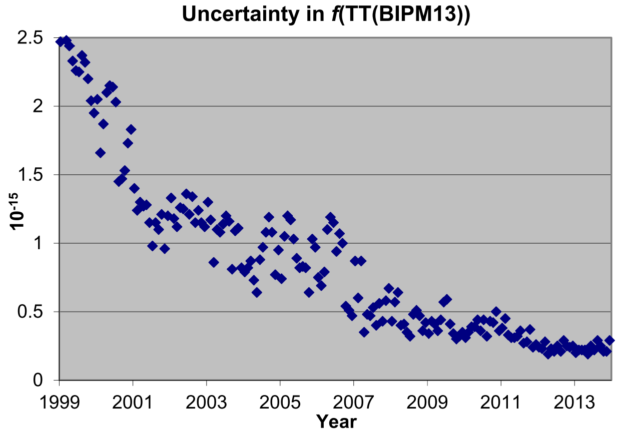

Fig. 2. Standard uncertainty of the frequency difference between EAL and TT(BIPM13).

olation of the latest realization is provided either as a monthly update (between 2009 and 2012) or as an explicit formula (since 2013). The basic features of the procedure for computing TT(BIPM) are the following:

- the computation starts in 1993 and uses all PFS measurements submitted to the BIPM since 1992;
- the frequency of EAL with respect to the PFS is estimated for each month since 1993 following the algorithm in [9], using an estimated stability model of EAL which depends on the period considered and improves with time;
- the series of monthly values f(EAL-TT) is smoothed, interpolated and integrated with a 5-day step since MJD 48984 (28 December 1992), at which epoch continuity is ensured with previous realizations.

As for any post-processing, details of the algorithm may be changed whenever deemed necessary.

The uncertainty of the monthly estimations f(EAL-TT), shown in Fig. 2, also provides the estimated accuracy of TT(BIPM13). One can see that, since 2012, it is about $2 \cdot 10^{-16}$ on average. This is due to the ever increasing number of Cs fountain evaluations (about 530 in total since 1999, 61 of them in 2013 provided by seven different fountains in four different laboratories), and to the improved accuracy of each fountain evaluation. More details on the PFS evaluations reported to the BIPM may be found in Table 6 of the *BIPM Annual Report on Time Activities* [http://www.bipm.org/en/bipm/tai/annual-report.html].

From an analysis of nine Cs fountains over the period 2006–2012, it has been shown [13] that the evaluations reported to the BIPM are statistically consistent with their stated uncertainties. This allows us to validate the performance of TT(BIPM), considered as an average ensemble of the fountains.

4. Future prospects

4.1. Long-term stability and the impact of new frequency standards

The number of atomic fountains reporting data to the BIPM has continuously increased over the past decade. Since 2012, data from atomic fountains, either clocks or frequency standards, are numerous enough to allow using only them to form a timescale. This is principally due to the presence of four USNO Rb fountains continuously operated as clocks [15], but existing primary and secondary standards are also marginally sufficient to form a timescale by themselves.

As an example, test timescales have been computed over 630 days in 2012–2013 using data from (up to) 10 fountains [16]. It is shown that such fountain-only timescales have a long-term (40–80 days) stability, which is in the order of $\sim 2 \cdot 10^{-16}$, comparable to that of TT(BIPM). Such fountain-only scales are nearly independent of EAL/TAI for averaging durations up to a few months. On the one hand, some fountains operated as clocks do contribute to EAL, but their weight is limited to the maximum weight in the algorithm used for UTC calculation, in the order of 1% each. On the other hand, fountains operated as primary standards do have correlations with EAL/TAI through the frequency steering and the frequency prediction algorithm, but this correlation is for an averaging duration of several months. Indeed the frequency drift of EAL clocks used for quadratic frequency prediction is estimated with respect to TT(BIPM) over six months [7,8]. Also the steering procedure has a characteristic time constant of several months because it is announced two months in advance and takes into account several months of past observations and furthermore no monthly steering has been necessary for TAI since September 2012. For these reasons, fountain-only timescales are nearly independent of EAL/TAI and are a useful tool to estimate its stability up to an averaging duration of a few months.

Such fountain-only scales are still not robust enough because of the small number of devices and of laboratories involved, but they are promising and may be a way forward for the future generation of TAI and UTC. In addition, other clock designs may provide the same kind of long-term stability and continuous operation needed to generate the reference timescale. For example, NASA/JPL efforts exist to develop a frequency standard based on the hyperfine transition at 40.5 GHz in $^{199}Hg^{+}$ ions [17] or 29.95 GHz in $^{201}Hg^{+}$ ions [18] trapped in a linear ion trap. For the $^{199}Hg^{+}$ transition, a stability floor of less than $2 \cdot 10^{-16}$ and a drift lower than $2.7 \cdot 10^{-17}$/day have been reported.

Assuming a few tens of such clocks are independently operated in a number of laboratories worldwide, they could be used to generate a robust timescale with stability at $1 \cdot 10^{-16}$ and below for averaging durations of 10 days to months. This would fulfill all present needs for the *time* stability of a reference time scale: for example a one-month time stability in the hundreds of ps would be in the order of the noise of the present best time transfer techniques generally used to access it; also a one-year time stability in the 1–2 ns would fulfill the needs of all applications requiring long-term stability; the most demanding may be the timing of millisecond pulsars whose pulses may be tagged with ns accuracy by giant radiotelescopes, e.g., the future Square Kilometer Array telescope [19]. If these clocks become available, the main obstacle to obtain the full performance of such a timescale may be limitations in time transfer techniques (see Section 4.3 below).

4.2. Towards real time realizations and predictions

Considering the evolving needs of time metrology future reflections are needed for the generation of UTC. The algorithms developed to calculate UTC should reflect the new scientific discoveries and new physical realities and the accessibility of UTC should meet the new needs of time laboratories and users.

The network of UTC time links to compare distant clocks is, until now, supported by two independent techniques, the two-way satellite time and frequency transfer (TWSTFT, or shorter, TW) and those based on GNSS observations, see [20] for more information on these time transfer techniques. All UTC contributing laboratories operate GPS or GPS/GLONASS equipment for time transfer, providing several types of measurement, e.g., single frequency code, dual frequency code, dual frequency code and phase for GPS (in order of decreasing statistical uncertainty, from nanoseconds to a few hundred picoseconds) [21]. Moreover, new satellite systems under development in Europe (Galileo), in China (BeiDou) and in India (GAGAN) will provide in the next future a very important number of measurements. The TW technique is operated in about a dozen institutes contributing to UTC today; in Europe, North America, and Asia, a complete set of redundant measurements is available [22]. A better, global use of this ensemble of measurements will optimize the impact of time links in UTC calculation by improving its metrological properties.

A possible way of making full use of these systems to better exploit all the available measurements is to use redundant time links to solve the time scale system [23]. Until now, TW links are used, when TW is available, for computing clock differences between each contributing laboratory and one laboratory that has been chosen as the reference (so-called "pivot"); otherwise GPS data are used to link other laboratories to the pivot; in this non-redundant approach, the clock differences are considered uncorrelated. As a consequence, the pivot laboratory has its uncertainty underestimated so that it is unrealistically small. A new approach would be a weighted least squares solution of a redundant system with a new expression of the uncertainty considering the correlations for the GNSS-based links. For the TW, the time link uncertainty is not expected to change.

The BIPM Time Department implemented the computation of UTCr considering the convenience of allowing the contributing laboratories to access to a realization of UTC more frequently than through the monthly *Circular T*, and consequently to assess on a shorter delay the level of synchronization of the local UTC(k) to the international reference. A next development could be therefore a real time prediction of UTC. In such a way all users could have a real time access to UTC, with particular impact on the synchronization of GNSS system times to the international reference.

4.3. Possible limitations of time transfer techniques

The time transfer techniques presently used in the generation of TAI are TW and techniques using GNSS phase and code measurements. Time links using GNSS phase and code achieve time stability of about 100 ps over one day (i.e. $1 \cdot 10^{-15}$ in frequency) to about 300 ps over one month (i.e. $1 \cdot 10^{-16}$ in frequency) [24,25]. The operational performance of TW is also of the same order of magnitude [24], limited by severe constraints in signal strength, bandwidth, and cost of renting the use of geostationary satellites. Some improvement may be expected for GNSS techniques, e.g., through new systems that bring more measurements and new codes such as the Galileo E5 signal [26,27]; new processing techniques should also improve results with the present measurements, e.g., through the use of integer ambiguity resolution [28,29]. For TW also, some improvement could be brought to the time transfer results by buying more bandwidth and more satellite transponder time; in addition, new techniques are being developed, such as using bandwidth synthesis [30] or using the carrier phase [31]. Although the latter technique could bring order of magnitude improvements, it is unlikely to be practical to operate with commercial geostationary satellites. Present techniques are therefore likely to be limited around the $1 \cdot 10^{-16}$ level, at averaging times of no less than several days.

Obviously phase + code two-way microwave operation would be a way to go but will need a dedicated space payload to overcome the operational constraints of using geostationary communications satellites. The prototype in this category is the ACES microwave link [32] due to fly with the ACES mission in 2016. Its expected time stability is about 7 ps at one-day ($<1 \cdot 10^{-16}$) and about 20 ps at ten-day averaging ($2 \cdot 10^{-17}$). Free space optical techniques may also be promising. The most advanced satellite time transfer system currently in operation is T2L2 (Time Transfer by Laser Light) on board the Jason 2 satellite [33]. However, such techniques that depend on the weather will always be limited for operational Earth-based time transfer.

Since several years, a lot of developments have occurred that use optical fibers for frequency comparisons and, more recently for disseminating time signals using a single fiber to avoid uncorrelated noise over two fibers. Among those, one technique using active stabilization and calibration of the propagation delay [34,35] was demonstrated on optical paths of several hundred kilometers with an accuracy in the order of a few tens of ps and a time deviation below 1 ps up to one-day averaging (i.e. a frequency stability in the order of 10^{-17}). Another technique uses the usual two-way method and equipment to their full bandwidth capability and was demonstrated on a distance of ∼70 km with an accuracy below 100 ps [36], and on a 540-km fiber link also used for frequency transfer with an accuracy in the order of 250 ps and a time stability (1 d) in the order of 20 ps [37]. In all cases, it seems that systematic effects (delay calibration, power sensitivity, fiber chromatic dispersion, polarization mode dispersion) can be characterized to less than 50 ps; therefore these techniques provide the best time transfer accuracy and can be used as a reference to calibrate other techniques.

One can therefore envision that these techniques will be fundamental for frequency transfer over continental regions and that they could also provide time transfer with unprecedented calibration accuracy. Such fiber networks are currently being implemented, in particular in Europe (see for example the Joint Research Project NEAT-FP of the European Metrology Research Program aiming at accurate time/frequency comparison and dissemination through optical telecommunication networks [38]). However, as such optical fiber links require amplifier stations about every 100 km, they are not suited for intercontinental links.

In an ideal case, we could have an "ACES-like" technique providing accurate time links between selected "hubs" over the different continents and networks of optical fibers providing accurate time links within the continents, therefore providing worldwide time transfer at a level of 10–100 ps for all averaging times. This could revive (with two orders of magnitude improvement) the situation in ∼2000 when the UTC network was based on a few intercontinental links with all other shorter-distance links. Such a situation is unlikely to happen in a close future because no "ACES-like" technique is expected to be available for long-term operation after the ACES mission, and also because the realization of the continental networks of optical fibers for time transfer will take time, but it could be a medium-term goal.

At shorter term, a more realistic situation is with one technique (GNSS phase and code) providing time links with a similar level of performance for all UTC stations, with one much more accurate technique (optical fiber) available on selected links and possibly other techniques (e.g., TW) available on some other links with various levels of performance. This is a case where it is desirable to use all available information, solving a redundant system of time links to provide the most accurate solution for TAI (see previous section).

4.4. Towards new definitions

As indicated in Section 2, the definition of TAI as "*a coordinate time scale defined in a geocentric reference frame with the SI second as realized on the rotating geoid as the scale unit*" explicitly refers to coordinate time, recognizing the need for a relativistic approach. In relativity, one has to distinguish proper time τ, as produced by an ideal clock, from coordinate time t. For a clock at rest on the Earth's surface, assuming that tidal terms (whose dominant term is semi-diurnal with amplitude in rate that may amount to a few 10^{-17}) are negligible, the relation between proper time and coordinate time is

$$\mathrm{d}\tau/\mathrm{d}t = 1 - 1/c^2\left[U(t,x) + v(t,x)^2/2\right] = 1 - W/c^2 \quad (4)$$

where c is the velocity of light, U is the Newtonian gravitational potential, v is the velocity of the clock in a non-rotating geocentric frame. The quantity W is termed the gravity (gravitational + rotational) potential at the clock. The geocentric coordinate time t is referred to as TCG. Any time differing from TCG by a constant rate may also be chosen as a coordinate time in the geocentric system, and this is the case of TAI, which is defined so that "*its scale unit is the SI second on the geoid*."

This is also the case of Terrestrial Time (TT), which, by Resolution B9 (2000) of the International Astronomical Union (IAU) [39], is explicitly defined with respect to TCG by the relation

$$\mathrm{d}TT/\mathrm{d}TCG = 1 - L_G \tag{5}$$

where $L_G = 6.969290134 \cdot 10^{-10}$ is a defining constant. This constant has been computed as $L_G = W_0/c^2$, taking for W_0 the value 62636856 $\mathrm{m^2\,s^{-2}}$ recommended by the International Association of Geodesy (IAG) in year 2000, at the time of the new definition. This value will be noted below $W_0(2000)$.

Because TAI is defined with respect to the rotating geoid, the transformation from proper time to TAI requires, in principle, the actual value (W_0) of the gravity potential on the geoid. Relation (4) transforms to:

$$\mathrm{d}\tau/\mathrm{d}TAI = 1 - (W - W_0)/c^2 \tag{6}$$

In practice, Eq. (6) is applied as

$$\mathrm{d}\tau/\mathrm{d}TAI = 1 + gh/c^2 \tag{7}$$

where h is the orthometric height of the clock and g the average value of gravity between the geoid and the clock.

Because a change in height of one meter causes a change in rate of about $1 \cdot 10^{-16}$, Eq. (7) can be somewhat loosely applied for present-day primary frequency standards, assuming that the geoid, the reference level of the height system, and the height are all correctly realized or measured with an uncertainty below one meter. This is no more the case when considering clock accuracy in the order of $1 \cdot 10^{-17}$ and below, for which an uncertainty in the order of 1 cm is needed. A further complication, not considered here, is that Eq. (4) must be completed with tidal terms at this level of accuracy.

The geoid is classically defined as the level surface of the gravity potential closest to the topographic mean sea level. Therefore the value of the potential on the geoid W_0 depends on the global ocean's level, which changes with time. In addition, there are several methods to realize that the geoid is "closest to the mean sea level", so that there is yet no adopted standard to define a reference geoid and W_0 value (see, e.g., a discussion in [40]). Several authors have considered the time variation of W_0 (see, e.g., [41,42]), but there is some uncertainty in what is taken into account in such a linear model. A recent estimate [42] over 1993–2009 is $\mathrm{d}W_0/\mathrm{d}t = -2.7 \cdot 10^{-2}\ \mathrm{m^2\,s^{-2}\,yr^{-1}}$, mostly driven by the sea level change of +2.9 mm/yr. The rate of change of the global ocean level could vary during the next decades; nevertheless, to state an order of magnitude, considering a systematic variation in the sea level in the order of 2 mm/yr, different definitions of a reference surface for the gravity potential could yield differences in frequency in the order of $2 \cdot 10^{-18}$ in a decade.

The W_0 value and the definition of the geoid are the responsibility of the International Association of Geodesy (IAG). There is evidence of inconsistency between the current definition of the geoid (the equipotential closest to the mean sea level) and the use of a fixed W_0 value for the potential on the geoid. Likely the W_0 value should be updated to reflect the mean sea level.

The choice of the value $W_0(2000)$ provides a formal definition of a surface where clocks run at the same rate as TT, which has been named the chronometric geoid [43]. Assuming that the "classical" geoid remains linked to the mean sea level, these two surfaces would differ in the future. Indeed, if the IAG updates the conventional value of the gravity potential on the geoid W_0, this will have no implication on the L_G, value which remains a fixed conventional value relating TCG and TT. We note, however, that such a new definition of the geoid and a new value of W_0 will necessitate a reformulation of the definition of TAI if it is desired to keep TAI as a practical realization of TT in a world where clocks with 10^{-17} accuracy exist. This is because the definition of TAI formally refers to the geoid, while that of TT does not. The reformulation of the TAI definition, as well as its application, is under the responsibility of the CCTF.

Changing the wording in the definition of TAI will be one task, but it may be the easy one. Indeed practical methods to apply Eq. (6) that relates proper time to TAI will always necessitate determining the gravity potential at the location of the clocks, a difficult task at the 10^{-17} level worldwide [44]. In past years, it has been shown [45] that an uncertainty of $2\text{–}3 \cdot 10^{-17}$ could be achieved for the location of the NIST in Boulder (Colorado, USA).

We note, as many authors before [46,47], that the problem may be reversed with accurate clocks and accurate frequency comparison techniques providing a means to compute the difference of gravity potential between the locations of the clocks. In order to be useful for geodesy, both clocks and frequency comparison techniques should be accurate to the 10^{-17} level and should be operated on different continents. While height networks can be directly linked when on the same continent, larger uncertainties persist in the global determination of the geoid and of vertical references from effects affecting the sea surface topography [48]. Comparisons of accurate clocks could therefore help in the future to establish a worldwide vertical datum.

It is also obvious that the existence of clocks with accuracy of 10^{-17} and below will necessarily lead to a new definition of the second. This is a wide topic for discussion and is not further considered here.

5. Conclusions

In this paper, the present status and the future challenges of international timescales are discussed. Possible developments in term of participating clocks, algorithms and time transfer techniques are considered in order to improve the long-term stability of UTC. The problem of accessibility of UTC together with the technical limitations is analyzed. The current use of frequency standards for TAI and TT(BIPM) highlights the impact of the new ultra-accurate frequency standards on international timescales. It is shown how they could improve the long-term stability, need new definitions and bring new applications for international timescales.

Acknowledgements

We thank the time laboratories for their contribution to international timescales by participating to UTC and UTCr and providing frequency standards evaluations.

References

[1] 13th General Conference on Weights, Measures, Comptes rendus de la 13e CGPM (1967/68), 1969, p. 103.
[2] 14th General Conference on Weights, Measures, Comptes rendus de la 14e CGPM (1971), 1972, p. 77.
[3] BIPM Circular T, monthly publication, ftp://ftp2.bipm.org/pub/tai//publication/cirt/.
[4] G. Petit, et al., UTCr: a rapid realization of UTC, Metrologia 51 (1) (2014) 49–56.
[5] G. Panfilo, E.F. Arias, Algorithms for TAI, IEEE Trans. Ultrason. Ferroelectr. Freq. Control 57 (1) (2010) 140–150.
[6] CIPM recommendation 1 (CI-2013): updates to the list of standard frequencies, in: Comité international des poids et mesures, 102nd meeting, 2013, p. 144.
[7] G. Panfilo, A. Harmegnies, L. Tisserand, A new prediction algorithm for the generation of international atomic time, Metrologia 49 (1) (2012) 49–56.
[8] G. Panfilo, A. Harmegnies, L. Tisserand, A new weighting procedure for UTC, Metrologia 51 (3) (2014) 285–292.
[9] J. Azoubib, M. Granveaud, B. Guinot, Estimation of the scale unit duration of time scales, Metrologia 13 (1977) 87–93.
[10] G. Petit, A new realization of terrestrial time, in: Proc. 35th Precise Time and Time Interval (PTTI) Meeting, 2003, pp. 307–316.
[11] G. Petit, The long-term stability of EAL and TAI (revisited), in: Proc. Joint Meeting of the European Time and Frequency Forum (EFTF) and the IEEE International Frequency Control Symposium (IEEE-FCS), Geneva, Switzerland, 2007, pp. 391–394.
[12] A. Clairon, et al., Ramsey resonance in a Zacharias fountain, Europhys. Lett. 16 (1991) 165–170.
[13] G. Petit, G. Panfilo, Comparison of frequency standards used for TAI, IEEE Trans. Instrum. Meas. 62 (6) (2013) 1550–1555.
[14] J. Guéna, et al., Progress in atomic fountains at LNE-SYRTE, IEEE Trans. Ultrason. Ferroelectr. Freq. Control 59 (2012) 391–410.
[15] S. Peil, et al., Evaluation of long term performance of continuously running atomic fountains, Metrologia 51 (2014) 263–269.
[16] G. Petit, A timescale based on the world's fountain clocks, in: 45th Precise Time and Time Interval (PTTI) Meeting, 2013.
[17] E.A. Burt, W.A. Diener, R.L. Tjoelker, A compensated multi-pole linear ion trap mercury frequency standard for ultra-stable timekeeping, IEEE Trans. Ultrason. Ferroelectr. Freq. Control 55 (12) (2008) 2586–2595.
[18] E.A. Burt, S. Taghavi-Larigani, R. Tjoelker, A new trapped ion atomic clock based on $201Hg^+$, IEEE Trans. Ultrason. Ferroelectr. Freq. Control 57 (3) (2010) 629–635.
[19] J.M. Cordes, et al., New Astron. Rev. 48 (2004) 1413.
[20] E.F. Arias, G. Panfilo, G. Petit, Timescales at the BIPM, Metrologia 48 (4) (2011) S145–S153.
[21] Z. Jiang, E.F. Arias, Use of the global navigation satellite systems for the construction of the international time reference UTC, in: Proc. China Satellite Navigation Conference, 2013, pp. 457–468.
[22] Z. Jiang, H. Konaté, W. Lewandowski, Review and preview of two-way time transfer for UTC generation – from TWSTFT to TWOTFT, in: Proc. IFCS–EFTF 2013, 2013, pp. 501–504.
[23] G. Petit, Z. Jiang, Using a redundant time links system in TAI computation, in: Proceedings of the 20th EFTF, 2006, pp. 436–439.
[24] A. Bauch, et al., Comparison between frequency standards in Europe and the US at the 10^{-15} uncertainty level, Metrologia 43 (2006) 109–120.
[25] G. Petit, Z. Jiang, Precise point positioning for TAI computation, Int. J. Navig. Obs. 2008 (2008), http://dx.doi.org/10.1155/2008/562878, Article ID 562878.
[26] P. Defraigne, et al., Advances in multi-GNSS time transfer, in: Proceedings of the 2013 UFFC, EFTF, 2013.
[27] M.C. Martínez-Belda, P. Defraigne, C. Bruyninx, On the potential of Galileo E5 for time transfer, IEEE Trans. Ultrason. Ferroelectr. Freq. Control 60 (2013) 121–131.
[28] J. Delporte, et al., GPS carrier phase time transfer using single difference integer ambiguity resolution, Int. J. Navig. Obs. 2008 (2008), Article ID 273785.
[29] G. Petit, et al., GPS frequency transfer with IPPP, in: Proceedings of the 28th EFTF, 2014.
[30] J. Amagai, T. Gotoh, Development of two-way time and frequency transfer system with dual pseudo random noises, J. Natl. Inst. Inf. Commun. Technol. 57 (2010) 197–207.
[31] M. Fujieda, et al., Carrier-phase two-way satellite frequency transfer over a very long baseline, Metrologia 51 (2014) 253–262.
[32] C. Salomon, L. Cacciapuoti, N. Dimarcq, Atomic clock ensemble in space: an update, Int. J. Mod. Phys. D 16 (2007) 2511.
[33] P. Exertier, et al., Status of the T2L2/Jason2 experiment, Adv. Space Res. 46 (2010) 1559–1565.
[34] P. Krehlik, et al., IEEE Trans. Instrum. Meas. 61 (9) (2012) 2573–2580.
[35] Ł. Śliwczyński, et al., Metrologia 50 (2013) 133–145.
[36] M. Rost, et al., Metrologia 49 (6) (2012) 772–778.
[37] O. Lopez, et al., Simultaneous remote transfer of accurate timing and optical frequency over a public fiber network, Appl. Phys. B, Lasers Opt. 110 (1) (2013) 3–6.
[38] http://www.ptb.de/emrp/neatft_home.html.
[39] All IAU resolutions may be found at: http://www.iau.org/administration/resolutions/general_assemblies/.
[40] L. Sánchez, Towards a vertical datum standardisation under the umbrella of global geodetic observing system, J. Geod. Sci. 2 (4) (2012) 325–342.
[41] M. Burša, et al., The geopotential value W_0 for specifying the relativistic atomic time scale and a global vertical reference system, J. Geod. 81 (2007) 103–110.
[42] N. Dayoub, S.J. Edwards, P. Moore, The Gauss–Listing geopotential value W_0 and its rate from altimetric mean sea level and GRACE, J. Geod. 86 (9) (2012) 681–694.
[43] P. Wolf, G. Petit, Relativistic theory for clock syntonization and the realization of geocentric coordinate times, Astron. Astrophys. 304 (1995) 654–661.
[44] G. Petit, P. Wolf, Computation of the relativistic rate shift of a frequency standard, IEEE Trans. Instrum. Meas. 46 (2) (1997) 201–204.
[45] N.K. Pavlis, M.A. Weiss, The relativistic redshift with 3×10^{-17}, uncertainty at NIST, Boulder, Colorado, USA, Metrologia 40 (2003) 66–73.
[46] M. Soffel, et al., Relativistic theory of gravimetric measurements and definition of the geoid, Manuscr. Geod. 13 (1988) 143–146.
[47] A. Bjerhammar, On a relativistic geodesy, Bull. Géod. 59 (3) (1985) 207–220.
[48] H. Sünkel, T. Baker (Eds.), Sea Surface Topography and Geoid, IAG Symposia, vol. 104, Springer, 1990, pp. 116–128.