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ATOMIC TIME SCALES FOR THE 21ST CENTURY

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RESUMEN

El Bureau Internacional de Pesas y Medidas, en coordinación con organizaciones internacionales e institutos nacionales, mantiene y disemina el Tiempo Universal Coordinado (UTC). Existen también otras escalas de tiempo para satisfacer distintas aplicaciones. Este artículo presenta el estado actual en la elaboración de estas escalas de tiempo.

ABSTRACT

The International Bureau of Weights and Measures, in coordination with international organizations and national institutes, maintains and disseminates Coordinated Universal Time (UTC). Other timescales exist for different purposes. This article describes the state-of-the-art in the elaboration of these time scales.

Key Words: standards — time

1. INTRODUCTION

Time scales are developed for different applications. National times (referred to as "legal", or "official") are maintained for providing time within a country under the responsibility of the national metrology institute, although in some cases astronomical observatories maintain the national time. International coordination is necessary for facilitating the interactions between the different countries. Taking advantage of well-established structures, international time coordination arises from the joint actions of three organizations: the International Bureau of Weights and Measures (BIPM), in charge of the computation of the international reference time scale Coordinated Universal Time (UTC); the International Telecommunication Union (ITU), responsible for fixing the rules for the dissemination of UTC and for establishing the procedure for its synchronization to Earth's rotation time; and the International Earth's Rotation and Reference Systems Service (IERS), which studies the irregularities of the Earth's rotation, determines the relationship between rotational and atomic times and announces the dates of application of the procedure for their synchronization.

In a process embedded in the international coordination for metrology, where the ultimate objective is the traceability of physical and chemical measurements to the International System of Units (SI, Bureau International des Poids et Mesures 2006), national realizations of the atomic time scale become traceable to UTC by participating in the relevant international comparison at the BIPM. A laboratory "k" fulfilling this condition maintains a local realization (or approximation) to UTC, identified with the acronym UTC(k).

The system is a metrological pyramid where the BIPM is at the top giving traceability to the SI units to national institutes. These disseminate the SI within their respective territories and follow the mechanisms that guarantee the confidence in measurements at two levels: within the frontiers, for supporting the societal activities, and between nations, thus assuring confidence in measurements in all kinds of international exchanges: financial, commercial, scientific, etc.

Time scales are constructed to fulfil particular needs. UTC provides the international reference, with outstanding frequency stability (3 parts in 10^{16}), and high frequency accuracy (few parts in 10^{16}); it is consequently suited for all applications, from the most demanding, to those covering the needs of civil timekeeping. The local realizations UTC(k) approximate UTC with offsets ranging from a few nanoseconds up to microseconds, and are characterized by uncertainties between 5 and 20 ns. Other time scales are developed and maintained for particular applications. Global navigation satellite systems (GNSS) define internal time scales for the purpose of synchronizing the system and producing the navigation solutions. They are computed from individual clock readings and are synchronized to realizations of UTC with offsets limited to tolerance values specified for each system.

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The composite timescales, that is, those that are constructed on the basis of an ensemble of clocks, obey algorithms whose characteristics depend on the requested quality of the time scale. The basic information for the establishment of such a time scale is the difference between the clocks in the ensemble. The devices used for evaluating the clock differences depend on the location of the clocks, either within a room in a laboratory or in different geographical locations. UTC is the extreme case where the clocks in the ensemble (more than 400) are spread world-wide.

2. SOME BASIC CONCEPTS

In time metrology, a time scale is characterized by the stability and the accuracy of the underlying frequency. The frequency stability of a time scale represents its capacity to maintain a fixed ratio between its unitary scale interval and its theoretical counterpart. The frequency accuracy of a time scale represents the aptitude of its unitary scale interval to reproduce its theoretical counterpart. After the calculation of a time scale on the basis of an algorithm conferring the required frequency stability, the frequency accuracy can be improved by comparing the frequency (rate) of the time scale with that of primary frequency standards (PFS), and by applying, if necessary, frequency (rate) corrections.

The Free Atomic Scale (EAL) is the first step in the calculation of UTC; it is the weighted average of the contributing clocks treated by an algorithm especially designed for mid-term frequency stability (about 3 parts in 10^{16} over intervals of 20 to 40 days). Its unitary interval is not constrained to be close to the SI second. It is calculated monthly at the BIPM on the basis of about 420 industrial atomic clocks in 72 national institutes and observatories spread world-wide.

International Atomic Time (TAI) is a continuous and uniform time scale whose unitary interval agrees with the SI second by a few parts in 10^{16}. By comparison of the unit interval of EAL to the duration of the SI second realized by primary frequency standards in a small number of laboratories, it may result that a correction to the frequency is needed. This process, called “steering of EAL” provides accuracy to TAI. TAI has no tie to the Earth’s rotation time. It is not represented by clocks, it is not broadcast; it provides a reference for frequency only. It has the stability of EAL, better than that of any of the clocks used for its computation. TAI is the basis of the realizations of time scales used in dynamics, for modelling the motions of artificial and natural celestial bodies, with applications in the exploration of the solar system, tests of theories, geodesy, geophysics, environmental studies, etc.

Coordinated Universal Time (UTC) is calculated monthly at the BIPM by applying to TAI the number of leap seconds accumulated at the moment of its computation (35 until 1 January 2014). It has the same metrological qualities as TAI, but presents one-second discontinuities at the moment of insertion of a leap second to compensate for the irregular rate of rotation of the Earth. It is represented by clocks in the laboratories that contribute data to its maintenance, and has been adopted as the world reference for time coordination. It is defined in a recommendation of the International Telecommunication Union (ITU 2002), including the procedure for insertion of leap seconds. This procedure limits the offset between UT1 and UTC to a maximum value of 0.9 s.

BIPM Circular T is the monthly publication that provides at five-day intervals, the values [UTC-UTC(k)] for each contributing laboratory k. It gives traceability to the SI second and to UTC to national time standards from which legal times in many countries are defined.

3. CLOCK COMPARISONS

The calculation of a time scale on the basis of the readings of clocks located in different laboratories requires the use of methods of comparison of distant clocks. A prime requisite is that the methods of time transfer do not contaminate the frequency stability of the clocks; in the past, they were often a major limitation in the construction of a time scale.

UTC is built with the contribution of 72 laboratories spread over the planet; therefore a strategy for the clock comparison, consistent with the designed algorithm needs to be well defined. Based on the principle of non-redundant comparisons, the BIPM establishes a network of international time links.

The uncertainty of clock comparisons ranges between a few tens of nanoseconds and a nanosecond for the best links, a priori sufficient to allow a comparison of the best atomic standards over integration times of a few days. This assertion is strictly valid for frequency comparisons, where only the denominated Type A (statistical) uncertainty affects the process. In the case of time comparisons, the systematic uncertainty (Type B), coming from the calibration, should also be considered. In the present situation, calibrations contribute an uncertainty that surpasses the statistical component, and which can reach 20 ns for uncalibrated equipment (§ 6 of *BIPM Circular T*). It can be inferred that repeated equipment calibrations are indispensable for clock comparison.

A network of international time links has been established by the BIPM to organize these comparisons. The participating laboratories provide time transfer data in the form of a comparison of their UTC(k) with respect to another time scale (currently a GNSS time scale) or to another local realization of UTC (this is a case of two-way observations).

3.1. *Use of GNSS for time transfer*

The use of GPS satellites in time comparisons introduced a major improvement in the construction and dissemination of time scales. It consists of using the signal broadcast by GPS satellites, which contains timing and positioning information. It is a one-way method, the signal being emitted by a satellite and received by specific equipment installed in a laboratory. For this purpose, GPS receivers have been developed and commercialized to be used specifically for time transfer.

The common-view (CV) method proposed by Allan & Weiss (1980) relies on the reception by several receivers of the same emitted signal. It is still in use for clock comparisons when it is necessary to eliminate the error sources common to the two observing stations, mostly originated from the satellite clocks and orbits. GPS CV had been used for the calculation of UTC at the BIPM until 2006. Then, advances in obtaining precise satellite orbits and clock parameters allowed the introduction of another technique, named All in View (AV) (Petit & Jiang 2008) that eliminates the constraint of having simultaneous observations, thus becoming independent of the length of the baseline for having suitable observed satellites.

The International GNSS Service (IGS) provides high precision GPS satellite clock products referred to the time scale of the IGS (IGST), whose relative frequency instability is of order 10^{15} for a one day averaging time, two orders of magnitude better than that of the GPS Time. Since this minimizes the impact of the error coming from satellite orbits and clocks, it has been possible to use the AV method instead of the GPS CV with the benefit of adding data from satellites at high elevations improving the statistical uncertainty of the time links, particularly the very long ones (Petit & Jiang 2008).

The GPS links obtained using dual-frequency receivers, denominated GPS P3 (Defraigne et al. 2001a,b), provide ionosphere-free data and allow clock comparisons with nanosecond statistical uncertainty, or better. This kind of link uses GPS code measurements only.

Most remaining error sources are under 0.1 ns, the precision with which TAI is reported. Code-multipaths effects can reach 1 ns on a short term basis and higher values in the long-term, representing the ultimate limit to code-only time transfer either with CV or AV. Tropospheric delay is still present in the data, introducing short-term noise and bias of a few 0.1 ns, with slow variations depending on weather conditions. The addition of phase measurements from geodetic-type receivers minimizes the effects of these two error sources. The precise positioning technique (PPP, Petit & Jiang 2008; Kouba & Héroux 2001) in which dual frequency phase and code measurements are used for comparing via GPS the reference clock in a station to a reference time scale has been implemented for use in the computation of time links for UTC and is being used on a routine basis since September 2009. By this technique we obtain the smallest statistical uncertainty of clock comparison, at present 0.3 ns.

Thanks to new hardware and to improvements in data treatment and modeling, the uncertainty of clock comparison via GPS is below 1 ns today. The effects of ionospheric delay introduce one of the most significant errors in GPS time comparisons, in particular in the case of clocks compared over long baselines. Dual-frequency receivers installed in many participating laboratories permit the removal of the delay introduced by the ionosphere, thus increasing the accuracy of time transfer. GPS observations with single-frequency receivers used in regular UTC calculations are corrected for ionospheric delays by making use of ionospheric maps produced by the IGS. All GPS links are corrected for satellite positions using IGS post-processed precise satellite ephemerides.

After many years of limited operations with a small number of satellites, GLONASS is now flying the complete constellation. After a series of studies and tests, GLONASS CV links have been successively included in the calculation of UTC since November 2009 (Jiang & Lewandowski 2012). Precise orbits provided by the Information Analysis Centre (IAC) from the Russian Federation and ionospheric maps provided by the IGS are used to compute corrections.

As a first step towards multi-system time transfer, the BIPM has developed a link combination strategy; combination of GPS and GLONASS is officially used for establishing six links for UTC (Jiang & Lewandowski 2012).

3.2. *Two-way satellite time and frequency transfer (TWSTFT)*

The TWSTFT (Hanson 1989; Kirchner 1991) technique utilizes a geostationary telecommunication satellite to compare clocks located in two receiving-emitting stations. This technique is independent from GNSS, thus adding redundancy to the system. Two-way observations are scheduled between pairs of laboratories so that their clocks are simultaneously compared at both ends of the baseline. The two-way method has the advantage over the one-way method of eliminating or reducing some sources of systematic error, such as ionospheric and tropospheric delays and the uncertainty in the positions of the satellite and the ground stations. A number of laboratories operate two-way equipment, allowing links within and between North America, Europe and the Asia-Pacific region. With the installation of automated stations in all laboratories, the TWSTFT link observations in TAI are made every day at two-hour intervals with an uncertainty (statistical) below 1 ns.

The combination of TW and GPS PPP results in a link characterized by the accuracy of TW (∼1 ns) and the short term stability of GPS PPP (Jiang & Lewandowski 2012). This combination is regularly used for the evaluation of about 10 links in UTC.

3.3. *Characterization of the relative delays of time transfer equipment*

Measuring the delays of the equipment for time transfer is fundamental for the stability of UTC and for its dissemination. Campaigns for determining differential delays of GNSS time equipment are organized by the BIPM to compensate for internal delays in laboratories by comparing their equipment with traveling BIPM equipment, which have been conducted since 2001, result in about 65% of the GNSS equipment used in UTC to be calibrated at least once (Lewandoswki & Tisserand 2010a,b,c and `http://www.bipm.org/jsp/en/TimeCalibrations.jsp`). The situation for the TWSTFT links is different; the laboratories organize calibrations of the TWSTFT equipment with the support of the BIPM (Piester et al. 2005, 2009).

3.4. *Time links comparison*

For two decades, GPS C/A-code observations provided a unique tool for clock comparisons in TAI, rendering impossible any test of its performance with respect to other methods. The present situation is quite different; the introduction of the TWSTFT technique and of the GLONASS observations has allowed the opportunity of comparing results for a time link using independent techniques, making the system more reliable. For the links where GNSS and TW techniques are available, all links are computed and compared; the best is used in the calculation of UTC, and the other(s) kept as backup (Jiang & Lewandowski 2012). The time links and the results of time link comparisons are available at `ftp://tai.bipm.org/TimeLink/LkC`..

4. THE ALGORITHM OF CALCULATION OF EAL/TAI/UTC

Different algorithms can be considered depending on the requirements on the scale; for an international reference such as UTC, the requirement is extreme reliability and long-term (about a month) frequency stability. UTC therefore relies on the largest possible number of atomic clocks of different types, located in different parts of the world and connected in a network that allows precise time comparisons.

The original algorithm ALGOS for defining EAL was developed at the BIH in the 1970s (Thomas et al. 1994; Guinot & Thomas 1988) and gives the difference between EAL and each participant clocks as:

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

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.

ALGOS is basically composed of three algorithms designed to guarantee the frequency stability and accuracy of TAI

- The weighting algorithm optimized to guarantee the long-term stability of TAI; the weight attributed to a clock reflects its long-term stability, since the objective is to obtain a weighted average that is more stable in the long term than any of the contributing elements (Guinot & Thomas 1988; Thomas & Azoubib 1996; Azoubib 2001). In the EAL computation, the weight attributed to each clock is the reciprocal of the individual classical variance computed from the frequencies of the clock, relative to EAL, over one year of data. A maximum weight is fixed to avoid clocks having a predominant role.

- The prediction algorithm used in ALGOS to avoid time and frequency jumps due to different clock ensembles being used in consecutive calculation periods; since August 2011 a quadratic model (Panfilo et al. 2012) is used to describe the atomic clocks' behavior and the frequency of the clocks is taken as constant on a month period.

- The steering algorithm used to improve the accuracy of TAI. International Atomic Time TAI is a realization of TT, a coordinate time in a geocentric reference system. TAI gets its stability from the industrial atomic clocks kept in the contributing laboratories, and its accuracy from a small number of PFS maintained by a few metrology laboratories. The frequency of EAL is compared with that of PFS using all available data, 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 measurements, which are reported more or less regularly to the BIPM. Data from several PFS are combined to estimate of the duration of the scale unit of TAI (Azoubib & Granveaud 1977; Arias & Petit 2005).

5. TT(BIPM), BIPM'S BEST REALIZATION OF TERRESTRIAL TIME

Terrestrial Time (TT) is a coordinate time in the geocentric reference system defined by the International Astronomical Union. TAI provides one realization of TT but, as it is computed in almost real-time and has operational constraints, it does not provide an optimal realization. The BIPM therefore computes in deferred time TT(BIPM) (Petit 2003, 2009), which is based on a weighted average of the evaluations of the frequency of TAI by the PFS. TT(BIPM) is computed each January[2]. Since 2009, an extrapolation of the latest realization is published each month[3]. Its computation starts in 1993 and uses all PFS measurements submitted to the BIPM since 1992.

6. CONCLUSION

The BIPM calculates on a routine basis the atomic scales TAI, UTC and TT(BIPM). Clock and time transfer data are provided by time laboratories spread world-wide, and processed at the BIPM with an algorithm designed to guarantee the reliability, long-term frequency stability, high frequency accuracy and accessibility of the scales. Broad dissemination of UTC is achieved at different levels and by different means; monthly BIPM Circular T gives traceability to UTC and the SI second to its local realizations UTC(k) in national institutes; participants to the calculation disseminate UTC(k) following the rules established by the ITU; GNSS reinforce the dissemination of UTC via approximations broadcast in their navigation messages.

The maintenance of UTC requests the improvement of all the elements serving to its calculation. The development of new time transfer equipment and processing techniques allows to improve the methods of clock comparison; developing and operating primary frequency standards in laboratories is essential to the accuracy of TAI; and the refinement of the algorithm of calculation improves the long-term stability of TAI.

REFERENCES

BIPM 2006, The International System of Units (SI) (8th ed.; Sèvres, France: Bureau International des Poids et Mesures), `http://www.bipm.org/utils/common/pdf/si_brochure_8.pdf`

BIPM 2013, BIPM Circular T 305, `ftp://ftp2.bipm.org/pub/tai/publication/cirt.305`

International Telecommunication Union 2002, Recommendation ITU-R TF.460-6, `http://www.itu.int/rec/R-REC-TF.460-6-200202-I/en`

Allan, D. W., & Weiss, A. M. 1980, Proc. 34th Annual Frequency Control Symp., 334

Arias, E. F., & Petit, G. 2005, Proc. Joint IEEE FCS and PTTI, 244

Azoubib, J., Graveaud, M., & Guinot, B. 1977, Metrologia, 13, 87

Azoubib, J. 2001, 15th Meeting of the CCTF, Document CCTF/01-14 (`http://www.bipm.org/cc/CCTF/Allowed/15/CCTF_01_14.pdf`)

Defraigne, P., Bruyninx, C., Clarke, J., Ray, J., & Senior, K. 2001a, Proc. 15th European Frequency and Time Forum (EFTF), 517

Defraigne, P., Petit, G., & Bruyninx, C. 2001b, Proc. 33rd Ann. Precise Time and Time Interval (PTTI), 341

Guinot, B., & Thomas, C. 1988, Annual Report of the BIPM, Time Section, 1, D3

Hanson, D. W. 1989, 43rd Annual Symp. on Frequency Control, 174

Jiang, Z., Arias, E. F., Lewandowski, W., & Petit, G. 2011, Proc. Joint Conf. IEEE IFCS & EFTF, 1064

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[2] The latest TT(BIPM12) is available at `ftp://tai.bipm.org/TFG/TT(BIPM)/TTBIPM.12`.

[3] See e.g. `ftp://tai.bipm.org/TFG/TT(BIPM)/TTBIPM.12.ext`.

Jiang, Z., & Lewandowski, W. 2011, Metrologia, 49, 57

Jiang, Z., & Lewandowski, W. 2012, Proc. EFTF, 126

Jiang, Z., & Lewandowski, W. 2012, Proc. EFTF, 335

Kirchner, D. 1991, Proc. IEEE, 79, 983

Kouba, J., & Héroux, P. 2001, GPS Solutions, 4, 31

Lewandowski, W., & Tisserand, L. 2010a, Rapport BIPM-2010/02

Lewandowski, W., & Tisserand, L. 2010b, Rapport BIPM-2010/03

Lewandowski, W., & Tisserand, L. 2010c, Rapport BIPM-2010/04

Panfilo, G., Harmegnies, A., & Tisserand, L. 2012, Metrologia, 49, 49

Petit, G. 2003, Proc. 35th Ann. Precise Time and Time Interval (PTTI), 307

Petit, G. 2009, Proc. 7th Symp. on Frequency Standards and Metrology, ed. L. Maleki (Singapore: World Scientific), 475

Petit, G., & Jiang, Z. 2008, Metrologia, 45,35

Petit, G., & Jiang, Z. 2008, Int. J. Navig. Obs., 562878

Piester, D., et al. 2005, Proc. Joint Conf. IEEE IFCS & PTTI, 316

Piester, D., Feldmann, T., Bauch, A., Fujieda, M., & Gotoh, T. 2009, Proc. EFTF V IFCS Joint Conf., 1076

Thomas, C., Wolf, P., & Tavella, P. 1994, BIPM Monographie 94/1