Status of UTC/TAI

E. Felicitas Arias[1,2], *Gianna Panfilo*[1], and *Gérard Petit*[1]

[1]International Bureau of Weights and Measures (BIPM)
Pavillon de Breteuil, 92310 Sèvres, France
farias@bipm.org

[2]Associated astronomer at the Paris Observatory

Abstract

This article presents how timescales are established and maintained at the International Bureau of Weights and Measures (BIPM), on the basis of international cooperation. We describe the characteristics of International Atomic Time (TAI) and Coordinated Universal Time (UTC) and the main features of the methods used for their calculation.

1. Introduction

The International Bureau of Weights and Measures (BIPM), with the support of the timing community, maintains the international time scales: International Atomic Time (TAI); Coordinated Universal Time (UTC); and a realization of Terrestrial Time, TT(BIPM). These serve as a reference for different applications. The algorithm for the calculation of TAI has been designed to guarantee the reliability, long-term frequency stability, frequency accuracy and accessibility of the scale. It relies critically on the methods of clock comparison.

TAI is an integrated time scale built by accumulation of seconds. It is the basis for the realization of UTC and is used for all applications that require a continuous scale, e.g. in the modelling of the motion of artificial and natural celestial bodies, in the exploration of the solar system, testing theories, geodesy, geophysics, and studies of the environment.

UTC is derived from TAI by the application of an integral number of seconds that compensate for the irregular rate of rotation of the Earth (34 s as of August 2011). It is realized by approximations denominated UTC(*k*) in national laboratories contributing data to the BIPM. UTC is the time scale used for world-wide time coordination. TAI and UTC are published each month with a delay of a few days after the end of the month of the data in *Circular T* [1].

TT(BIPM) is a time scale optimized for frequency accuracy. It is evaluated annually by making use of all available primary frequency standards data reported to the BIPM by national laboratories.

2. Metrological quality of the timescales

The reliability of TAI is ensured by about 350 industrial clocks operated in national laboratories, mainly caesium atomic standards and active auto-tuned hydrogen masers.

The frequency instability of TAI, estimated by the Allan variance, is 3 parts in 10^{16} for averaging times of about 30 days. In the very long term, the stability is in fact given by the accuracy of primary frequency standards (PFS) and is limited over a decade by the accuracy at the level of parts in 10^{15} assuming that the present performances remain constant.

The frequency accuracy of TAI is improved by comparing its frequency with that of PFS, and by applying, frequency corrections if necessary. Fifteen PFS, which include 11 caesium fountains developed and maintained in some of the national laboratories, have contributed frequency measurements since 2007, more or less regularly, to improve the accuracy of TAI, which is today known with an uncertainty of about 3 parts in 10^{16}.

The value of accessibility to a world-wide time scale is demonstrated by its usefulness in providing a method of dating events for everyone. This depends on the precision that is required for various applications. To reach its ultimate precision, TAI is calculated in a post-process using clock data at 5-day intervals over one

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

month. The process is designed in such a way that the measurement noise in clock comparisons is eliminated or at least minimized.

3. An essential tool: clock comparisons

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

The uncertainty of clock comparisons today is as low as one nanosecond in accuracy and a few hundred picoseconds in stability 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 statistical uncertainty affects the process. In the case of time comparisons, the systematic uncertainty, coming from the calibration of time transfer equipment, should also be considered and presently contributes an uncertainty that surpasses the statistical component. We can conclude that repeated equipment calibrations are indispensable for clock comparisons.

A network of international time links has been established by the BIPM to organize these clock comparisons. Every participating laboratory is compared to a unique pivot laboratory (currently the Physikalisch-Technischen Bundesanstalt (PTB) in Germany).

3.1 Use of global navigation satellite systems (GNSS) for time transfer

The use of the Global Positioning System (GPS) satellites in time comparisons introduced a major improvement in the construction and dissemination of time scales in the 1980s. The Russian satellite system for global navigation, GLONASS, came into routine use for time comparisons in TAI/UTC by the end of 2010. GNSS time transfer is a one-way method, the signal being emitted by a satellite and received by specific equipment installed in a laboratory. For this purpose, GNSS receivers have been developed and commercialized for use specifically in time transfer. The common-view method proposed in the 1980s by Allan and Weiss [2] relies on reception of the same emitted signal by several receivers. It was used extensively for clock comparisons by GPS at the BIPM until mid-2006. It is used today at the BIPM for clock comparisons via GLONASS and for clock comparisons at the national laboratories because it eliminates the instability of the satellite clocks.

The uncertainty of clock synchronization via GPS has today been reduced to a fraction of a nanosecond thanks to new hardware and improvements in data treatment and modelling. The older single-channel, single-frequency C/A code receivers have mostly been replaced in time laboratories by multi-channel receivers, which allow the simultaneous observation of satellites over the horizon. The ionospheric delay is one of the most significant errors in GPS time comparisons, in particular over long baselines, for such receivers. Dual-frequency receivers installed in the majority of participating laboratories permit the removal of the ionospheric delay, thus improving the accuracy of time transfer. Such ionosphere-free data, known as GPS P3 [3, 4], allow clock comparisons with nanosecond statistical uncertainty or better. Data from single-frequency receivers used in regular TAI calculations are corrected for ionospheric delays by making use of ionospheric maps produced by the International GNSS Service (IGS). All GPS links are corrected for satellite positions using IGS post-processed precise satellite ephemerides. The availability of GPS satellite clock corrections and a stable time scale, both produced by the IGS [5], allowed the adoption in 2006 of the so-called GPS all-in-view method [6], thus eliminating the constraint of simultaneous satellite visibility for long baselines and allowing the computation of time links with similar uncertainty, regardless of the distance.

The techniques mentioned above use GPS code measurements only. Improved results are obtained by the use of the carrier phase combined with the code, as a result of the very low noise of the phase measurements. This method, known as Precise Point Positioning (GPS PPP [7]) has been used at the BIPM since 2009.

Time comparisons by GLONASS [8] are calculated using only satellites in common-view at pairs of laboratories, due to the current non-availability of GLONASS clock solutions. It is hoped that the IGS will provide these parameters in the near future.

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

Independent to GNSS, the TWSTFT [9, 10] technique utilizes a telecommunications geostationary satellite to compare clocks located in two receiving−emitting stations. Two-way observations are scheduled between pairs of laboratories so that their clocks are simultaneously compared at both ends of the baseline using the satellite's transponder. This 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. However, arrangements must be made to hire use of the transponder and plan the simultaneous observations. With the installation of automated stations in most laboratories, some of the TWSTFT link observations in TAI are made at two-hour intervals, with the consequence of achieving a statistical uncertainty below 1 ns.

3.3 Characterization of the relative delay of time transfer equipment and evaluation of link uncertainties

Measuring the delays of a laboratory's time transfer equipment is fundamental to the stability of TAI 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 the BIPM's travelling GNSS equipment. Successive campaigns with BIPM travelling receivers have been conducted since 2001 with the result that about 65 % of the GPS equipment used in TAI has been calibrated [11]. The situation for the TWSTFT links is different; the laboratories organize calibrations of the TWSTFT equipment with the support of the BIPM. Pending such calibration for all stations, other two-way links in TAI are calibrated at the BIPM using the corresponding GPS link.

The BIPM estimates Type A (u_A) and Type B (u_B) standard uncertainties of all time links in TAI [12]. The statistical uncertainty u_A is evaluated by taking into account the level of phase noise in the raw data and the magnitude of effects varying over a typical duration below one month; u_B is the uncertainty of the calibration.

For two decades, GPS C/A-code observations have provided a unique tool for clock comparisons in TAI, rendering it impossible to test its performance with respect to other methods. The present situation is quite different. The introduction of the TWSTFT technique, and later, the implementation of the combination of the phase and code of the GPS signal, as well as the use of GLONASS observations, has facilitated the comparison of the results of clock comparisons traditionally obtained with the simplest GPS technique to those coming from an independent technique, or a different treatment of GNSS data, and have made the system more reliable. At present, 85 % of the links in TAI are obtained by using GPS equipment and about 15 % of the links are provided by TWSTFT observations. Approximately 50 % are equipped with two or more different techniques. Only 5 % of laboratories are still equipped with old-type receivers.

4. The calculation of UTC and TAI

Time laboratories provide readings of all their clocks with respect to a stable local reference time scale, either one individual atomic clock or a clock ensemble. Clock readings are then combined at the BIPM through an algorithm designed to optimize the frequency stability and accuracy, and increase the reliability of the time scale above the level of performance that can be realized by any individual clock in the ensemble. The ALGOS algorithm in use in the BIPM Time Department produces the international reference UTC every month. The calculation of UTC is carried out in three successive steps:

- The free atomic time scale EAL (Echelle Atomique Libre) is computed by ALGOS as a weighted average of about 350 free-running industrial atomic clocks world-wide. A clock weighting procedure has been designed to optimize the long-term frequency stability of the scale.
- 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.
- Leap seconds, as announced by the International Earth Rotation and Reference Systems Service (IERS), are inserted to maintain agreement with the time derived from the rotation of the Earth. The resulting time scale is UTC.

In addition, the PFS are used in post–processing to calculate another time scale known as TT(BIPM), also a realization of terrestrial time TT [13, 14]. TT(BIPM) is a time scale optimized for frequency accuracy. It is evaluated annually by making use of all available PFS data reported to the BIPM by national laboratories.

5. Dissemination of the timescales

The time scales TAI and UTC are disseminated every month by the BIPM *Circular T*. Access to UTC is provided in the form of differences [*UTC* – *UTC*(*k*)], thus at the same time making the local approximations UTC(*k*) traceable to UTC. The uncertainties of the differences are also published [15, 16]. The values of the frequency corrections to TAI, and their intervals of validity, are regularly reported. This information is needed by the laboratories to steer the frequency of their UTC(*k*) to UTC. *Circular T* provides wide access to the best realization of the second through the estimation of the fractional deviation d of the scale interval of TAI with respect to the SI second, calculated as explained above. The values of d for the individual contributions of the PFS are also published, giving access to the second as realized by each of the PFS. Access to GPS Time with an uncertainty of a few nanoseconds and to GLONASS Time with an uncertainty of a few tens of nanoseconds is provided via their differences with respect to TAI and UTC. Each monthly issue of *Circular T* provides information on the time links used for that particular computation together with their respective uncertainties, and the technique used in the characterization of the time transfer equipment or link. The daily differences between [*UTC* − *GPS Time*] and [*UTC* − *GLONASS Time*] are reported in *Circular T*. Also the relationship between TAI and UTC and the predictions of UTC(USNO) and UTC(SU) broadcast by GPS and GLONASS respectively are provided. The BIPM Time Department's ftp server [17] gives access to clock data and time transfer files provided by the participating laboratories, as well as the rates and weights for clocks in TAI in each month of calculation. This information is particularly useful for laboratories in the study of the behaviour of their clocks. Results for a complete year are published in the *BIPM Annual Report on Time Activities* [18], together with information about the equipment in contributing laboratories, time signals and time dissemination services, as reported to the BIPM by the laboratories. Data used for the calculation of TAI, *Circular T*, some tables of the *Annual Report* and other relevant results and information are available on the BIPM Time Department's ftp server.

6. References

1. BIPM *Circular T*: monthly. http://www.bipm.org/jsp/en/TimeFtp.jsp?TypePub=publication.
2. Allan D.W., Weiss A.M., *Proc. 34th Annual Frequency Control Symposium*, 1980, 334-346.
3. Defraigne P., Petit G., Time transfer to TAI using geodetic receivers, *Metrologia, 2003,* **40**, 2003, 184-188.
4. Petit G., Jiang Z., Stability and accuracy of GPS P3 TAI time links, *Proc. 18th EFTF*, CD-Rom (file 066.pdf), 2004.
5. Senior K., Koppang P., Ray J., Developing an IGS time scale, *IEEE Trans. UFFC,* 2003, **50**, 585-593.
6. Petit G., Jiang Z., GPS All in View time transfer for TAI computation, *Metrologia,* 2008, **45**, 35-45.
7. Petit G., Jiang Z., Precise point positioning for TAI computation, *IJNO Article* ID 562878, doi:10.1155/2008/562878, 2008.
8. Lewandowski W., Jiang Z., Use of GLONASS at the BIPM, 2010, *Proc. 41st Annual PTTI Meeting*, 2010, 5-14.
9. Hanson D.W., Fundamentals of two-way time transfers by satellite, *43rd Annual symposium on frequency control*, 1989, 174-178.
10. Kirchner D., Two-way Time Transfer Via Communication Satellites, *Proc. IEEE*, 1999, **19**(7), 983-990.
11. http://www.bipm.org/jsp/en/TimeCalibrations.jsp12.
12. Lewandowski W., Azoubib J., *Proc. 34nd PTTI*, 2003, 413-424.
13. Petit G., Atomic time scales TAI and TT(BIPM): present status and prospects, *Proc. 7th Symposium on Freqency standards and metrology*, Pacific Grove, 2008.
14. Petit G., A new realization of Terrestrial Time, *Proc. 35th PTTI*, 2003, 307-316.
15. W. Lewandowski, D. Matsakis, G. Panfilo, and P. Tavella, "The evaluation of uncertainties in [UTC−UTC(k)]," *Metrologia*, **43**, 2006, pp. 278–286.
16. Lewandowski W., Matsakis D., Panfilo G., Tavella P., Analysis of Correlations, and Link and Equipment Noise in the Uncertainties of [UTC − UTC(k)], *UFFC*, 2008, **4**, 750-760.
17. http://www.bipm.org/jsp/en/TimeFtp.jsp.
18. BIPM *Annual Report on Time Activities*, published annually by the BIPM, electronic version available at http://www.bipm.org/en/scientific/tai/time_server.html.