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Current and future realizations of coordinate time scales

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Abstract. Two atomic time scales maintained at the International Bureau of Weights and Measures (BIPM) are realizations of terrestrial time: International Atomic Time (TAI) and TT(BIPM). They are calculated from atomic clocks realizing proper time in national laboratories. The algorithm for the calculation of TAI has been designed to optimize the frequency stability and accuracy of the time scale. Plans for the future improvement of the reference time scales are presented.

Keywords. coordinate time scales, atomic time scales

1. Introduction

Time and frequency metrology provides time references for experiments confined to a small environment a well as applications in astronomy and Earth sciences in an extended environment, where time constitutes a coordinate in an arbitrarily chosen space-time coordinate system.

While a clock realizes proper time and provides a reference for observations in its vicinity, only a coordinate time scale can form the basis of a world-wide time reference. We adopt a rotating geocentric reference system where the time-coordinate is the geocentric coordinate time. Such a time scale is to be constructed from an ensemble of clocks, each realizing a proper time. An algorithm has to be designed to produce the world time reference from these individual clock proper times. The choice of the algorithm will depend on the interval over which the frequency stability is to be assured and a compromise between frequency stability and accuracy, and should be adapted to the characteristics of the standards involved and the techniques used to compare them. This algorithm should produce a time scale that is more stable and accurate than any of the individual participating clocks. To make the best use of the time and frequency standards operating in national laboratories today, time scale algorithms should apply in the framework of general relativity.

International Atomic Time (TAI) is a realization of terrestrial time maintained since 1988 at the International Bureau of Weights and Measures (BIPM). It uses data from about 350 atomic clocks and a dozen primary frequency standards operating in national metrology laboratories and scientific institutes world-wide. TAI is calculated from thirty-day data batches and is published with a latency of about 15 days after the last date of data. The frequency stability of TAI, over 30-40 days is better than 4 parts in 10^{16}, and its frequency accuracy is a few parts in 10^{16}. However, TAI has some long-term instabilities that make it unsuitable for applications such as pulsar timing. For this purpose, another atomic time scale is calculated at the BIPM under the acronym TT(BIPMYY) using an algorithm that eliminates the instabilities present in TAI.

TAI forms the basis for realizing a number of time scales used in dynamics, for modelling the motions of artificial and natural celestial bodies, and in the exploration of the solar system, tests of theories, geodesy, geophysics, studies of the environment. In all these applications, relativistic effects are important.

2. The SI unit of time

The atomic second is the SI unit of time, defined by the 13$^{\text{th}}$ General Conference on Weights and Measures (Terrien 1968) based on the hyperfine transition of caesium 133. The definition of the second should be understood as the definition of the unit of proper time; it applies in a small spatial domain which shares the motion of the caesium atom used to realize the definition. In a laboratory sufficiently small to allow the effects of the non-uniformity of the gravitational field to be neglected when compared to the uncertainties of the realization of the second (a few parts in 10^{16} for caesium fountains), the proper second is obtained after application of the special relativistic correction for the velocity of the atom in the laboratory.

3. General relativity and atomic time; definition of TAI

In 1980, the Consultative Committee for the Definition of the Second (CCDS, now Consultative Committee for Time and Frequency, CCTF) declared that TAI is a coordinate time defined in a geocentric reference frame, and that its scale unit is the SI second as realized on the rotating geoid. The IAU endorsed this definition only when a global treatment of space-time reference systems was recommended in the framework of general relativity. After much controversy this finally happened in 1991 with the adoption of a specified metric (IAU 1991). In 2000 the IAU adopted a metric extended to higher order terms (IAU 2000). In these developments, several theoretical coordinate times were defined, for use in the vicinity of the Earth and for the dynamics of the solar system. All these coordinate times are realized on the basis of TAI after relativistic transformations. TAI itself appears as a realization of an ideal Terrestrial Time TT. Terrestrial Time is obtained from a Geocentric Coordinate Time TCG by a linear transformation chosen so that the mean rate of TT is close to the mean rate of the proper time of an observer located on the rotating geoid.

As seen above, TAI is the reference time scale, defined in the context of general relativity. Since 1988 it has been calculated at the BIPM as the result of international cooperation. An algorithm developed at the Bureau International de l'Heure (BIH) in the 1970s, denoted ALGOS (BIH 1974), (Guinot & Thomas 1988), (Audoin & Guinot 2001) has fixed the principles of the construction of TAI. After numerous tests and various improvements, it remains the basis of the present calculation at the BIPM.

Coordinated Universal Time (UTC) is derived from TAI by the application of leap seconds. The dates of the insertion of leap seconds in UTC are decided and announced by the International Earth Rotation and Reference Systems Service (IERS). At then time of writing and at least until 31 December 2009, the difference between TAI and UTC amounts to 34 s.

Whereas TAI is the uniform time scale that provides a precise reference for scientific applications, UTC is the time scale of practical use that serves for international coordination in time keeping and is the basis of many legal national times.

4. Metrological quality of a reference time scale: the case of TAI

A time scale to be used as a reference should be continuous. It is characterized by its reliability, frequency stability and accuracy, and accessibility. The algorithm ALGOS produces a continuous non-stepped time scale. TAI and UTC have the same metrological quality, with the exception that UTC is intentionally stepped by the application of leap seconds to compensate for the irregular rate of rotation of the Earth.

The *reliability* of a time scale is closely linked to the reliability of the clocks involved in its construction. Reliability is also associated with redundancy; in the case of TAI, a large number of clocks are required; this number is today about 350, most of them high-performance caesium atomic standards and active auto-tuned hydrogen masers.

The *frequency stability* of a time scale is its capacity to maintain a fixed ratio between its unitary scale interval and its theoretical counterpart. One measure of the frequency stability of a time scale is its Allan variance (Allan *et al.* 1988), which is the two-sample variance designed for the statistical analysis of time series, and depends on the sampling interval.

The *frequency accuracy* of a time scale is 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 requested frequency stability, frequency accuracy can be improved by comparing the frequency of the time scale with that of primary frequency standards, and by applying, if necessary, frequency corrections.

The *accessibility* of a world-wide time scale is its aptitude to provide a means of dating events for everyone. This depends on the precision which is required. In the case of TAI the ultimate precision requires a delay of a few tens of days in order to reach the long-term frequency stability required for a reference time scale. In addition, the process needs to be designed in such a way that the measurement noise is eliminated or at least minimized, which requires a minimum number of data sampling intervals.

The frequency instability of TAI, estimated today as 4 parts in 10^{16} for averaging times of 30 to 40 days (Petit 2008), is obtained by processing clock and clock comparison data at 5-day intervals over a monthly analysis, with a delay to publication of about 10 days after the last date of reported data. In the very long term, over a decade, the stability is maintained by primary frequency standards and is limited by the accuracy at the level of parts in 10^{15} assuming that the present performances are constant.

5. The algorithm for TAI and UTC

The time laboratories realize a stable local time scale using individual atomic clocks 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 calculation of UTC is carried out in three successive steps:

a) The free atomic time scale EAL (Echelle Atomique Libre) is computed as a weighted average of free-running atomic clocks spread world-wide. A clock weighting procedure has been designed to optimize the long-term frequency stability of the scale. No constraint is imposed to match the interval unit of EAL to the SI second.

b) The frequency of EAL is steered to maintain agreement with the definition of the SI second, and the resulting time scale is International Atomic Time TAI. The steering correction is determined by comparing the EAL frequency with that of primary frequency standards.

c) Leap seconds are inserted to maintain agreement with the time derived from the rotation of the Earth. The resulting time scale is UTC.

Different algorithms can be considered depending on the requirements of the scale; for an international reference such as UTC, the requirement is extreme reliability and long-term 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 between remote sites.

The algorithm ALGOS for defining EAL is structured in three parts, each one associated with an algorithm: the *weighting algorithm* optimized to guarantee the long-term stability of the time scale (Azoubib 2001); the *prediction algorithm* used to avoid time and frequency jumps due to different clock ensembles being used in consecutive calculation periods (Thomas *et al.* 1994), and the *steering algorithm* used to improve the time scale accuracy (Arias & Petit 2005).

In time-scale algorithms, clock weights are generally chosen as the reciprocals of a statistical quantity which characterizes their frequency stability, such as a frequency variance (classical variance, Allan variance, etc.). If strictly applied, this gives a time scale which is more stable than any contributing element. 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, estimated over the current 30-day interval and over the past eleven consecutive 30-day intervals. The weight determination thus uses clock measurements covering a full year. This reduces the weight of both clocks that are highly sensitive to seasonal changes and hydrogen masers that show a large frequency drift. It thus helps to improve the long-term stability of EAL.

The weight of a clock is considered as constant during the 30-day period of computation and continuity with the previous period is assured by clock frequency prediction, a procedure that renders the scale insensitive to changes in the set of participating clocks. The algorithm is able to detect abnormal behaviour of clocks, and to disregard them if necessary; this is done in an iterative process that starts by the weights obtained in the previous month, and serves as an indicator of the behaviour of the clock in the month of computation.

To limit individual clock contributions, preventing domination of the scale by a small number of very stable clocks, a maximum value for the weight is chosen for each month of calculation, expressed as a fraction between 0 and 1. In ALGOS the maximum weight is chosen as a function of the total number of clocks in a period of calculation.

In the generation of a time scale, the prediction of the atomic clock behavior plays an important role; in fact the prediction is useful to avoid or minimize frequency jumps of the time scale when a clock is added or removed from the ensemble or when its weight changes. Considering two successive one-month intervals of TAI calculation we impose several constraints on the prediction term at the boundary date to avoid or minimize time and frequency jumps in the resulting time scale. In the case of commercial caesium clocks, for averaging times around 30 days the predominant noise is random walk frequency modulation. All clocks in TAI are treated with this same linear frequency prediction model, but a revision appears to be necessary to take into account the increasing number of participating hydrogen masers, for which the predominant frequency noise is a linear drift. Hydrogen masers represent today about 12% of the total weight of clocks in TAI.

TAI accuracy is assured from measurements of a small number of primary frequency standards (PFS) developed by a few metrology laboratories. The frequency of EAL is compared with that of the primary frequency standards using all available data over a one-year interval, 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

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steering correction are expected to ensure accuracy without degrading the long-term (several months) stability of TAI. The value of this correction varies, with a maximum fixed at 6×10^{-16} in a month of calculation. 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 the duration of the scale unit of TAI (Azoubib *et al.* 1977), (Arias & Petit 2005). As at June 2009, twelve primary frequency standards, including nine caesim fountains, provide the best representation of the SI second with uncertainties of a few parts in 10^{16}, and contribute to improving the accuracy of TAI.

6. TT(BIPM)

An algorithm similar to that used to evaluate the frequency of EAL is used in post-processing to calculate another time scale strictly identified by the acronym TT(BIPMYY), where yy indicates the last two digits of the year of computation. TT(BIPM) is also a realization of the ideal Terrestrial Time TT (Petit 2003), (Petit 2008). TT(BIPM) is calculated every year and its frequency is steered using all available measurements of primary frequency standards reported to the BIPM by national laboratories. TT(BIPM) is a time scale optimized for frequency accuracy. The accuracy of TT(BIPM) for 2008 is estimated to be 5×10^{-16}.

TT(BIPM) provides a stable and accurate reference for characterizing the performance of the frequency of EAL and the frequency drift of the H-masers and caesium clocks. The frequency of EAL, when compared to that of TT(BIPM), presents a drift of 4×10^{-16} whose origin is under study.

7. Clocks in TAI

As at June 2009, 68 time laboratories from about 50 countries participate in the calculation of TAI at the BIPM. They contribute data each month from about 350 clocks. About 83% of clocks are either commercial caesium clocks of the Symmetricom/HP/Agilent 5071A-type or active, auto-tuned hydrogen masers. Commercial caesium clocks with high-performance tubes realize the atomic second with a relative accuracy in frequency of 1×10^{-13}, and they have an excellent long-term frequency stability. Active hydrogen masers also benefit from high-frequency stabilities of the order of 10^{-15} over 1 day.

8. Further improvement and perspectives

The present frequency stability of TAI is estimated to be 0.4×10^{-15} over one month. This is obtained through the procedures for clock weighting and frequency prediction described in the previous sections. An improvement in the stability would be possible if an increased number of more stable clocks participated in the formation of TAI. Such progress do not rely on the BIPM. However, improving the algorithm is the responsibility of the BIPM.

The effect of the linear prediction algorithm of the clock frequency has been studied at the BIPM for different types of clocks in TAI (Panfilo & Arias 2009). ALGOS predicts the clock frequency with a linear model that is well adapted to the caesium clocks, but not to the hydrogen maser clocks which represent 12% of the total weight in EAL. A test version of EAL without hydrogen masers has been calculated to evaluate the effects of the equal modelling of the clock frequencies. A new mathematical expression for the prediction of the hydrogen maser frequency is proposed taking into account the drift. Tests over a 3-year period have been performed applying the linear prediction to the caesium clocks and a quadratic prediction to the hydrogen masers. A version of EAL on the basis of the proposed frequency prediction for hydrogen masers, but with the classical clock weighting, has been evaluated. When all clocks are predicted with the linear model, a drift of about 4 parts in 10^{16} is observed between EAL and TT(BIPM). The results seem to indicate that inappropriate modelling of the frequency drift of hydrogen masers could be responsible for 20% of this drift. In this test one month of past data has been used to evaluate frequency drift between EAL and TT(BIPM); a longer period will also be tested. EAL still shows a significant drift after having introduced a quadratic model for the hydrogen maser clocks; further work needs to be done, and in particular a revision of the clock weighting algorithm.

Since 1971 the definition of the second has been based on the transition between two hyperfine levels of the ground state of the 133-caesium atom. Primary frequency standards (in particular caesium fountains) realize the definition of the second with an uncertainty of one part in 10^{15} (BIPM 2009) . In some laboratories a new generation of fountains is under study with the goal of reducing the uncertainty to parts in 10^{16}.

New devices make use of the properties of other radiations. In the microwave region, rubidium has been used for the construction of a double Cs-Rb fountain (Guéna *et al.* 2008). Frequency standards based on optical radiations (ytterbium, mercury, strontium) have been constructed in several metrology institutes (Dubé *et al.* 2006), (Fouche *et al.* 2007), (Tamm *et al.* 2007) (the list of references is not exhaustive). The accuracy of these realizations is expected to exceed that of caesium fountains, and some have already been recommended by the International Committee for Weights and Measures (CIPM) for use as secondary representations of the second (Gill & Riehle 2006).

The current techniques and methods of time transfer are not yet able to perform frequency transfer at the level of the optical standards accuracy, limiting the possibility of their remote comparison. Work is under way within the time metrology community aimed at overcoming this difficulty. The CCTF has established in 2006 a working group for coordinating activities on highly accurate time and frequency transfer.

9. Conclusion

Two realizations of Terrestrial Time TT are maintained at the BIPM; TAI is the continuous, atomic time scale which serves as the basis for constructing UTC. The instability of TAI over 30 to 40 day intervals is of 4 parts in 10^{16}; however, long-term instabilities of 1 to 2 parts in 10^{15} mean that TAI cannot be used as a reference for applications requiring long-term stability. TT(BIPM) is computed yearly based on all available measurements of primary frequency standards; its long-term instability is better that that of TAI in a factor at between two and three (Petit 2003), and its accuracy is of 5 parts in 10^{16}.

The algorithm used for the clock frequency prediction is under revision. The frequency of caesium clocks is well predicted by a linear model, but this is not the case for hydrogen masers where a quadratic model seems to better represent their drift. Preliminary studies indicate that the drift observed in the last years between EAL and TT(BIPM) could be partially explained by the effects of the inappropriate modelling of the hydrogen masers.

The 133-caesium atom provides the definition of the SI second as well as its unique realization. Progress in fundamental physics applied to the development of new standards for metrology has led the CIPM to recommend a list of radiations for providing secondary representations of the second. However, studies on highly accurate frequency transfer are still necessary to allow the comparison of these standards at the best of their performances. In view of this evolution, the metrological community has started discussions on a possible new definition and realization of the second which could arrive in the next decade.

The SI unit of length, the meter, is realized through a list of radiations approved for practical realization of the meter. With the establishment of a list of appropriate radiations for realizing the second, we could imagine that access to the SI second could be achieved in the future similar to the meter, with different levels of uncertainty, through the various entries in this list.

References

Allan D. W., Hellwig, H., Kartaschoff, P., Vanier, J., Vig, J., Winkler, G. M. R., & Yannoni, N. F. 1988, *Proc. of the* 42nd *Annual IFCS*, 419

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

Audoin, C & Guinot, B. 2001, *The measurement of time*, Cambridge University Press

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

Azoubib, J. 2001, *Proc.* 32nd *PTTI*, 195

Bureau International de l'Heure 1974, *BIH Annual Report for 1973*, Observatoire de Paris

Bureau International des Poids et Mesures 2009, *BIPM Annual Report on Time Activities for 2008*, 26

Dubé, P., Madej, A. A., Bernard, J. E., & Shiner, A. D. 2006, *Proc. of the 2006 IEEE IFCS*, 409

Fouche M., Le Targat, R., Baillard, X., Brusch, A., Tcherbakoff, F., Rovera, G. D., & Lemonde, P. 2007, *IEEE Trans. Instr. Meas*, 56, 236

Gill, P. & Rihele, F. 2006, *Proc.* 20th *EFTF*, 282

Guna, J., Chapelet, F., Rosenbusch, P., Laurent, P., Abgrall, M., Rovera, G. D., Santarelli, G., Tobar, M., E., Bize, S., & Clairon, A. 2008, *Proc. of the* 22nd *EFTF*, CD-ROM

Guinot, B. & Thomas, C. 1988, *Annual Report of the BIPM Time Section*, 1, D1-D22

International Astronomical Union 1991, *Proceedings of the* 21st *General Assembly*, Resolution A4, Kluwer, Dordrecht, The Nederlands

International Astronomical Union 2000, *Proceedings of the* 24th *General Assembly*, Resolutions B1.3 and B1.9, Astronomical Society of the Pacific, Provo, USA.

Panfilo, G. & Arias, E. F. 2009, *Special issue of UFFC*, submitted

Petit, G. 2003, *Proc.* 35th *PTTI*, 307

Petit, G. 2008, *Proc.* 7th *Symposium on Freqency standards and metrology*, in press

Tamm, Ch., Lipphardt, B., Schnatz, H., Wynands, R., Weyers, S., Schneider, T., & Peik, E. 2007, *IEEE Trans. Instrum. Meas.*, 56, 601

Terrien, J. 1968, *Metrologia*, 4, 43

Thomas, C, Wolf, P., & Tavella, P. 1994, *IEEE Trans. Instrum. Meas.*, 56, 601

Thomas, C. & Azoubib, J. 1996, *Metrologia*, 33, 227