IMPROVEMENTS IN INTERNATIONAL TIMEKEEPING

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ABSTRACT. International Atomic Time and Coordinated Universal Time are calculated at the Bureau International des Poids et Mesures on the basis of international cooperation for time keeping. The process of calculation has been progressively adapted to the technology improvement in clocks and time transfer techniques, as well as to the increasing accuracy of primary frequency standards. Improvements in the last ten years are presented in this article.

1. INTRODUCTION

In 1875, seventeen countries signed in France the Metre Convention, arranged to meet every four years at the Conférence Générale des Poids et Mesures (CGPM), and created the Bureau International des Poids et Mesures (BIPM), located at Sèvres. At that epoch, the BIPM was the guardian of the two prototypes: the metre, defining the unit of length; and the kilogramme, defining the unit of mass. Short time afterwards the unit of time was added to the list of base units, but its realization and maintenance remained a task conferred to astronomers.

The original system of units grew up, and became in 1960 the International System of Units (SI), which comports seven base units. The definitions of some units evolved to render the system more accurate; in the last years efforts have been settled in different metrology institutes and in the BIPM to approach them to the fundamental constants of physics.

The definition of the unit of time has been since the beginning a responsibility of the CGPM, but this was not the case of its maintenance until the end of 1980s. The 13^{th} CGPM (1968) decided to adopt a new definition of the SI unit of time based on a transition of the caesium 133 atom; the 14^{th} CGPM (1972) introduced the use of International Atomic Time (TAI). Coordinated Universal Time (UTC) was defined for practical reasons (McCarthy, this volume); its real time representation is provided by time laboratories.

In 1988, the responsibility for maintaining the reference time scales TAI and UTC was conferred to the BIPM, with the obvious implication of insuring the consistency between the scale unit of TAI and the second of the SI. This activity is known as international time keeping, and requires coordinated activities in metrology institutes and observatories maintaining atomic clocks and primary frequency standards. For that, the BIPM organizes a network of time links on the basis of the voluntary participation of laboratories in member states and associates to the Metre Convention. Time laboratories contribute their data to be used in the construction of the reference time scales, and as a feed back their independent local time scales are traced to the international reference UTC.

The access to UTC, as well as other relevant information concerning UTC and TAI are provided monthly via the publication of BIPM *Circular T*.

The activities of the Time section of the BIPM are focused on the maintenance of TAI and UTC, task that requires not only of the routine work of data collection and calculation, but that moreover implies research activities on algorithms, clock behaviour and techniques of comparisons of distant clocks.

2. THE REQUESTED PROPERTIES OF A TIME SCALE

A time scale is characterized by its *reliability*, *frequency stability* and *accuracy*, and *accessibility*. The algorithm used for the elaboration of a time scale will depend on what is requested for these characteristics.

The *reliability* of a time scale is closely linked with the reliability of the clocks whose measurements are used for its construction; at the same time, *redundancy* is also requested.

The *frequency stability* of a time scale is its capacity of maintaining a fixed ratio between its unitary scale interval and its theoretical counterpart.

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 is improved by comparing the frequency of the time scale with that of primary frequency standards, and by applying, if necessary, frequency corrections.

The *accessibility* to a worldwide time scale is its aptitude to allow all users with a means of dating events. It depends on the precision which is required. In the case of a reference time scale, where long term frequency stability is required, to attain to the ultimate precision requires a delay of a few tens of days. Furthermore, the process needs to be designed in such a way that the measurement noise is eliminated or at least minimized, this requiring a minimum of data sampling intervals.

3. INTERNATIONAL ATOMIC TIME (TAI): ITS CHARACTERISTICS

Many factors have contributed in the last ten years to the improvement of TAI. The progress in clocks and techniques for clock comparison has been accompanied at the BIPM by updates of the calculation algorithm to render it more adapted to the improvements in technology.

The increasing number of clocks, most of them with higher frequency stability and accuracy, have made TAI more reliable. The algorithm of calculation treats data over a 30-day period, during which a clock is considered to have a constant weight. The continuity with the previous period of computation is given by a prediction of the frequency of clocks, in an attempt of rendering the scale insensitive to changes in the set of participating clocks.

The calculation of TAI is based on clock differences, so requiring the use of methods of comparison of distant clocks. A prime requisite is that the methods of time transfer used for clock comparison do not degrade the frequency stability of the clocks. In fact, time transfer has been in the past a major limitation to the construction of a reference time scale. TAI relies today on a network of time links where many baselines are technique-redundant. The progress in GPS work, and the introduction of time comparisons through geostationary telecommunications satellites allows today to compare the best atomic standards over integration times of few days with nanosecond (statistical) uncertainty.

The frequency accuracy of TAI is improved by the frequency measurements of primary frequency standards developed in a few time laboratories reporting data to the BIPM. Caesium fountains provide the best representations of the SI second, with frequency accuracy of order 10^{-15} - 10^{-16}. In order to keep the unitary scale interval of TAI as close as possible to its definition, a process called frequency steering has been implemented.

The instability of TAI, is estimated today as $0.5\text{x}10^{-15}$ for averaging times of 20-40 days

(Petit, 2005). 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 10^{-15} assuming that the present performances are constant. The frequency accuracy of TAI is estimated today as better than $3\text{x}10^{-15}$.

4. THE SCHEME OF CALCULATION

The algorithm known as Algos (BIH, 1974; Guinot and Thomas, 1988; Audoin and Guinot, 2001), developed at the Bureau International de l'Heure (BIH) in 1973 has fixed the principles that are still at the basis of the construction of TAI. The quantities which intervene in the calculation are time and frequency differences at specified dates, denominated "standard dates". These dates are modified julian dates (MJD) ending by 4 and 9. Each participating laboratory k maintains a local realization of UTC denominated UTC(k); it serves as the reference for local frequency and clock differences. Clock comparison data are reported in the form of time series of $[UTC\ (k)\ \text{-}\ S\ ]$, where S is a time marker or emitter received by two or more laboratories. Comparisons of time between two laboratories (j, k) are expressed by the series of differences between their respective local realisations of UTC at the standard dates, $[UTC(j)\ \text{-}\ UTC(k)]$.

Making use of the clock and time transfer data, the algorithm calculates an averaged time scale called *Free Atomic Scale* (Echelle Atomique Libre EAL). EAL has an optimized frequency stability for a selected averaging time (20-40 days), but is not constrained to be accurate in frequency.

Frequency measurements of primary frequency standards allow to evaluate the relative deviation between the scale interval of TAI and the SI second. Depending on its value, a correction is applied to the frequency of EAL, process known as "the steering of TAI". By doing this, we obtain TAI, that benefits of the optimized frequency stability of EAL and that is accurate in frequency as a consequence of the steering procedure.

The last step consists in producing UTC by adding to TAI an integer number of seconds. The output of the process are the differences $[UTC\ \text{-}\ UTC(k)]$ published in monthly BIPM *Circular T*, providing access to UTC through its local approximations UTC(k).

5. IMPROVEMENTS IN THE REALIZATION OF THE INTERNATIONAL TIME SCALES

The improvement of TAI/UTC is a continuous process that depends on the contributing laboratories in which concern:
a) the number and quality of the participating clocks,
b) the introduction of more performing techniques of time comparison,
c) the progress in the primary frequency standards,
and on the actions of the BIPM Time section, in dialogue with the time and frequency community in issues related to:
d) international coordination for time keeping,
e) improvement of the algorithm for the calculation of TAI,
  e_1) clock weighting and clock frequency prediction,
  e_2) calculation of time links,
  e_3) TAI frequency steering.

5.1. Clocks in TAI

The number of laboratories contributing to TAI increased from 46 in 1995 to 56 in 2005. They are mostly located in national metrology institutes, but some of them are in observatories that continued with time keeping activities after the transition from astronomical to atomic time.

The number of participating clocks every month oscillates about 300, representing an increase of about 20% in ten years. 84% of clocks are commercial, high-performance caesium standards, characterized by a frequency stability of about $1\text{x}10^{-14}$ over 5 days; these clocks realize the atomic second with a relative frequency accuracy of $5\text{x}10^{-12}$, almost one order of magnitude better than the standard model mostly used in laboratories a few years before. Active, auto-tuned hydrogen masers have slightly increased in number in the mid 1990s, oscillating between 17 - 20% of the total number of participating since then. They present high frequency stability (better than 1 part in 10^{15}) over one day, but they do not realize the atomic second. Fig. 1 shows the evolution in the type of clocks that have contributed to the construction of TAI since 1995.

To improve the stability of EAL, a weighting procedure is applied to the clocks. The weight of a clock is considered constant during the 30-day period, and continuity with the previous period is assured by a prediction of the clock's frequency. These procedure renders the scale insensitive to changes in the set of participating clocks.

To avoid the possibility that very stable clocks increase their weights to the point of dominating the scale, a maximum relative weight ω_{max} is fixed. The choice of the value for ω_{max} has evolved accordingly with the evolution of clocks in TAI. Fig. 2 shows an histogram with the percentage (averaged for a year) of clocks of different types having reached the maximum relative weight since 1995.

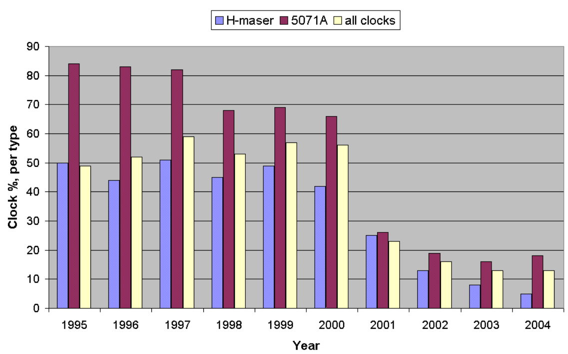

Figure 1: Clocks having contributed to TAI since 1995.

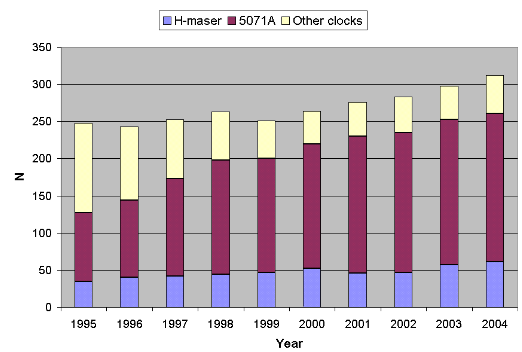

Figure 2: Evolution of the maximum weight of clocks in TAI.

5.2. Clock comparison in TAI

The calculation of TAI and UTC is based on clock comparison data. Since clocks are located in different laboratories, it is required to use methods of comparison of distant clocks. The methods of time transfer should not contaminate the frequency stability of the clocks; this has been in the past the major limitation in the construction of a reference time scale. At the state of art in commercial clock technology, this is not a constraint today. The uncertainty of clock comparison is today between a few tens of nanoseconds and a nanosecond for the best links, a priori sufficient to compare the best atomic standards over integration times of a few days. This assertion is strictly valid for frequency comparisons, where only statistical uncertainty affects the process. In the case of time comparisons, the systematic uncertainty coming from the equipment calibration should be considered in addition. In the present situation, calibration contributes with an uncertainty that surpasses the statistical component, and that can reach 20 ns for non calibrated equipment. It can be inferred that repeated equipment calibrations are indispensable for clock comparison.

The use of GPS satellites in time comparisons introduced a major improvement in the 1980s in the construction and dissemination of time scales. It consists in 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 Russian satellite system of global navigation GLONASS is not used for time comparison in TAI on a routine basis, since the satellite constellation is not yet complete and stable, and the time laboratories are at present completing their equipments for GLONASS reception. Nevertheless, studies conducted at the BIPM and in other laboratories prove (Bogdanov et al., 2002; Lewandowski et al., 2005) that the system is potentially useful for accurate time transfer.

Modern GPS and GPS/GLONASS receivers installed in national time laboratories that contribute to the calculation of TAI provide in an automated way time transfer data.

Thanks to new hardware and to improvements in data treatment and modelling, the uncertainty of clock synchronization via GPS fell from a few hundreds of nanoseconds at the beginning of the 1980s to 1 ns today. Old single-channel, single-frequency C/A Ũ code receivers are being replaced in time laboratories by multi-channel receivers, which allow the simultaneous observation of all satellites over the horizon. The effects of ionospheric delay introduce one of the most significant errors in GPS time comparison and in particular, in the case of clocks compared over long baselines. GPS observations with single-frequency receivers used in regular TAI calculations are corrected for ionospheric delays by making use of ionospheric maps produced by the International GPS Service (IGS) (Wolf and Petit, 1999). Dual-frequency receivers installed in some of the participating laboratories permit the removal of the delay introduced by the ionosphere, thus increasing the accuracy of time transfer. All GPS links are corrected for satellite positions using IGS post-processed precise satellite ephemerides.

Precise-code data from GPS geodetic-type, multi-channel, dual-frequency receivers has been introduced since June 2004 in the calculation of TAI (Defraigne and Petit, 2003). These links, denominated by GPS P3 links, provide ionosphere-free data and allow clock comparisons with nanosecond uncertainty or better.

After about 25 years of experimentation, the method of two-way satellite time and frequency transfer (TWSTFT) is currently used in TAI since 1999 (Lewandowski and Azoubib, 2000). The TWSTFT technique utilizes a telecommunication 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. The clocks are directly compared, using the transponder of the satellite. It has the advantage of a two-way method over the one-way method of eliminating or reducing some sources of systematic error such as ionospheric and tropospheric delays, uncertainty on the positions of the satellite and the ground stations. The differences between two clocks placed in the two stations are directly computed. Until the mid-2004, intervals of 5-minute measurements were made three days per week, impeding the technique to reach its highest potential performance, which is sub-nanosecond uncertainty. With the installation of automated stations in most laboratories, some of the TWSTFT link observations in TAI are at daily or even sub-daily intervals, with the consequence of setting the uncertainty below the nanosecond.

For two decades, GPS C/A-code observations have provided a unique tool for clock comparison in TAI, rendering impossible any test of its performance with respect to other methods. The present situation is quite different. For the links where the two techniques are available, both GPS and TWSTFT links are computed; the best being used in the calculation of TAI, the other kept as a backup. The GPS P3 links have further increased the reliability of the system of time links, providing a method of assessing the performance of the TWSTFT technique. Comparison of results obtained on the same baselines with the different techniques (Arias et al., 2005) shows equivalent performances for GPS geodetic-type dual-frequency receivers and TWSTFT equipment, when two-way sessions have a daily regularity (1 ns or less).

At the moment, 80% of the links in TAI are obtained by using GPS equipment (65% with GPS time-receivers; 15% with GPS geodetic-type receivers) and about 14% of the links are provided by TWSTFT observations.

Calibration of the laboratory's equipment for time transfer is fundamental for the stability of TAI and for its dissemination. Campaigns of GPS time equipment differential calibration are organised by the BIPM to compensate for internal delays in laboratories by comparing their equipment with travelling GPS equipment.

A network of international time links has been established by the BIPM to organise these comparisons (see Fig. 3). It is a star-like scheme with links from laboratories to a pivot laboratory in each continent, and long baselines providing the links between the pivot points.

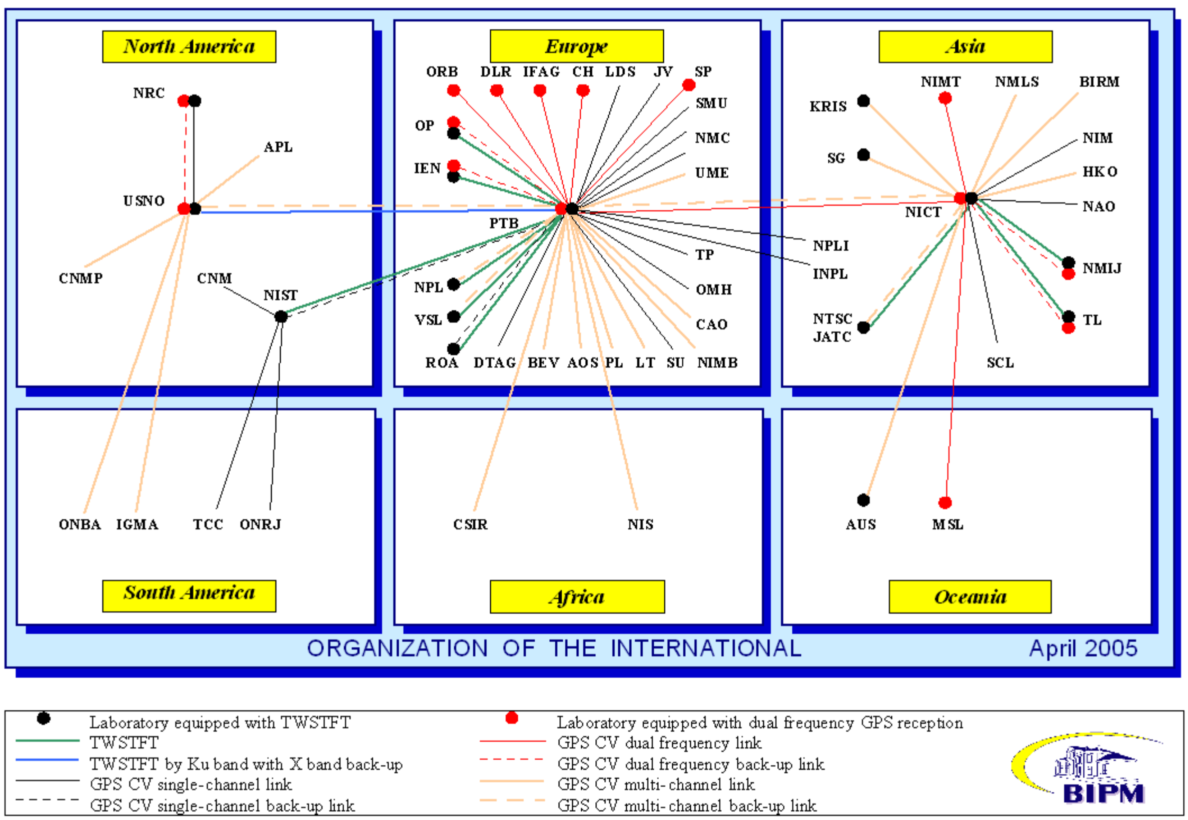

Figure 3: Network of international time links for TAI as in April 2005.

5.3. Improvement of the frequency accuracy of TAI

The frequency accuracy of TAI is assured by the primary frequency standards developed in some laboratories reporting their frequency measurements to the BIPM. A report of a PFS includes the measurement of the frequency of the standard relative to that of a clock participating in TAI, and a complete characterization of its uncertainty as published in a peer-reviewed journal. Five caesium fountains and two optically pumped caesium beam standards have contributed, more or less regularly, in the last two years to TAI with measurements over 10 to 30-day intervals. Two magnetically deflected caesium beam standards of the PTB (CS1 and CS2) are operated in a continuous manner and contribute permanently to both the accuracy of TAI and the stability of

EAL. In 2005, the definition of the second of the SI is realised, at best, by the primary frequency standards with an accuracy of order 10^{-15}.

Based on the frequency measurements of the PFS reported to the BIPM during a 12-month period, the fractional deviation d of the unitary scale interval of TAI from its theoretical value (the unitary scale interval of TT) is evaluated, together with its uncertainty.

In order to keep the unitary scale interval of TAI as close as possible to its definition, a process called *frequency steering* has been implemented. It consists in applying a correction to the frequency of EAL when d exceeds a tolerance value, generally fixed to 2.5 times its uncertainty. These frequency corrections should be smaller than the frequency fluctuations of the time scale in order to preserve its long term stability. Over the period 1998-2004, frequency steering corrections of $+/-$ $1\text{x}10^{-15}$ have been applied, when necessary, for intervals of two months at least. The values of d demonstrated that the unitary scale interval of TAI had significantly deviated from its definition and that the steering procedure was in need of revision. A different strategy for the frequency steering was adopted in July 2004. A frequency correction of variable magnitude, up to $0.7\text{x}10^{-15}$ is applied for intervals of one month at least, if the value of d reach 2.5 times its uncertainty.

5.4. Dissemination of TAI/UTC

The time scales TAI and UTC are disseminated every month by *Circular T* (BIPMa). Access to UTC is provided in the form of differences $[UTC - UTC(k)]$ making at the same time the local approximations UTC(k) traceable to UTC; starting in January 2005, their uncertainties are also published (Lewandowski et al., 2005).

The values of the frequency corrections on TAI and their intervals of validity are regularly reported. This information is needed for the laboratories to steer the frequency of their UTC(k) to UTC.

Circular T provides wide access to the best realisation of the second through the estimation of the fractional deviation d of the scale interval of TAI with respect to its theoretical value based on the SI second. The values of d for the individual contributions of PFS are also published, giving access to the second as realised by each of the primary standards.

Within *Circular T*, the time links used for the calculation of one month, with their respective uncertainties are detailed, accompanied by information about the technique used in the calibration of the time transfer equipment or link.

The ftp server of the BIPM time section gives access to clock data, time transfer files provided by the participating laboratories, results of link comparisons, 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 their clocks behaviour (www.bipm.org).

Results for a complete year are published in the *Annual Report of the BIPM Time Section* (BIPMb), together with information about the laboratories' equipment, time signals and time dissemination services, as reported by the laboratories to the BIPM.

Data used for the calculation of TAI, *Circular T*, some tables of the *Annual Report* and all relevant results and information are available on the ftp server of the BIPM Time section.

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