ROLE OF THE BIPM IN UTC DISSEMINATION TO THE REAL TIME USER

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Abstract

The generation and dissemination of International Atomic Time, TAI, and Coordinated Universal Time, UTC, are explicitly mentioned in the list of the principal tasks of the BIPM, that appears in the Comptes Rendus of the 18e Conférence Générale des Poids et Mesures, in 1987. These time scales are used as the ultimate reference in the most demanding scientific applications and must, therefore, be of the best metrological quality in terms of reliability, long-term stability, and conformity of the scale interval with the second, the unit of time of the International System of Units. To meet these requirements, it is necessary that the readings of the atomic clocks, spread all over the world, that are used as basic timing data for TAI and UTC generation, must be combined in the most efficient way possible. In particular, to take full advantage of the quality of each contributing clock calls for observation of its performance over a sufficiently long time. At present, the computation period treats data in blocks covering two months. TAI and UTC are thus deferred-time time scales that cannot be immediately available to real-time users.

The BIPM can, nevertheless, be of help to real-time users. The predictability of UTC is a fundamental attribute of the scale for institutions responsible for the dissemination of real-time time scales. It allows them to improve their local representations of UTC and, thus, implement a more thorough steering of the time scales diffused in real time. With a view to improving the predictability of UTC, the BIPM examines in detail timing techniques and basic theories in order to propose alternative solutions for timing algorithms. This, coupled with a recent improvement of timing data, makes UTC more stable and, thus, more predictable. At a more practical level, effort is being devoted to putting in place automatic procedures for reducing the time needed for data collection and treatment: monthly results are already available ten days earlier than before.

1 INTRODUCTION

The Comité International des Poids et Mesures, CIPM, reviewed the role of the Bureau International des Poids et Mesures, BIPM, in the 1980s. Its conclusions were made known in the Convocation to the 18e Conférence Générale des Poids et Mesures[1]; insofar as it concerns the time activities, they were as follows: "The purpose of the BIPM is to provide the physical basis necessary to ensure worldwide uniformity of measurements. Therefore, its principal tasks are [among others]: ...to establish and disseminate the International Atomic Time, and in collaboration with the appropriate astronomical organizations, Coordinated Universal Time;..."

The definition of TAI was approved by the CIPM in 1970, and recognized by the CGPM, in 1971[2]. It reads as follows: "International Atomic Time (TAI) is the time reference coordinate established by the Bureau International de l'Heure on the basis of the readings of atomic clocks operating in various establishments in accordance with the definition of the second, the unit of time of the International System of units." An addition was made to this definition in 1980[3] in order to place TAI in the context of General Relativity. In 1988 responsibility for TAI was transferred to the Time Section of the BIPM, fulfilling one of the explicit missions given above.

To be used as the ultimate time reference in the most demanding scientific applications, TAI must be of the best metrological quality, in particular in respect of long-term stability. This calls for observation of the performance of each contributing clock over a sufficiently long period of time. At present, the computation takes two-month blocks of data, so TAI, and consequently UTC, are deferred-time time scales that present an *intrinsic* delay of access to the real-time users of two months. In addition, the definition given above also implies that TAI and UTC are the results of a collective effort: national laboratories provide timing data to the BIPM, which in turn produces TAI and distributes it as time corrections to national time scales. An additional *material* delay of access is thus linked to the time needed for data exchange and analysis. For example, the definitive UTC updates for the months of September and October 1995 were made available to users on the 17th of November 1995.

Real-time users have access to local representations of UTC, UTC(k), maintained by national laboratories, and to derived time scales, such as GPS time and GLONASS time, diffused by global satellite systems. These real-time time scales are often linked to the output of a physical clock. Their close agreement to UTC then supposes both an excellent stability performance of the physical clock on site, and also an excellent predictability of UTC over an averaging time of from 1 to 2 months.

In December 1993, the recent commercial availability of HP 5071A cesium clocks and of active auto-tuned hydrogen masers, both presenting a remarkable frequency stability, led the BIPM to propose, in collaboration with D. Allan, of Allan's TIME, the realization of a real-time prediction of UTC, UTCp[4]. As shown in Figure 1, it was suggested that the proposed UTCp be directly linked to the output of a physical clock, kept for instance at the BIPM, steered on a software clock, UTCs. UTCs is obtained with a delay of a few days from data of a small number of very good clocks kept in only some laboratories. At the time, this proposal gave rise to much discussion inside the time community and in the face of the many arguments advanced against, the project was abandoned. The subject was again evoked during the meeting of the CCDS Working Group on TAI, which was held in March 1995[5]. It then appeared that the UTCp as previously proposed is only another local representation of UTC, with the same quality as most of the UTC(k) kept by national centers having at their disposal the data from a sufficient number of clocks. Rather than providing UTCs and UTCp, it was then concluded that the role of the BIPM was, in the first instance, to improve the predictability of UTC so as to facilitate the steering of real-time time scales to UTC. The progress that has been made in this is discussed in Section 2. In Section 3, we examine the possible reduction in that part of the delay of access which results from the time taken for data collection and treatment, already mentioned above.

2 IMPROVING THE PREDICTABILITY OF UTC

The predictability of UTC over averaging times of between 1 and 2 months can be quantitatively examined by studying its medium-term stability. We refer here to the stability of the freely running time scale EAL[6] with the hypothesis that the full stability of EAL is transferred to UTC without any degradation.

Table 1 illustrates the stability of EAL: values of the Allan deviation $\sigma_y(\tau)$ have been computed by application of the N-cornered hat technique to data obtained in comparisons between EAL and five of the best independent time scales in the world. These are those maintained at the NIST (Boulder, Colorado, USA), the VNIIFTRI (Moscow, Russia), the USNO (Washington DC, USA), the PTB and the LPTF (Paris, France).

Table 1 Stability of the time scale EAL estimated from data covering the period January 1993 – April 1995

τ/d	$\sigma_y(\tau)$
10	4.0×10^{-15}
20	3.4×10^{-15}
40	3.1×10^{-15}
80	3.7×10^{-15}
160	4.6×10^{-15}

The best performance is obtained for averaging times of 40 days and corresponds to $\sigma_y(T) = 3.1 \times 10^{-15}$. In terms of predictability, it means that the time error accumulated over $T = 40$ d, which can be roughly estimated by the quantity $\sigma_y(T)T$, is about 12 ns (1 σ). Already, several timing centers take advantage of this performance by combining it with high quality local time scales obtained, for instance, in near real time from a set of HP 5071A clocks. This is the case for UTC(USNO), which is used as the basis of GPS time, and which has remained within less than 5 ns of UTC for several months.

In fact, the predictability of UTC has quite naturally improved over the last two years, simply because the quality of the timing data has itself improved over the same period. This is now well known[7], and is linked to:

(*a*) the massive replacement of older clock designs by the new HP 5071A. For instance, in May – June 1995, 69 of the 232 weighted clocks in UTC computation were HP 5071A units, most of them presenting a flicker floor level characterized by an Allan deviation of about 6×10^{-15} over averaging times from 20 to 40 days,

(*b*) the operation in timing centers of several auto-tuned and active hydrogen masers presenting frequency drifts smaller than several parts in 10^{17} per day, which make them outstanding tools for timekeeping, and

(c) the efficient smoothing of time comparison data collected over only a few days, including intercontinental distances, thanks to the worldwide use of the GPS common-view technique.

The natural improvement of UTC is felt in another way. Although definitive values of UTC are delivered only every two months, provisional values are given after collecting timing data over one month and published in the BIPM *Circular T*: for example, on the 17th of October for the month of September, definitive values for September-October being available on about the 17th of November. As shown in Table 2, the time differences between provisional and definitive values have always been less than 4 ns over the last year. Thus, timing laboratories maintaining a UTC(k) can already use the provisional UTC values with some confidence.

Table 2 Time differences between definitive and provisional values of UTC for a one year period beginning in September 1994

Computation interval	Date t	Δt / ns
September – October 1994	49599	+1
	49609	+2
	49619	+4
	49649	0
November – December 1994	49659	0
	49669	-1
	49679	-1
	49709	0
January – February 1995	49719	-5*
	49729	-8*
	49739	-10*
	49769	0
March – April 1995	49779	+1
	49789	+3
	49799	-4
	49829	0
May – June 1995	49839	+1
	49849	-1
	49859	-1
	49889	0
July – August 1995	49899	0
	49909	0
	49919	0
	49929	+1
	49959	0
September – October 1995	49969	+1
	49979	+1
	49989	+2
	50019	0

* Artificially large values for the month of January 1995 were caused by the absence of timing data from one laboratory.

Further improvement in the predictability of UTC would require a revision of the stability algorithm which produces EAL. Several possible changes have been the subject of experiments on real clock data collected at the BIPM. These studies mainly concern the use of hydrogen masers, a change in the upper limit of weights, and shortening of the computation time of TAI.

It has been shown that the introduction of hydrogen maser data in the EAL computation did not degrade its stability for the period 1988 – 1994, although frequency drifts were not taken into account[8]. For averaging times close to the EAL computation time (60 days), the variation of the maser frequencies relative to EAL was dominated by an important drift in just one of them, which, in consequence was given a small weight. However, EAL stability is improving and the frequency drift of some hydrogen masers may become significant when compared with the intrinsic EAL noise, without leading to their deweighting. If this proves to be the case, it will be necessary to use a specific weighting procedure and mode of frequency prediction for hydrogen masers, based on estimates of their frequency drift. The CCDS Working Group on TAI has not yet taken any decision on this point and tests are being carried out. It is already recognized, however, that periods of observation of at least one year are necessary to make good estimates of frequency drifts.

Another research study concerns the possible shortening of the computation time of EAL. So far, however, no definitive results have been obtained on this point: averaging over 30-*day periods rather than 60-day periods, improves the long-term stability of* EAL *only if it is* associated with an increase in the upper limit of weight[9]. Following a decision of the CCDS Working Group on TAI, the maximum allowable weight of a clock in EAL was increased from 1000 to 2500[5] beginning with the computation over the two-month interval May – June 1995, but with no reduction of EAL computation time.

In addition, following the advice of the Working Group, studies are in hand to assess the advantages of using an upper limit of relative weights, rather than one of absolute weights. Tests show that an upper contribution of 1.4% for any individual clock would have helped to improve the stability of EAL for all averaging times during the period May 1993 – August 1994[10, 11]. This criterion imposes a very severe discrimination even among HP 5071A clocks and primary standards, some of these not being stable enough to reach the upper limit. It also deweights laboratories for which GPS data are not of the first quality. It does, however, result in an improvement in the stability of the resulting time scale for all averaging times. In particular, $\sigma_y(T) = 2.0 \times 10^{-15}$ for $T = 40$ d leading to an accumulated time error of less than 8 ns (1 σ) over the same averaging time. The next step is the combination of the use of an upper limit of relative weight with a reduction of the computation time of EAL. If convincing results are obtained, they will be presented during the March 1996 CCDS meeting with a view to possible changes in the TAI algorithm. In order to help national laboratories keep their local UTC as close as possible to UTC, two additional decisions were taken by the CCDS Working Group on TAI and were put into operation immediately after the meeting: all time differences published in *Circular T* are given within ± 1 ns, and the frequency steering corrections applied by the BIPM for improving TAI accuracy are published in advance. Finally, clock data are now requested every five days rather than every ten days. When this is fully implemented, possibly at the beginning of 1996, local time scale prediction will be based on a larger number of points and is, thus, likely to be more efficient.

3 REDUCING THE DELAY OF ACCESS DUE TO DATA COLLECTION AND TREATMENT

Besides the intrinsic delay of access to UTC due to the mode of computation, there exists an additional delay related to the time needed for data collection and analysis at the BIPM. The use of electronic mail and of INTERNET anonymous FTPs has significantly reduced the transfer time of timing data, and has increased their reliability: it avoids 'hand manipulation' of data and, thus, reduces trivial errors. The ideal configuration would be a complete automation of the complete process according to standardized procedures. The BIPM is working on this in collaboration with national laboratories and appropriate CCDS Working groups. Good progress has already been made, which we illustrate by taking the TAI computation over the period September – October 1995.

The TAI computation relies on timing data made available to the BIPM by 45 national laboratories or timing centers, all of them keeping a local representation of UTC. Some of these laboratories, such as the OP or CH, collect data inside their country before sending it to the BIPM. The total number of contributing laboratories can, thus, reach 65, but the BIPM has only 45 direct contacts. For September – October 1995, 3 of the 45 centers provided no data because of local operating problems.

The first type of data requested from a laboratory is a set of GPS common-view observations obtained on site. Raw data collected directly, on a weekly basis, from the output of the GPS time receiver are preferred. The transfer of these data to the BIPM works remarkably well through electronic mail. Some laboratories, three in September – October 1995, send a monthly file on a floppy disk through Express Mail, this is also quite convenient to us. A small problem lies in the fact that there exists a number of different formats for these files. The CCDS Group on GPS Time Transfer Standards has already worked on it in publishing the Technical Directives for GPS Time Receivers[12] which, in particular, include a standardized format for GPS data. This is now being implemented in local GPS receivers: already 10 laboratories were using this standardized format for the period September – October 1995. Besides facilitating the task of the BIPM, it should also lead to a reduction of the noise of GPS time links.

The second type of data requested from a laboratory is a set of time differences between its local UTC and individual free-running clocks. Since the last meeting of the CCDS Working Group on TAI, clock data for month n are requested on the 5th of month $(n + 1)$, in a file arranged according to a specified format. It is also recommended to collect data for MJDs ending in 4 and 9, that is to say every 5 days rather than 10 days, over a short epoch surrounding 0 h UTC. Except for laboratories keeping a large number of clocks, the monthly clock data file includes only a few lines, very often less than 10 lines.

Over the period September – October 1995, all clock data files received through electronic mail corresponded to the specified format and could immediately be analyzed. Only one of them did not yet include data for MJD ending in 4. Some contributing laboratories do not yet have at their disposal electronic mail and send their data on a paper sheet transmitted by fax. This was the case for five laboratories during the period September – October 1995. In these cases, we copy by hand these data and check it as far as we can. Generally, the same laboratories do not yet have at their disposal a GPS receiver specifically designed for time and can only give occasional values of a rough estimation of $UTC(k) - GPS$ time. A poor quality time link also leads to some deweighting of the clocks involved. However, the role of the BIPM includes the distribution of time to all contributing laboratories and we try to publish our *Circular T* only when the whole set of laboratories has sent their data.

For the period September – October 1995, a provisional UTC was computed and published in mid-October, with data covering the month of September. Data for the seven standard dates of October were requested by the 5th of November. On the 13th of November, only two laboratories had still omitted to send their data. One of these laboratories had experienced an interruption in data of several months in the spring and summer 1995, so that its clocks were still in their test period. The TAI could, thus, be safely computed with these missing data. Unfortunately, it was impossible to contact the second laboratory, which contributes about 1.5% of the total weight, and we finally issued the results of UTC for October in *Circular T94* on the 17th of November.

The last standard date of this two-month computation is MJD = 50019 and corresponds to the 29th of October. That part of the material delay of access to TAI due to data collection and analysis was, thus, about 19 days, which still seems very long. However, progress on this point is soon expected and it is intended to issue *Circular T* before the 12th of the month during 1996.

4 CONCLUSIONS

The Time Section of the BIPM produces time scales which are used as the ultimate reference in the most demanding scientific applications. They also serve for the synchronization of national time scales and local representations of UTC, upon which all time signals used in current life are based. This work is, thus, in complete accordance with the fundamental missions of the BIPM.

To fulfill the metrological requirements these time scale are necessarily computed after the fact and cannot, therefore, be distributed to real-time users. This apparent disadvantage can, however, be almost completely overcome by ensuring that the predictability of UTC is such that individual laboratories maintaining their own UTC(k) can use it to predict the differences UTC-UTC(k) with the required accuracy. Considerable effort at the BIPM is now being devoted to making this possible through a better combination of the contributing data and through the reduction of the delay of access due to data exchange and treatment by the automation of data transfer procedures.

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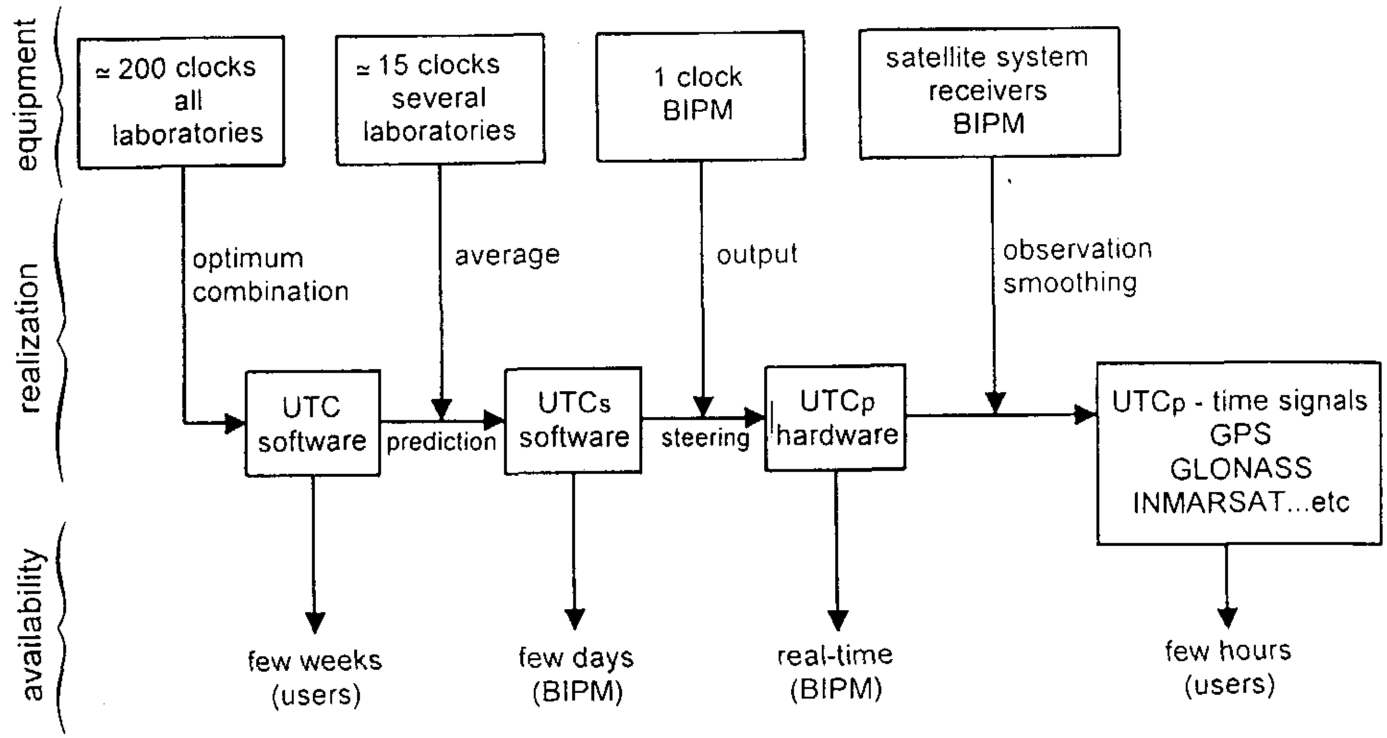

Figure 1. Block diagram of the realization of the real-time prediction of UTC, UTCp