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A REAL-TIME PREDICTION OF UTC

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Abstract

The reference time scale for all scientific and technologic applications on the Earth, the Universal Coordinated Time UTC, must be as stable, reliable and accurate as possible. With this in view the BIPM and before it the BIH, have always calculated and then disseminated UTC with a delay of about 80 days. There are three fundamental reasons for doing this.

i) It takes some weeks for data, gathered from some 200 clocks spread world-wide, to be collected and for errors to be eliminated.

ii) Changes in clock rates can only be measured with high precision well after the fact.

iii) The measurement noise originating in time links, in particular using Loran-C, is smoothed out only when averaging over an extended period.

Until mid-1992, the ultimate stability of UTC was reached at averaging times of about 100 days and corresponded to an Allan deviation $\sigma_y(\tau)$ of about $1{,}5\times10^{-14}$ when compared to the best primary clock in the world, the PTB CS2.

For several years now, a predicted UTC has been computed by the USNO (Washington D.C., USA) through an extrapolation of the values [UTC - UTC(USNO)] as published in deferred time by the BIPM. This is made available through the USNO Series 4, through the USNO Automated Data Service, and through GPS signals. Due to the instability of UTC, the poor predictability of the available clocks, and the intentional SA degradation of GPS signals, the real-time access to this extrapolated UTC has represented the true deferred-time UTC only to within several hundreds of nanoseconds.

Recently, there have been dramatic improvements in several domains.

i) New commercial Hewlett-Packard caesium clocks and active auto-tuned hydrogen-masers, both presenting a remarkable frequency predictability, are now available in timing centres.

ii) The widespread use of GPS in common-views, combined with improved performances of contributing clocks, has improved the stability of UTC, namely $\sigma_y(\tau)$

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to the order of $8x10^{-15}$ for averaging times of 40 days, and this could also help to decrease the delay of access to UTC.

iii) The SA is now overcome both for GPS common-views and for real-time access to GPS time. In addition, other time dissemination methods, which are not intentionally degraded, are now very promising.

iv) Modern computer capability and improvements in data communication capability allow quicker and more efficient automatic data transmission.

By taking advantage of these advances, it may soon be possible to obtain a real-time estimate of UTC, provisionally entitled UTCp, from the 1pps output of a commercial clock maintained at the BIPM. In this project the BIPM clock is steered to a software time scale computed by combining present data with extrapolated frequencies, relative to UTC, from a small ensemble of highly predictable clocks maintained in several timing centres. In this way and with definitive computation of UTC performed every month, it seems feasible to maintain a representation of UTC to within ± 60 ns (20 ns standard deviation).

The physical clock which delivers UTCp will be used to measure timing signals, such as those from GPS, GLONASS, INMARSAT and a hydrogen-maser on board the Russian satellite Meteor 3M. Anyone measuring those timing signals could then link local time scales to the estimated UTC, in near real-time, by simple data communication with the BIPM where time corrections between timing signals and UTCp would be continuously available.

We are now studying in detail how all this might be done with a view to carrying out some pilot experiments.

INTRODUCTION

It is anticipated that rapid advances in telecommunications will yield very high rates of data transport. The advent of the Synchronous Digital Hierarchy (SDH) and the Synchronous Optical Network (SONET) requires the best of clock technology and transmission systems. This growing need for synchronism within the telecommunication community was expressed recently by Dr Ghani Abbas, System Design/International Standard Manager of a major telecommunications company in the UK, who said:

> "New technologies, such as SDH, SONET, ..., are being introduced into the telecom transport networks. These technologies require good quality synchronization as well as better short term clock stability. In order to meet the synchronization needs of these new emerging technologies, a convenient tie to UTC to better than 100 ns is required. In the long term this requirement will be a global one."

The fundamental role of UTC is to be the ultimate reference time scale for any application on the Earth. Thus UTC must be as stable, reliable and accurate as possible. This can be accomplished correctly only if UTC is computed in deferred-time [1].

To be reliable, UTC is based on a weighted average of the readings of about 200 clocks spread world-wide in national timing centres. To compute this average the BIPM needs several weeks for data collection and verification. In addition, the need for long-term stability calls for the observation of each participating clock for a time sufficient to detect any frequency change with high precision and to treat it correctly. Since the beginning of the UTC computation, the length of the period of observation has always been two months. This averaging time is sufficient to average the measurement noise to be less than the clock noise. The measurement noise is dependant upon the time link. In particular, it is essential to average data using Loran-C as the time comparison method, for at least two months in order to reach the stability of some atomic clocks.

Until mid-1992, the ultimate stability of UTC was reached for averaging times of about 100 days and corresponded to an Allan deviation $\sigma_y(\tau)$ of about $1{,}5 \times 10^{-14}$ when compared to the best primary clock in the world, the PTB CS2.

Conformity of the UTC scale unit with the SI second on the rotating geoid is obtained through frequency steering after comparisons with the best primary frequency standards, the PTB CS1 and CS2. Twelve such corrections, each of order $0{,}5 \times 10^{-14}$, were applied between 1989 and mid-1992 in order to ensure a UTC accuracy of 2×10^{-14} [2].

The deferred-time access to UTC described above does not satisfy the needs of the telecommunication community. The sole possibility is to provide a prediction of UTC in real-time and to make it readily available.

For several years now, a predicted UTC has been computed by the USNO (Washington D.C., USA) through an extrapolation of the values [UTC - UTC(USNO)] as published in deferred time by the BIPM [3]. This is made available through the USNO Series 4, the USNO Automated Data Service, and GPS signals. Due to the instability of UTC and mainly to the intentional SA degradation of GPS signals, real-time access to this extrapolated UTC represents the true deferred-time UTC only to within several hundred of nanoseconds.

The aim of this paper is to show that it may be soon possible to provide a better real-time prediction of UTC thanks to recent significant advances in timing technology. It also explains the actions already taken, and shortly to be taken by the BIPM with the help of several national timing laboratories.

The first section of this paper shows the improvement of UTC stability during 1993. Further steps, in particular a reduction in the time of access, will be taken from the beginning of 1994. In the second section, we show how associating the improved qualities of UTC, which remains a deferred-time scale, with the improvement in available clocks and data transfer systems makes it possible to obtain a good real-time prediction of UTC. It is based on present data and extrapolated frequencies, relative to UTC, from a subset of the clocks contributing to UTC with a very good time predictability and with long-term frequency stability of less than 1×10^{-14}. This prediction of UTC, computed every few days, is used to steer a physical clock, maintained at the BIPM, the output of which can be measured, in real-time, against other time scales. The time scale corresponding to the physical 1pps output from this BIPM clock is named UTCp. We anticipate that UTCp will represent UTC within ±60 ns (20 ns standard deviation). In the third section we explain how UTCp could be made available to users.

1. IMPROVEMENT OF UTC STABILITY

The important changes which have occurred in time metrology since 1992 are the widespread use of GPS in strict common views and the maintenance in timing centres of clocks with high predictability such as auto-tuned active hydrogen-masers and the new caesium clocks from Hewlett-Packard.

1.1. GPS time comparisons

In September 1993, 38 of the 45 timing centres keeping a local representation of UTC, UTC(k), were equipped with GPS timing receivers. Most of them follow the international tracking schedule published by the BIPM and regularly send their GPS observations to the BIPM. This means that nearly all time links involved in the TAI computation are now obtained by one of the most accurate time transfer methods available and undergo a unified treatment. The international GPS network is organized as shown in Figure 1: it features local stars on a continental scale and two long-distances links, OP-NAOT and OP-NIST, chosen because of the excellence of the GPS antenna coordinates of these three laboratories and also because measured ionospheric delays are routinely available at locations close to these sites.

The current computation of GPS time comparisons incorporates a number of refinements. For most links the BIPM uses strict common views (synchronization within 1 s) in order to remove the clock-dither noise brought about by SA [4]. There is then no impediment to wide use of Block II satellites. In addition, a major source of error is reduced thanks to the accurate knowledge of GPS antenna coordinates and their world-wide homogenization in the ITRF [5]. Since October 1993, results obtained for both of the long-distance links have been corrected in deferred time for precise satellite ephemerides.

It appears that the precision of one single measurement [UTC(k_1) - UTC(k_2)] is now about 2 ns for short distances and 8 ns for long distances [6]. An important consequence is the improvement of the short-term stability of the resulting time scale. This can be seen in Figure 2 which compares the Allan deviations $\sigma_y(\tau)$ of the free atomic time scale EAL, relative to the PTB CS2, for two different periods, mid 1986-mid 1988 and 1992-1993 (UTC is deduced from EAL by frequency steering and addition of an integer number of seconds, UTC stability is thus very close to EAL stability except for very long averaging times). For the data covering the period 1992-1993, the measurement noise brought about by time comparison methods is already completely smoothed out for averaging intervals of 10 days, where formerly 40 days were required. The real qualities of the contributing clocks thus appear for short averaging intervals, τ = 10 days, which should allow reduction of the basic interval of computation.

1.2. Hydrogen-masers and new commercial caesium clocks

A dramatic improvement in the stability of the clocks contributing to UTC has recently been observed. In particular, active hydrogen-masers with specific auto-tuning modes and caesium clocks of the new HP 5071A design have been introduced in the computation, nearly all of them with the maximum weight authorized by the BIPM algorithm [1]. Table 1 indicates the evolution of the composition of the UTC ensemble from the end of 1991 until mid-1993.

i) The percentage of clocks at upper limit of weight increased from 21% to 28%. This leads to a more efficient averaging of individual drifts and thus reduces the residual drift of the scale. It also helps to maintain its accuracy and avoid the need to apply steering corrections.

ii) Hydrogen-masers contribute about 12%. Their auto-tuning modes greatly reduce their natural tendency to drift and improve their long-term stability. For instance, the Russian hydrogen-masers kept by the PTB (CHI-75 from Kvarz) present frequency drifts of order 1×10^{-16}/day and the N5 unit (Sigma-Tau) from USNO has no significant drift.

iii) At mid-1993, data from 36 HP 5071A clocks were reported to the BIPM, nearly all of them entering with the maximum weight. This results from their excellent stability as shown in Figure 3 (data kindly transmitted by Dr G.M.R. Winkler from USNO). They present a flicker floor of order 6×10^{-15} for averaging intervals from 20 to 60 days. It is anticipated that about 50 HP 5071A will participate to UTC, each with maximum weight, in January 1994.

The widespread use of GPS and the introduction of clocks with remarkable predictability have already greatly improved the stability of UTC. Using data from the beginning of 1992, the best stability of EAL and UTC, compared to PTB CS2, is characterized by an Allan deviation $\sigma_y(\tau)$ of 8×10^{-15} and is reached for 40-day averaging intervals.

1.3. Further improvement of UTC stability and accuracy

The BIPM has already taken action to improve the stability of UTC still further. From *Circular T 72*, corresponding to January 1994, UTC will be computed on the basis of clock observations taken over 30 days rather than 60 days. This is now possible for the reasons described in sections 1.2. and 1.3.: wide use of GPS and good stability and predictability of contributing clocks.

The new algorithm to be implemented in 1994 for computation of UTC will be described elsewhere [7]. Tests carried out with real timing data for the years 1992 and 1993 show an improved stability of the 'one-month' time scale, when compared to PTB CS2, for all averaging times (see Figure 4). The best stability $\sigma_y(\tau)$ is reached for τ of order 30 days. Its value, of order $6x10^{-15}$, probably reflects the instabilities of both UTC and PTB CS2. The part of instability due to UTC alone can thus be estimated to be of order $4{,}5\ 10^{-15}$.

Another important consequence is the reduction of the delay in access to UTC. Nowadays, with a basic sample duration of two months and the slow delivery of some data, still reaching the BIPM via conventional post, the definitive results of UTC for month (n-1) and (n) are given on the 28th of month (n+1). With the wide use of efficient electronic mail, it should become feasible for the BIPM to obtain timing data in the form of files with pre-determined format. This should save time, in particular it will allow automatic data sorting and checking. The BIPM is already working hard on this point, encouraging all contributing laboratories to use a uniform data file format and to respect the deadline for making them available. The present objective of the BIPM is to produce the definitive results for UTC for month (n-1) on the 20th of month (n), before the end of 1994.

In future, it is anticipated that UTC may become a simple average of commercial HP 5071A and hydrogen-maser units, with specific frequency prediction modes for each clock type. This should improve both UTC stability and accuracy. Indeed, one HP 5071A unit has a manufacturer stated accuracy of order $1x10^{-12}$, but the actual performance has been shown to be much better: an ensemble of 36 HP 5071A clocks kept at USNO presents an average frequency of $3x10^{-14}$ relative to UTC, with an error bar, on the average frequency, of $2{,}5x10^{-14}$ [results kindly transmitted to the BIPM by Dr G.M.R. Winkler, USNO]. This suggests that ensembles of a large number of HP 5071A units can provide absolute frequency information that is competitive with the performance of the best current laboratory standards.

2. REALIZATION OF A REAL-TIME PREDICTION OF UTC, UTCp

2.1. Principle of realization

The real-time prediction of UTC, provisionally entitled UTCp, is the time scale corresponding to the 1pps output issued from a physical clock which is maintained at the BIPM. This physical clock is steered on a software time scale, provisionally entitled UTCs, computed at the BIPM as the optimum prediction of UTC from past knowledge of UTC combined with a small amount of clock data available with a short delay. The block diagram for the realization of UTCp is given in Figure 5.

An atomic time scale, UTCs, is computed from a small ensemble of clocks as a simple average of their readings. To produce an optimum prediction of UTC with a short time of access, the UTCs algorithm requires an estimation of the current values of the clock frequencies relative to UTC. This can be extrapolated from past values obtained from last UTC computation. The clocks contributing to UTCs should then be highly predictable.

One can easily imagine the UTCs clock ensemble composed of HP 5071A caesium clocks, auto-tuned active hydrogen-masers, and primary frequency standards operating continuously as clocks. Such clocks reach their flicker floor for averaging times ranging from 20 days to 40 days. Their frequencies relative to UTC, for the current month, can thus be predicted to be equal to their known frequencies relative to UTC, computed over the previous month.

Clocks of the UTCs ensemble will be chosen from those maintained in national timing centres. The BIPM will thus need the help of a small number of laboratories willing to make their timing data available to the BIPM regularly and with a very short delay. Technically this can be done using anonymous File Transfer Protocol (FTP) accessible through the INTERNET network. The BIPM could then retrieve clock and time transfer data for immediate treatment. In addition it would be essential to use data from a number of laboratories in order to detect simultaneous frequency steps of several clocks, which might occur due to external changes in a given laboratory.

The combination of the readings and predicted frequencies from clocks of the UTCs ensemble allows updating UTCs when new data is available. However, as updating involves several laboratories, the exchange of current GPS timing data from these laboratories is also necessary. Filtering of data takes a time of order 12 hours for short-distance links and 1 or 2 days for long-distance links. UTCs may thus reasonably be expected with a delay of access of several days. The requirement of access in real-time can be realized by steering a physical clock to follow UTCs. The output of this clock is the real-time time scale UTCp. Between two consecutive updates of UTCs, the quality of UTCp is maintained by the intrinsic qualities of the physical clock. The temporary loan of a HP 5071A unit to the BIPM, officially agreed by Hewlett-Packard during summer 1993, is an important step of our project. This unit is expected to be in operation before the end of 1993.

2.2. Expected qualities of UTCp

The ultimate stability of UTC, $\sigma_y(\tau) = 4{,}5\times10^{-15}$, corresponds to flicker noise of frequency and is reached for τ of order 30 days. The time error (1σ) on the optimum prediction of UTC over a τ-long prediction interval is equal to $\tau\times\sigma_y(\tau)/\sqrt{\ln 2}$ [8]. The part of the time error on the optimum prediction UTCp, accumulated after 30 days and due to the instability of UTC itself, can be estimated of order 16 ns.

A simple average of clock readings is more stable than any of its contributing elements. With an ensemble of 10 clocks equally weighted in the average and presenting flicker floors of order 6×10^{-15} over 30-day intervals, the expected flicker floor of the simple average is of order 2×10^{-15} and is reached for averaging intervals of 30 days. This leads to an additional accumulated error (1σ) after 30 days of order 7 ns.

The total error on the optimum prediction UTCs of UTC would then be of order 18 ns (1σ). In the future, it is anticipated that the 16 ns originating from UTC instability will be greatly reduced.

With a daily update of UTCs, the error accumulated by the physical clock maintaining UTCp comes from its intrinsic noise over a 1-day averaging period. This is theoretically less than 1 ns and is thus negligible. However an eventual abrupt frequency step of the BIPM clock would give an additional error of several nanoseconds. With one single clock, such a step can be detected only when external data arrives at the BIPM. In the future, we anticipate having three clocks at the BIPM, thus greatly reducing the probability of an undetected frequency step.

From the preceding values, one can reasonably estimate that the real-time UTCp will represent the true deferred-time UTC within ±60 ns (20 ns standard deviation).

2.3. First tests for the realization of UTCp

At a first step, the BIPM intends to retrieve clock and GPS data through the INTERNET network, three times a week (on Mondays, Wednesdays and Fridays), from two laboratories, the PTB and the USNO.

The advantages of this arrangement are that only two time links are needed, one long-distance link between the USNO and the PTB, and one short-distance link between the PTB and the BIPM, while the available ensemble of clocks is quite interesting. An ensemble of about 15 highly predictable and independent clocks could comprise:

- one PTB primary frequency standard operating as a clock, PTB CS1 or PTB CS2,
- one PTB active hydrogen-maser from the tandem of auto-tuned Russian units maintained at the PTB,
- one or two HP 5071A kept at the PTB,
- the Sigma-Tau N5 active hydrogen-maser kept at the USNO, and
- several HP 5071A from USNO, kept in different locations with individual environmental control.

Formal steps to initiate this particular collaboration, which requires specific inputs from the USNO and the PTB, have not yet been taken. If such a collaboration is approved and if the obtained results are convincing, tests could be carried out on a daily basis and with the gradual involvement of other laboratories. Implicit in this proposal is the implementation of a completely automatic system of data retrieval, checking and treatment. Whatever procedure is agreed, the BIPM clock will not participate in the computation of UTCs, its sole role being to follow UTCs in order to provide a physical output, UTCp, in real-time.

3. ACCESS TO UTCp

The UTCp, being physically available in real-time, can be made available through measurements of the time differences between UTCp and other time scales, observable from user laboratories, using satellite systems like GPS, GLONASS, INMARSAT, the hydrogen-maser on Meteor 3M, ... *etc*.

This leads to two requirements:

- calibrated reception equipment, capable of receiving all available signals, is required at the BIPM and must operate under excellent metrological conditions (accurate local coordinates, ionospheric measurements, multi-channel receivers, temperature and humidity control of the clock room, ... *etc*),
- development and implementation of efficient methods for the extraction, from real-time measurements, of the best estimates of the requested time differences [UTC - GPS time], [UTC - GLONASS time] ... *etc*.

The UTCp will be available in real-time at the BIPM, but the extraction and delivery of usable time differences takes some time. For example, efficient averages for smoothing out SA noise from raw GPS data requires the use of simultaneous measurements on several satellites taken for about one hour [9]. Once the BIPM has obtained the average time difference [UTCp - GPS time], it can deliver it via its INTERNET anonymous FTP. This will be updated when new data is available: the periodicity could be as short as one hour. A given user who also accesses GPS time from his local time scale could obtain the BIPM information through a connection to the BIPM INTERNET anonymous FTP. The user can take full advantage of this value only if:

- the INTERNET connection is established shortly after the BIPM has delivered an updated time difference,
- the user receiving equipment is well calibrated and is used under excellent metrological conditions, and
- an efficient method is available for restitution of GPS time in the user laboratory.

In the case of GPS, the restitution of GPS time detailed in Ref. 9 adds an uncertainty of about 10 ns. In the best case, the user will then access UTCp within ±75 ns (25 ns standard deviation) and with a delay not less than one hour. This performance may be improved when timing equipment becomes commercially available for satellite systems which do not present intentional signal degradation.

CONCLUSIONS

The production and distribution in real-time of a predicted UTC calls for the computation in short deferred-time (of order several days) of a software time scale, UTCs, from a small ensemble of clocks with good predictability, and the steering on UTCs of a commercial clock maintained at the BIPM. Its real-time output is the time scale UTCp, which represents the true deferred-time UTC within 20 ns (1σ). Its availability is made through the delivery by the BIPM of time differences between UTCp and time scales distributed by global satellite systems, in near real-time (of order several hours) and with uncertainties of order 25 ns (1σ).

This BIPM project, suggested by Allan and Lepek [10], comes in response to current and anticipated needs within the telecommunications industry. It is also indirectly encouraged by Recommendation S 5 (1993) approved by the Comité Consultatif pour la Définition de la

Seconde (CCDS) during its 12th meeting (24-26 March 1993). In this, the Comité Consultatif pour la Définition de la Seconde, recommends [11]

> "... that time centres provide information to facilitate time coordination to UTC in real time with a goal of 100 ns, standard deviation, when this is feasible, and that the technical problems implicit in this goal be carefully studied".

The BIPM is already carrying out studies on the real-time prediction of UTC. However it is important to underline that, even after experimentation has validated the concepts of a real-time predicted UTC, its concrete implementation at the BIPM will take place only after discussion in the CCDS and consultation with interested bodies.

Acknowledgements

The authors are grateful to Dr G.M.R. Winkler, USNO, Washington D.C., USA, for his support in this project, and to Gérard Petit and Jacques Azoubib, Time Section, BIPM, Sèvres, France, for helpful discussions. The BIPM thanks Hewlett-Packard for the loan of a commercial caesium clock HP 5071A, without which the provision of a real-time predicted UTCp could not even be considered.

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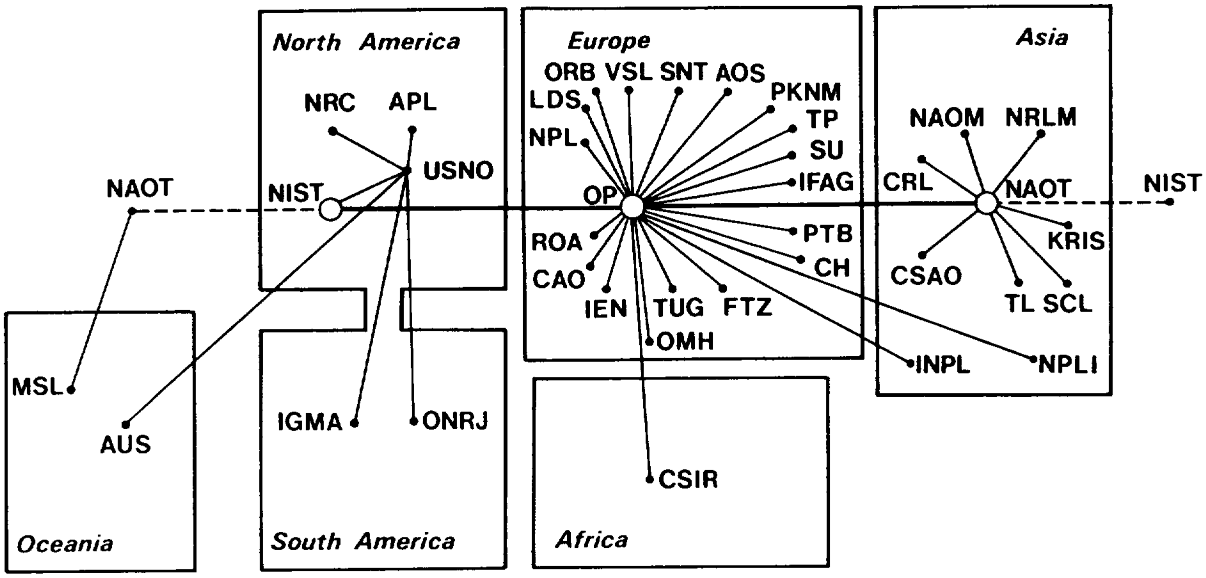

Figure 1. Organization of the international GPS network used in UTC computation (September 1993). Acronyms of laboratories can be found in Ref 2.

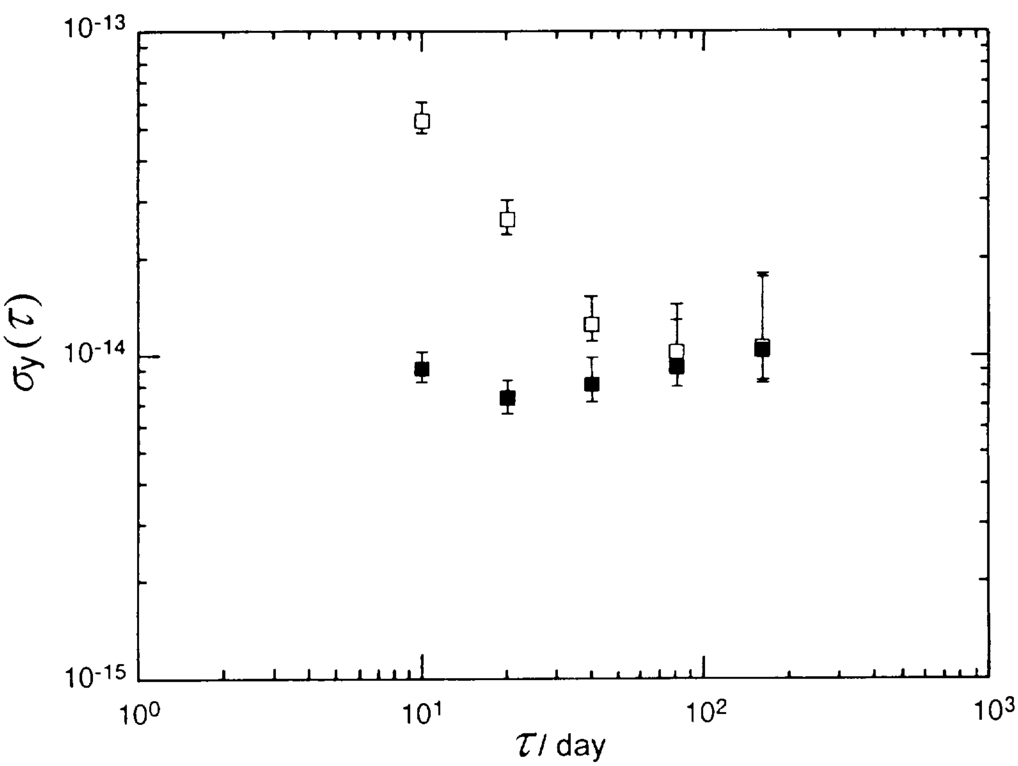

Figure 2. Allan standard deviation of the time difference [EAL - PTB CS2] computed with 10-day data covering a two-year period:

□ *mid 1986-mid 1988,*

■ *1992-1993.*

		Nov - Dec 1991	Nov - Dec 1992	May - Jun 1993
	Total number of clocks	194	194	215
	Max contribution	1,6%	1,4%	1,2%
	Number at max contribution	41	44	61
H-masers	Total number	20	23	27
	at max contr	8 (12,8%)	10 (14,0%)	11 (13,2%)
	under test	6	4	6
HP 5071A	Total number	0	8	36
	at max contr	0	1 (1,4%)	14 (16,8%)
	under test	0	4	20

Table 1. ***Contribution of hydrogen-masers and HP 5071A clocks in UTC computation.***

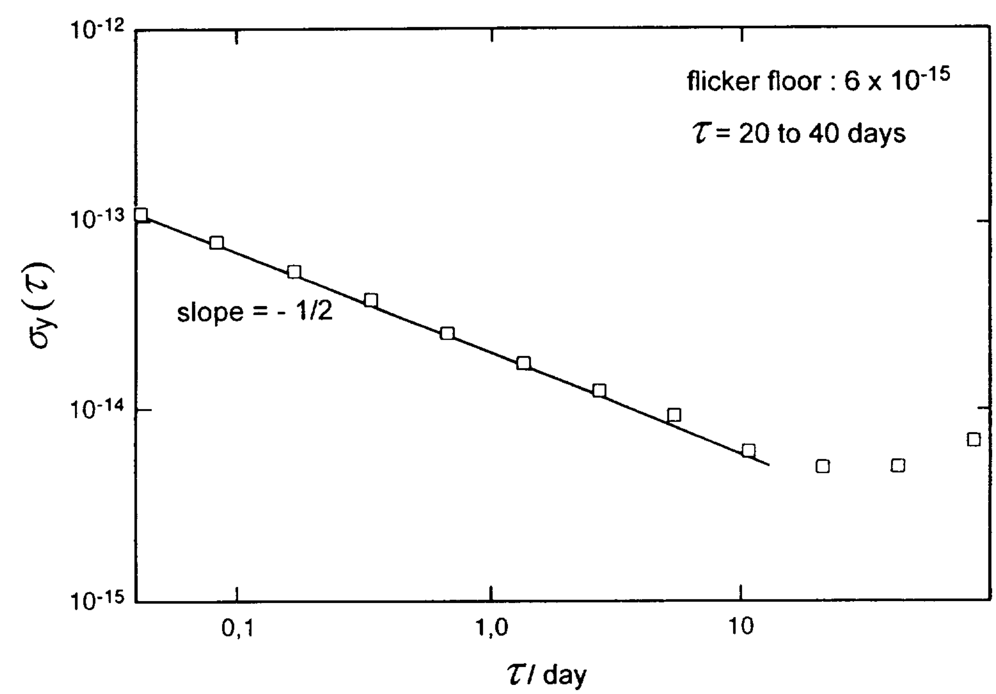

Figure 3. ***Allan standard deviation of the time difference between the HP 5071A clock serial number 114 and the Sigma-Tau hydrogen-maser N5, both kept by USNO. (Log-Log graph).***

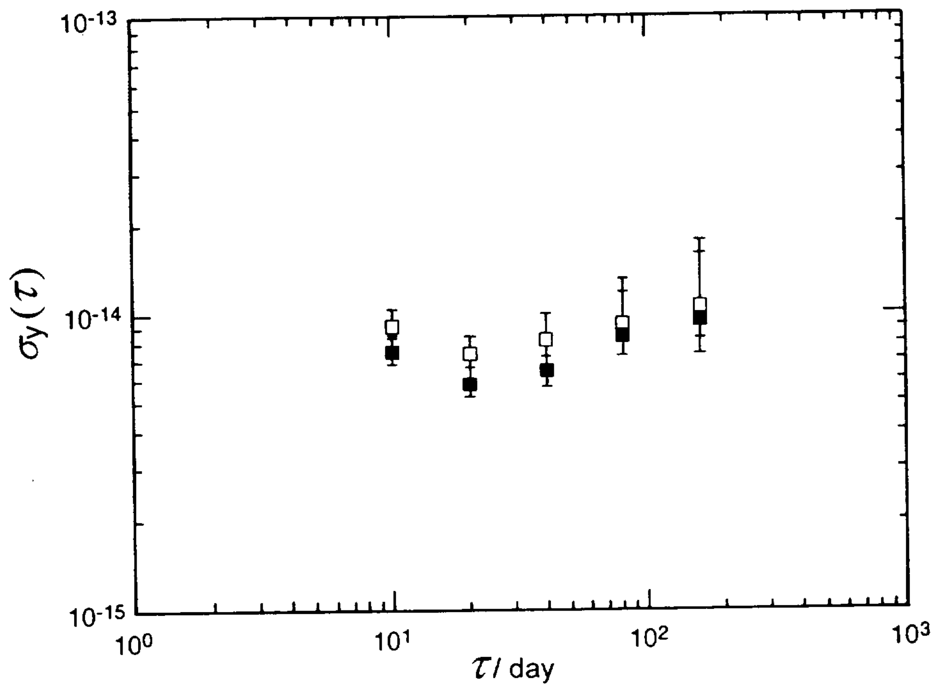

Figure 4. Allan standard deviation of the time difference [EAL - PTB CS2] computed with 10-day data covering years 1992 and 1993:

□ *EAL computed with two-month basic intervals,*

■ *EAL computed with one-month basic intervals.*

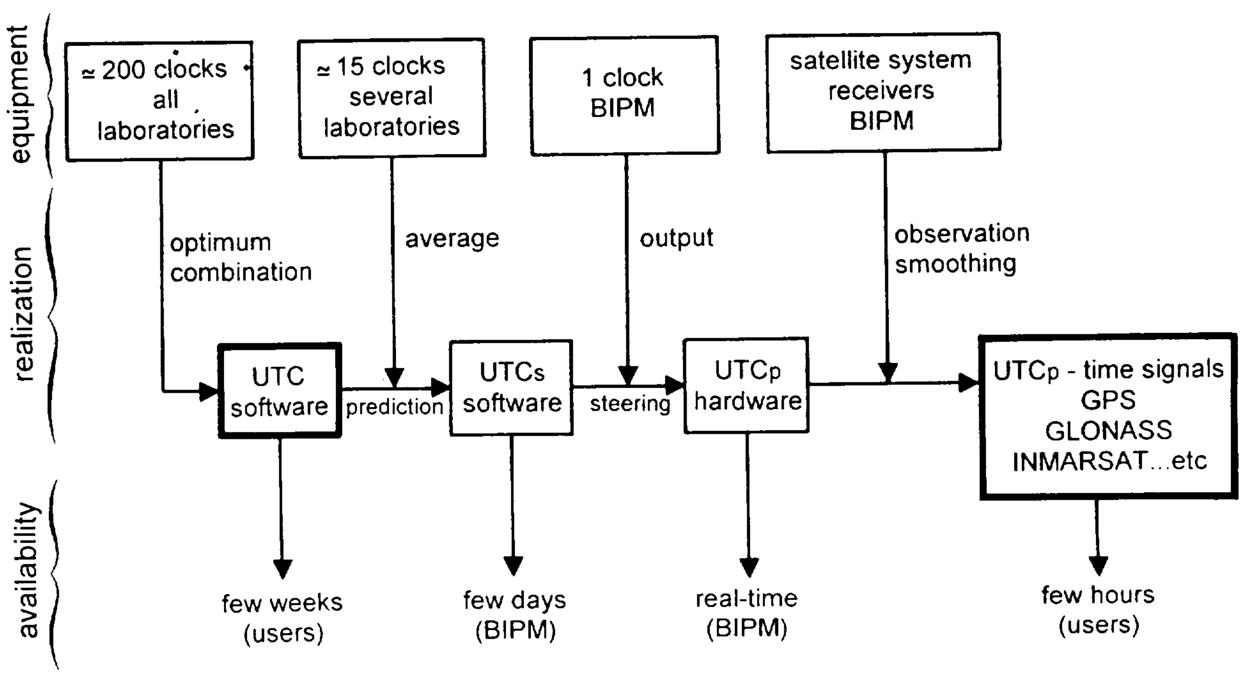

Figure 5. Block diagram of the realization of the real-time prediction of UTC, UTCp.

QUESTIONS AND ANSWERS

David Allan, Allan's Time: I think the long–term hope is that this will be of great service to the user community, especially the telecommunication user community who has specified a need at the sub–100 ns level. And of course, the hope would be that other countries would have their UTC scales also synchronized, so that this would track the real time UTCP in any country at this very high level. NIST and USNO have both been very actively steering their clocks. The Observatory time unfortunately has been kept within something like less than 100 ns, maybe 50 ns. Is that true, Dr. Winkler?

Dr. Winkler: Yes.

David Allan: Of course, GPS broadcasts the UTC/USNO correction. So in addition to being able to have something of the order of tens of ns directly from BIPM on an operational basis, GPS will be broadcasting UTC BIPM. So I think with this cooperative as Dr. Thomas indicates we hope that it continues to go on. I think it has been excellent today. With international cooperation we can see UTC BIPM as represented by UTCP being a real time scale in every country at the hundred ns level, or certainly better.

Dr. Winkler: My comment is that indeed what I would like to see is an evaluation of the existing predictions which are available in real time. In fact, the correction between UTC at every moment is available on the computer. And I think that should be evaluated by you. You accessed that several times, I know that. Because, that prediction is based on a clock set which is much larger than the one which you will have.

The real problem is that until now we have only had the two months evaluation period. And if these corrections disappear, then of course the prediction will be immediately much more accurate and all of these values will converge to zero I hope.

Claudine Thomas: I hope so too.