CCTF 2004
Report of the BIPM Time section 2002-2004

Elisa Felicitas Arias

Work has been done at the BIPM Time section to carry out the recommendations adopted at the 15th Meeting of the CCTF (2001). Clock comparison for TAI has progressed with the inclusion of new techniques, the common views of GPS satellites by using single-channel receivers are complemented today by GPS multi-channel observations, GPS dual-frequency, multi-channel observations and links by TWSTFT. Calibration campaigns of GPS receivers have been organised without interruption during the period of this report. The algorithm for the calculation of TAI has been improved by adopting a new strategy to fix the upper limit of relative clock weights. An automated procedure has been implemented for the calculation of *Circular T*.

1. International Atomic Time (TAI) and Coordinated Universal Time (UTC)

Reference time scales TAI and UTC have been computed regularly and have been published in the monthly *Circular T*. Definitive results for 2001 and 2002 have been available in the form of computer-readable files in the BIPM home page and on printed volumes of the *Annual Report of the BIPM Time Section* (Volume 14 for 2001 and Volume 15 for 2002). The current format of this publication includes part of the information in the traditional printed publication, completed by tables accessible through the BIPM web site.

Circular T has been modified in contents and format to better fulfil the needs of users. In April 2003 we started providing the values of [*UTC-UTC(k)*] and [*TAI – TA(k)*] to 0.1ns [1]. Complementing this information, a new section has been included to give information on the time link used for each calculation. Since January 2004 we give also complete characterization of the uncertainty of the time links as well as the complete information on calibration of equipment and links [2].

The programmes used for the calculation of *Circular T* have been adapted or rewritten to render them suitable for an automated procedure. This procedure is currently used for each monthly calculation, allowing a shorter delay in the publication of *Circular T* and rendering the system even more reliable.

Research concerning time scale algorithms included studies which aim to improve the long-term stability of the free atomic time scale EAL and the accuracy of TAI.

1.1. EAL stability

Some 80 % of the clocks contributing to TAI are either commercial caesium clocks of the type HP5071A or active, auto-tuned active hydrogen masers, and together they contribute 86 % of the total weight with consequent improvement in the stability of EAL.

In January 1998 the weighting procedure applied to clocks in TAI had been shifted to the assignation of an upper limit to relative weights, instead of the previous absolute weighting procedure[3]. Analysis of the distribution of the relative weights attributed to clocks by the end of 2000 indicated that the maximum relative weight which has been fixed to 0.007 was no longer appropriate, since about 80% of high performance caesium clocks reached this value.

In January 2001 we implemented the first step in the establishment of a new procedure of fixing the maximum relative weight of clocks in TAI. We abandoned the practice of fixing the maximum weight to 0.007, to make this value dependent on the number of participating clocks (N) during the month of calculation ($\omega_{max} = A/N$). In a first step it has been adopted A=2.0; the final step, implemented in July 2002 set the value of A to 2.5, which proved to provide the highest stability free time scale of those obtained with the tested values [3].

The medium-term stability of EAL, expressed in terms of an Allan deviation, is estimated to be 0.6×10^{-15} for averaging times of twenty to forty days over the period. This improves the predictability of UTC for averaging times of between one and two months.

1.2. TAI accuracy

We have regularly used results of frequency measurements of primary frequency standards to ensure the accuracy of TAI.

Since June 2001 , individual measurements of the TAI frequency have been provided by nine primary frequency standards, including five Cs fountains (NIST-F1, IEN-CSF1, PTB-CSF1, SYRTE-FOM and SYRTE-F02):

- CRL-O1, which is the optically pumped primary frequency standard developed and evaluated at the NIST for the CRL, Tokyo (Japan). In the period covered by this report, it provided six measurements with periods between 10 and 20 days. The type B relative standard uncertainty of CRL-O1 is stated by the CRL between 3.9×10^{-15} and 5.5×10^{-15}.
- IEN-CSF1 is the caesium fountain operated at the IEN, Torino (Italy). Measurement reports started in April 2003; three reports over 5-10 days have been produced in the period. Its type B relative standard uncertainty as stated by the IEN is $1.1\text{-}2.0 \times 10^{-15}$.
- NIST-F1, which is the caesium fountain developed at the NIST, Boulder (USA). In the period covered by this report, it provided 8 measurements with periods between 15 and 45 days. The type B relative standard uncertainty is stated by the NIST as 1×10^{-15} at the beginning of the period and 0.4×10^{-15} at its end.
- PTB-CS1 and PTB-CS2 are classical primary frequency standards operating continuously as clocks at the PTB, Braunschweig (Germany). PTB-CS1 provided measurements over periods of 25-35 days; the type B relative standard uncertainty is stated as 8.0×10^{-15}. Frequency measurements for PTB-CS2 have been taken over periods ranging from 25 to 35 days. The published evaluation of its type B relative standard uncertainty is 12.0×10^{-15} for the period.

- PTB-CSF1 is the caesium fountain developed at the PTB. Five reports of measurements have been provided in the period. The type B relative standard uncertainty of PTB-CSF1 is stated by the PTB as 0.9-2.0 x 10^{-15}.
- SYRTE-JPO is the optically pumped caesium standard operated at the BNM-SYRTE, Paris (France). It provided 21 measurements in the period of this report, with periods between 10-30 days. The type B relative standard uncertainty of SYRTE-JPO is stated by the BNM-SYRTE as 6.4-8.0 x 10^{-15}.
- SYRTE-FOM is the portable caesium fountain operated at the BNM-SYRTE. Six measurements were provided since October 2002 over periods between 5 and 30 days. Its type B relative standard uncertainty as stated by the BNM-SYRTE is 0.8-1.1 x 10^{-15}.
- SYRTE-FO2 in the double rubidium-caesium fountain operated at the BNM-SYRTE. Seven measurements were provided starting in November 2002 over periods of 5 to 35 days. The type B relative standard uncertainty of SYRTE-FO2 stated by the BNM-SYRTE is 0.5-0.8 x 10^{-15}.

The global treatment of individual measurements led to a relative departure of the duration of the TAI scale unit from the SI second on the geoid ranging since June 2001 from $+5.0 \times 10^{-15}$ to $+11.9 \times 10^{-15}$, with an uncertainty of 2.0×10^{-15}.

2. Time links

Since the 15th Meeting of the CCTF (2001) time transfer in TAI has benefited from the inclusion of different time transfer techniques. TAI relies at present on 53 international time links between time laboratories equipped with GPS single-channel single-frequency receivers, GPS multi-channel single/dual-frequency receivers, GPS multi-channel dual-system receivers, and TWSTFT stations.

The commercial availability of newly developed receivers has stimulated interest in extending the classical common-view technique for use of multi-channel dual-code dual-system (GPS and GLONASS) observations, with the aim of improving the accuracy of time transfer. Sixteen links in TAI are at present calculated using GPS multi-channel single-frequency receivers. In June 2003 GPS P3 data obtained from geodetic-type dual-frequency receivers have been incorporated in the calculation of TAI, three of this links are currently used in the computation of *Circular T* [4]. Nine TWSTFT are currently used for TAI.

For those multi-technique links (GPS C/A common-views, GPS P3, TWSTFT) comparisons are performed; one is used as official in TAI, whether the others are computed as back-up. Calibration campaigns of GPS receivers have been organized by the BIPM, the result being the differential calibration of about 50% of the GPS time receivers [5, 6, 7], and the totality of the geodetic-type receivers in TAI [4]. The TWSTFT links used for TAI are calibrated by GPS common-view.

2.1. Global Positioning System (GPS)

For the organisation of GPS satellite common views performed with single-channel receivers, the BIPM Time section issues, twice a year, GPS international common view schedules. This schedules are not necessary in the case of satellite tracking with GPS multi-channel receivers. The international network of GPS time links used by the BIPM is organized to follow a pattern of local stars within a continent. All GPS links are corrected by using precise (rapid) operational satellite ephemerides produced by the International GPS Service (IGS). Time links calculated with GPS single-frequency observations are corrected by using the ionospheric maps produced by the IGS analysis centre CODE (Centre for Orbit Determination in Europe).

The BIPM publishes an evaluation of the daily time differences [*UTC – GPS time*] in its monthly *Circular T*. These differences are obtained by smoothing GPS data, taken at the OP from a selection of satellites at high elevation. The standard deviations characteristic of daily GPS results of individual measurements is about 2ns.

An important part of our work is to check the differential delays between GPS receivers which operate on a regular basis in collaborating timing centres. Differential delays may be applied in the regular TAI computation if its value is found to be significant and consistent over different evaluations. Alternatively, the internal delay of a receiver may be changed by a laboratory. Although the differential calibration method is, in principle, perfectly suited to maintain consistency, absolute calibrations should provide an independent check of the consistency of the TAI links. It is also desirable to obtain new measurements of receiver delays absolutely calibrated in the past.

The commercial availability of newly developed receivers increased the number of multi-channel GPS links in TAI. Besides the improvement of TAI robustness, the introduction of this technique will allow to suppress the need of the common view schedules and facilitates the operation at the BIPM and in laboratories.

The IGS/BIPM Pilot Project was run between 1998 and the end of 2002 with the aim of studying the utilisation of GPS phase and code measurements to provide accurate time and frequency comparisons. As one of the requirements of this project, the BIPM successfully organized campaigns for the calibration of the Ashtech Z12-T receivers (or similar). The pilot experiment TAIP3 started in April 2002 to study time links computed with GPS P3 data obtained from geodetic-type dual frequency receivers [4]. As a result of this experiment, some GPS P3 links are now used in the calculation of TAI.

Calibration of GPS time receivers have been organized without interruption since 2001. The calibration trips covered central and western Europe, the Asia-Pacific region and North America. About 50% of the time GPS receivers in TAI have been differentially calibrated. Continuing with this activity, we are ready to start a new trip of a receiver to south, central and north America.

2.2. Global Navigation Satellite System (GLONASS)

GLONASS international common-view schedules are also issued twice a year by the time section. GLONASS data taken by time laboratories are collected and studied at the BIPM, but not used in the current TAI computation.

The BIPM publishes an evaluation of the daily time differences [*UTC – GLONASS time*] in its monthly *Circular T*. These differences are obtained by smoothing GLONASS data, taken at the NMi-VSL, from a selection of satellites at high elevation. The standard deviations characteristic of daily results of individual measurements is about 30 ns. The combined standard uncertainty of the daily GLONASS values is, however, not better than several hundred nanoseconds, because no absolutely calibrated GLONASS time receivers are available.

The BIPM is currently equipped with four GPS/GLONASS or GLONASS-only time receivers from the 3S Navigation Company.

The staff of the BIPM Time section is actively involved in the work of the CCTF working group on GNSS time transfer standards.

The 3S Navigation receivers in operation at the BIPM have the capability to provide GLONASS phase measurements and software has been installed to allow automatic data retrieval. One of these receivers is used to collect data for the International GLONASS Service Pilot Project (IGLOS-PP).

2.3. Two-way time transfer

The TWSTFT technique is currently operational in six European, three North American and five Pacific Rim time laboratories. Eleven of them participate in the time links for TAI.

The introduction of TWSTFT into TAI has brought about an important change; TAI is no longer reliant on a single technique, because TWSTFT links are backed up by GPS links and vice versa. This situation increases the robustness of the construction of TAI.

The TWSTFT technique applied to clock comparison in TAI is reaching in this last months its potential capabilities thanks to the scheduling of daily and sub-daily observations for Europe and North America.

The BIPM Time Section publishes regular BIPM TWSTFT Reports in which TWSTFT links are computed and compared with the corresponding GPS links. The inclusion of GPS P3 links in TAI will provoke the evolution of these reports, which will become BIPM time transfer techniques reports in the future.

3. Other research studies

3.1. Space-time references

The Executive Committee of the IAU brought into existence in January 2001 the IAU Working Group on relativity for celestial mechanics, astrometry and metrology (RCMAM), assuring the continuity of the collaboration between the BIPM and the IAU.

Since 1 January 2001 the BIPM and the U. S. Naval Observatory (USNO) have been working together to provide the Conventions Product Centre (CPC) of the IERS. The task of the CPC is to maintain and update the IERS Conventions and associated software in electronic form, to study the consistency of the procedures used by the IERS analysis centres with the adopted conventions, and to analyse the impact of any inconsistencies on the IERS products. The final edition of the IERS Conventions (2003) is available, in electronic format [8], it has been submitted to the IERS Central Bureau for publication in November 2003. The BIPM has provided a visiting scientist position for one year starting on September 2003 to study the consistency of the IERS Products.

3.2. Pulsars

Because millisecond pulsars have the potential to sense the very long-term stability of atomic time, collaboration is maintained with radio-astronomy groups observing pulsars and analysing pulsar data. The Time section provides these groups its post-processed realization of Terrestrial Time TT(BIPM). A new realization, TT(BIPM2003) has been computed with data since 1993. A small collaboration is continuing with the Observatoire Midi-Pyrénées (OMP) in Toulouse to complete the processing of a small programme of survey observations carried out in past years[26].

3.3. Atom interferometry

A member of the time section is on a one-year leave on a CNES (Centre National des Etudes Spatiales) grant to study possible applications of atomic interferometry using laser cooled atoms in fundamental physics and metrology. The work has been carried out at the BNM-SYRTE.

3.4. Clocks in space

Scientists of the Time section are involved, in collaboration with the BNM-SYRTE, in the evaluation of the possible use for international time keeping, of highly stable and accurate space clocks, in particular those that will be operated within the ACES (Atomic Clock Ensemble in Space) experiment on board the international space station in 2005. With relative uncertainties expected in the low 10^{-16} region, such developments will be extremely important for the improvement of TAI accuracy and for experiments in fundamental physics.

4. References

1. BIPM, *Circular T 192*, 13 January 2003.
2. BIPM, *Circular T 184*, 14 May 2003.
3. Azoubib J., A revised way of fixing an upper limit to clock weights in TAI computation, *Proc. 32st PTTI*, 2001, 195.
4. Petit G., Jiang Z., Report of the TAI P3 experiment, GP/TL.130, BIPM Time section, 24 March 2004.

5. Lewandowski W., Tisserand L., Determination of the differential time corrections for GPS time equipment located at the OP, NPL, IEN, PTB and VSL, Rapport BIPM-2004/05.
6. Lewandowski W., Tisserand L., Determination of the differential time corrections for GPS time equipment located at the OP, PTB, AOS, KRIS, CRL, NIST, USNO and APL, Rapport BIPM-2004/06.
7. Lewandowski W., Tisserand L., Determination of the differential time corrections for GPS time equipment located at the OP, and CH, Rapport BIPM-2004/07.
8. McCarthy D., Petit G., IERS Conventions (2003), in electronic format at http://maia.usno.navy.mil/conv2003.html.