CCTF 2006

Report of the BIPM Time section[*] for the period 2004-2006

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TAI generation at the BIPM follows the workplan presented at the 16th Meeting of the CCTF (2004), as well as the adopted recommendations. Current clock comparisons for the generation of TAI are based on GPS satellite common-views using single and dual frequency receivers and TWSTFT links. The software that produces *Circular T* allows link comparison, whose results are made available through the internet. Calibration campaigns of GPS equipment have been organised without interruption during the period of this report. In conformity with recommendation CCTF3(2004), the strategy for correcting the frequency of TAI has been modified.

To allow a better use of primary frequency standard reports in TAI, the staff of the section has contributed to the organisation of a Working Group on Primary Frequency Standards, to accomplish the requests of recommendation CCTF2(2004).

Uncertainties of the differences [UTC-$UTC(k)$] are calculated routinely with an algorithm based on the method developed through the cooperation between the BIPM, the USNO and the INRIM. Consequently, the key comparison in time CCTF-K2001.UTC, defined by the CCTF(2001) started in January 2005; monthly updates are published after the calculation of *Circular T*.

With the aim of putting to the disposal of the participating laboratories and other users complete data used in the generation of TAI and some intermediate results, more information is posted on the internet, such as link comparison files and reports of primary frequency standards used for improving the accuracy of TAI.

Activities of some section members continued on the establishment of space-time references, mainly in cooperation with the IERS.

As the result of the decision of the International Committee for Weights and Measures (CIPM) of closing the length section, its staff and a part of its activities have been transferred to the Time section, which has became the Time, frequency and gravimetry section since 1 January 2006.

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 2004 and 2005 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*. 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.

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[*] Since 1 January 2006, Time, Frequency and Gravimetry Section.

1.1. EAL stability

Some 85 % of the clocks used in the calculation of time scales are either commercial cæsium clocks of the HP/Agilent 5071A type or active, auto-tuned hydrogen masers. To improve the stability of EAL, a weighting procedure is applied to clocks where the maximum relative weight each month depends on the number of participating clocks. About 14 % of the participating clocks have been at the maximum weight, on average, during 2005. This procedure generates a time scale which relies upon the best clocks.

Since 2003, it is estimated that the stability of EAL, expressed in terms of an Allan deviation, has been about 0.4×10^{-15} for averaging times of one month. Slowly varying long-term drifts limit the stability to around 2×10^{-15} for averaging times of six months.

1.2. TAI accuracy

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

Since April 2004 , individual measurements of the TAI frequency have been provided by ten primary frequency standards, including six Cs fountains (IT-CSF1, LNE-SYRTE FO2, NIST-F1, NPL-CSF1, NMIJ-F1 and PTB-CSF1):

- IT-CSF1 is the caesium fountain operated at the INRIM (formerly IEN), Torino (Italy). Nine measurement reports over 10-40 days have been produced in the period. Its type B relative standard uncertainty as stated by the INRIM is $0.6 - 1.2 \times 10^{-15}$.
- NICT-O1, which is the optically pumped primary frequency standard developed and evaluated at the NIST for the NICT (formerly CRL), Tokyo (Japan). In the period covered by this report, it provided four measurements with periods between 10 and 30 days. The type B relative standard uncertainty of NICT-O1 is stated by the NICT as 5.5×10^{-15}.
- NIST-F1, which is the caesium fountain developed at the NIST, Boulder (USA). In the period covered by this report, it provided six measurements with periods between 30 and 60 days. The type B relative standard uncertainty is stated by the NIST as 0.4×10^{-15}.
- NPL-CSF1 is the caesium fountain developed at the NPL. The first report, received in February 2005, contained measurements since February 2004. Since then, four reports have been produced over periods of 30-40 days. The type B relative standard uncertainty of NPL-CSF1 is stated by the NPL as 1.0×10^{-15}.
- NMIJ-F1 is the caesium fountain developed and operated at NMIJ/AIST (Japan). Three measurements have been reported since September 2005 over periods of 10 days. The type B relative standard uncertainty of NMIJ-F1 is stated by the NMIJ as $3.8 - 4.2 \times 10^{-15}$.
- PTB-CS1 and PTB-CS2 are classical primary frequency standards operating continuously as clocks at the PTB, Braunschweig (Germany). The type B relative

standard uncertainty is stated as 8.0 × 10^{-15} for PTB-CS1 and as 12.0 × 10^{-15} for PTB-CS2 during the period of this report.

- PTB-CSF1 is the caesium fountain developed at the PTB. One report covering 10 days of measurement has been provided in the period. The type B relative standard uncertainty of PTB-CSF1 is stated by the PTB as 2.6 × 10^{-15}.
- SYRTE-JPO is the optically pumped caesium standard operated at the LNE-SYRTE, Paris (France). It provided twenty measurements in the period of this report, with periods between 10-30 days. The type B relative standard uncertainty of this primary standard is stated by the LNE-SYRTE as 6.4 × 10^{-15}.
- SYRTE-FO2 in the double rubidium-caesium fountain operated at the LNE-SYRTE. Eight measurements were provided over periods of 15 to 25 days. The type B relative standard uncertainty of SYRTE-FO2 stated by the LNE-SYRTE is 0.6-0.8 × 10^{-15}.

The global treatment at the BIPM of individual measurements led to a relative departure *d* of the duration of the TAI scale unit from the SI second on the geoid ranging since April 2004 from +7.2× 10^{-15} to +1.7 × 10^{-15}, with an uncertainty of 1.8 × 10^{-15}.

Following the recommendation CCTF3(2004), the procedure for the frequency steering of TAI has been revised. Starting in July 2004, a monthly steering correction of a maximum 0.7 ×10^{-15} is applied as deemed necessary. The values of *d* plotted in fig.2 for the period of this report show that the procedure makes the frequency steering more efficient.

Since October 2005, we have used in this computation of *d* a revised estimation of the stability of the free atomic time scale EAL.

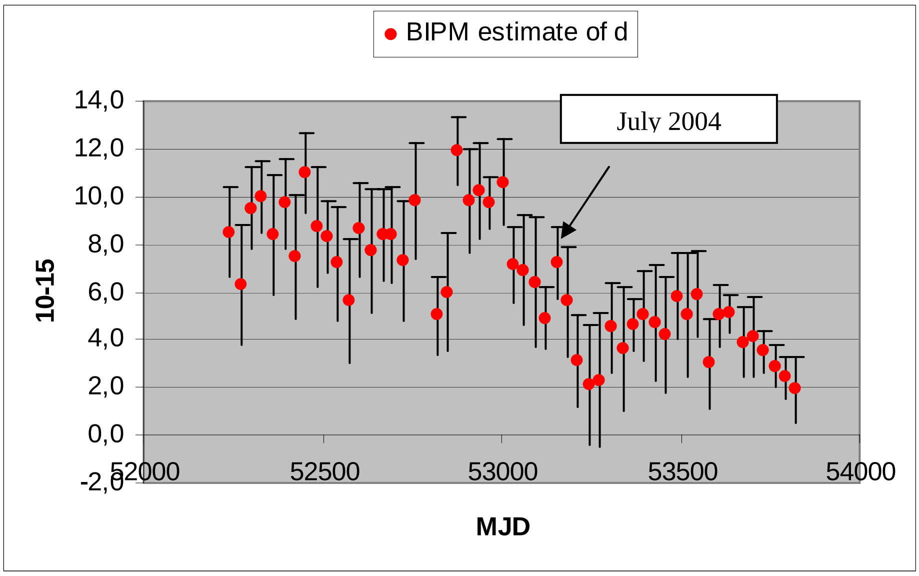

Fig 1. Relative departure *d* of the duration of the TAI scale unit from the SI second on the geoid in the period April 2004-July 2006.

2. Time links

TAI relies at present on 57 time links between time laboratories equipped with GPS receivers and/or operating TWSTFT stations.

Clock comparisons are made by three independent techniques: satellite common-view based on C/A code measurements from GPS single-frequency receivers; satellite common-view obtained with dual-frequency, multi-channel GPS geodetic type receivers (P3); and two-way satellite time and frequency transfer through geostationary telecommunications satellites (TWSTFT). Significant improvement is being made with the growing number of time links with P3 receivers (twelve official links in July 2006, and several more computed as additional links), and with the increase of the frequency of TWSTFT observations (up to twelve per day for links in Europe and with North America). The classical GPS single-channel single-frequency receivers that today represent only 25% of the time transfer equipment are being replaced to allow multi-channel, single or dual frequency observations. As a result, there has been an improvement in the accuracy for time transfer, and the whole system of time links becomes more reliable.

Data from geodetic-type receivers are collected for TAI computation, using procedures and software developed in collaboration with the Observatoire Royal de Belgique (ORB).

For those multi-technique links (GPS C/A common-views, GPS P3, TWSTFT) comparisons are performed; while one is used as official in TAI, the others are computed as back-up.

Testing continued on other time and frequency comparison methods and techniques. Exhaustive analysis proved that further improvement should be possible, in particular, for clock comparison over long distances by calculating GPS all-in-view solutions instead of the current GPS satellite common-views. The CCTF Working Group on TAI has established two study groups to analyze the benefits of this change. Results of link comparisons by the different techniques and methods are made available on the BIPM website.

GPS and GLONASS time and frequency transfer may also be carried out using dual-frequency, carrier-phase measurements in addition to code measurements. This technique, already in common use in the geodetic community, can be adapted to the needs of time and frequency transfer. Studies are conducted jointly with the IGS working group on clock products.

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. These 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 GNSS 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.

Calibration campaigns of GPS equipment have been organized by the BIPM, the result being the differential calibration of about 50% of the GPS time receivers and the totality of the geodetic-type receivers in TAI.

The method developed to perform the absolute calibration of the Ashtech Z12-T hardware delays allows us to use this receiver for differential calibrations of similar receivers worldwide. Calibration trips began in January 2001 and continued without interruption. In the term of the last year, 12 such calibrations have taken place concerning receivers in seven laboratories. For 2006, calibration results are also issued for the new type of receiver Septentrio PolaRx2, and other types of receivers are being investigated in collaboration with laboratories equipped with such receivers. The BIPM's second Ashtech Z12-T serves as a local reference with which the travelling Ashtech Z12-T is compared between calibration trips.

Geodetic-type receivers also provide raw phase measurements which may be used, along with the code measurements, to compute time links. This is routinely done by the IGS for some time laboratories which are also part of the IGS network. In addition, new Precise Point Positioning (PPP) software, obtained in collaboration with geodetic institutes, allows the BIPM to compute for studies, its own solutions for such time links. Comparisons between PPP, IGS, P3 and two-way links lead to insightful results on the stability of each technique.

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 *Circular T*. These differences are obtained by smoothing GLONASS data, which had been taken at the NMi-VSL (The Netherlands) until the end of 2004, from a selection of satellites at high elevation. Starting in January 2005, GLONASS data for the calculation of [*UTC – GLONASS time*] is provided AOS (Poland). The standard deviations characteristic of daily results of individual measurements is about 15 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.

Work has been undertaken, in cooperation with AOS, to implement calibration of GPS/GLONASS receivers, as a step for the future introduction of GLONASS data in the generation of TAI. This work is being developed in the scope of a doctoral thesis at AOS under the supervision of W. Lewandowski.

2.3. Two-way time transfer

The introduction of TWSTFT increases the robustness of the construction of TAI. TAI is no longer reliant on GPS only, because TWSTFT links are backed up by GPS links and vice versa.

The TWSTFT technique is currently operational in eight European, two North American and seven Asia-Pacific time laboratories. Seven TWSTFT links are routinely used in the computation of TAI; some others are in preparation for their introduction or re-introduction into TAI; this is the case of laboratories in the Asia-Pacific region that have undertaken modifications to improve their TW equipment. The TWSTFT technique applied to clock comparison in TAI is reaching its potential capabilities with the sessions scheduled every two hours for links within Europe and between Europe and North America.

The BIPM stopped the publication of TWSTFT reports; instead, files with results of time links and link comparison using GPS single-frequency, dual-frequency and TW observations are published monthly on the ftp server (tai.bipm.org/TimeLink/LkC).

3. Uncertainties of [*UTC* – *UTC* (*k*)]

Since January 2005, the values of the uncertainties of [*UTC* – *UTC* (*k*)] have been published in the BIPM *Circular T*. This has been recommended by the CCTF, and is required by the CIPM MRA for publication of the key comparison in time in the KCDB, as defined by the CIPM(2001). The BIPM Time section addressed this issue in cooperation with the INRIM and the USNO. In a first approach, an analytical solution was derived from the law of the propagation of uncertainty, taking into account that leap seconds and deterministic frequency steering of EAL do not affect these uncertainties. The analytical results were verified through Monte Carlo simulations using the software that generates UTC, and good agreement was found, giving confidence in the analytical estimation. Further refinement allowed the inclusion of: all available calibration information, more details for the correlation between the links, methods for optimizing the link structure, given uncertainty information, non-Gaussian behaviour, and different correlation properties of uncertainties due to calibration or due to random noise.

4. Key comparison CCTF-K2001.UTC

The key comparison in time CCTF-K2001.UTC was published for the first time in January 2005. Monthly updates are performed at the KCDB after the publication of *Circular T*. Timing centres in laboratories who are participants to the CIPM MRA, from member states and associates to the CGPM, take part in the key comparison.

5. Other research studies

5.1. Space-time references

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. A web and ftp site for the IERS Conventions has been established at the BIPM (http://tai.bipm.org/iers/) and a user discussion forum has been set-up (http://tai.bipm.org/iers/forum/) for users to offer comments related to the future updates of the IERS Conventions. First updates of the Conventions (2003) have been posted on the web site http://tai.bipm.org/iers/convupdt. These updates consider several new models for effects that affect the positions of Earth's points at the mm level, which is now significant. These modifications are studied with the help of the Advisory Board for the IERS Conventions updates, including representatives of all groups involved in the IERS.

Activities related to the realization of reference frames for astronomy and geodesy are developed in cooperation with the IERS.

5.2. Pulsars

Collaboration is maintained with radio-astronomy groups observing pulsars and analyzing pulsar data provided that it is of interest for us; for example, to study the potential capability of millisecond pulsars as a means of sensing the very long-term stability of atomic time. The Time section provides these groups with its post-processed realization of Terrestrial Time; TT(BIPM04) and TT(BIPM05) have been generated to this purpose. The collaboration continues with the Observatoire Midi-Pyrénées (OMP), Toulouse, on a programme of survey observations.

5.3. Atom interferometry

A member of the time section was on secondment at the LNE-SYRTE until August 2005 to study possible applications of atomic interferometry using laser cooled atoms in fundamental physics and metrology. A novel test of Lorentz Invariance using spin polarized atoms in a Cs atomic fountain at the LNE-SYRTE was carried out and published. It tests for the dependence of the transition frequency of the atoms on the orientation of their spin with respect to a putative preferred frame. The results improve previous limits on the corresponding parameters of a comprehensive test theory by 11 and 13 orders of magnitude.

Optical lattice clocks are being constructed and operated at several laboratories. They use a large number of neutral atoms (Sr, Yb, Hg, Ca) trapped in an optical potential, and are the most promising candidates for reaching 10^{-17} to 10^{-18} accuracies as they combine the advantages of single trapped ion, and freely falling neutral atom standards. Methods to circumvent limitations of such clocks imposed by the intensity of the trapping laser have been studied. It has been demostrated that gravity can be effectively used to reduce the intensity requirement by more than an order of magnitude. The proposed scheme is being implemented in the Sr standard of LNE-SYRTE.

5.4. Clocks in space

Scientists of the Time section are involved, in collaboration with the LNE-SYRTE, in the evaluation of the possible use for international time keeping, of highly stable and accurate space clocks. Within the scope of this cooperation, P. Wolf is supervising a doctoral student at OP, on the development, modelling and data analysis of the microwave link (MWL) time transfer system of the future ACES (Atomic Clock Ensemble in Space) mission. The MWL will allow the comparison of distant clocks at an uncertainty of 1×10^{-16} after an integration time of one day, an order of magnitude below the best performance of present systems. This is an essential step towards the comparison of future clocks at or below that uncertainty.

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