Bureau International des Poids et Mesures (BIPM) – Time Department–

http://www.bipm.org/metrology/time-frequency/

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Overview

The international time scales TAI and UTC have been regularly computed during the period of the report. Results have been published in monthly *BIPM Circular T*, which represents the key comparison CCTF-K001.UTC. The frequency stability of TAI, expressed in terms of an Allan deviation, is estimated to 3×10^{-16} for averaging times of one month.

Sixteen primary frequency standards contributed during the period 2011-2015 to improve the accuracy of TAI, fourteen providing regularly measurement reports since 2012. They all are caesium fountains developed and maintained in metrology institutes in China, France, Germany, India, Italy, Japan, the Russian Federation, the United Kingdom and the United States of America. The scale unit of TAI has been estimated to match the SI second to about 2 to 9 parts in 10^{16} within the period.

Routine clock comparison for TAI/UTC is undertaken using different techniques and methods of time transfer. All laboratories contributing to the calculation of UTC at the BIPM are equipped for Global Navigation Satellite Systems (GNSS) signals reception. GPS C/A observations from time and geodetic-type receivers are used with different methods, depending on the characteristics of the receivers. Dual-frequency receivers allow performing iono-free solutions. Also observations of GLONASS are used for the computation of TAI/UTC. Thanks to this evolution, the statistical uncertainty of time comparisons is at the sub-nanosecond level for the best GNSS time links. Some laboratories operate two-way satellite time and frequency transfer (TWSTFT) stations allowing time comparisons independent from GNSS through geostationary communication satellites. Combination of time links (TWSTFT/GPS PPP (Precise Point Positioning) and GPS/GLONASS) has been routinely used in the computation of TAI since 2011. The uncertainty of time comparison by GNSS has been limited by the calibration of the equipment to 5 ns; in 2014 the BIPM established a new calibration scheme, supported by some regional calibrations that will allow reducing the uncertainty of GNSS calibrations by a factor 2 at least. The calibration of TWSTFT links can be maintained at the nanosecond order.

Extensive comparisons of the different techniques and methods for clock comparisons are computed regularly and published on the ftp server of the section, as well as complete information on data and results (ftp://tai.bipm.org/TimeLink/).

Because TAI is computed on a monthly basis and has operational constraints, it does not provide an optimal realization of Terrestrial Time (TT), the time coordinate of the geocentric reference system. The BIPM therefore computes an additional realization TT(BIPM) in post-processing, which is based on a weighted average of the evaluation of the TAI frequency by the primary frequency standards. The last updated computation of TT(BIPM), named TT(BIPM14) has an estimated accuracy of order 3×10^{-16}. The monthly extension of TT(BIPM) can be directly derived from TAI (ftp://tai.bipm.org/TFG/TT(BIPM)/TTBIPM.14).

The algorithm used for the calculation of TAI has been significantly improved during the period covered by this report. The model for clock frequency prediction was revised, and a new model is in use since August 2011. As a consequence of this modification, the drift observed in the atomic free scale (EAL) with respect to the primary standards has completely disappeared. A new algorithm for the computation of clock weights has been developed and implemented in the calculation of TAI since January 2014. It is based on the principle that a good clock is a predictable clock, instead of using stability criteria as before. This method leads to a better distribution of weights among the different types of clocks, in particular gives a stronger role of the hydrogen-masers. The consequence is an improvement of the frequency stability of EAL at short- and long-term.

Radiations other than the caesium 133, most in the optical wavelengths, have been recommended by the International Committee for Weights and Measures (CIPM) as secondary representations of the second. These frequency standards are at least one order of magnitude more accurate than the caesium. Their use for time metrology is still limited by the state of the art of frequency transfer. Experiments using optical fibres on baselines up to 1000 km confirmed the capabilities of the method. It remains, however, limited to continental time and frequency transfer. New techniques are under study for extending the transfer onto intercontinental scale. This is part of the collective effort of the time metrology community aiming at a possible redefinition of the SI second.

Research work is also dedicated to space-time reference systems. The BIPM provides, in partnership with the US Naval Observatory, the Conventions Product Centre of the International Earth Rotation and Reference Systems Service (IERS). IERS activities in cooperation with the Paris Observatory on the realization of reference frames for astrogeodynamics, contribute to the maintenance of the international celestial reference frame in the scope of the IAU activities.

In January 2012 the Time Department started a pilot experiment for the implementation of a rapid UTC (*UTCr*). The aim of this project was to study the feasibility of providing some link to UTC on a more frequent basis than that of monthly *Circular T*. This experiment proved the capacities at the BIPM and at the contributing laboratories for assuring this rapid provision and after approval by the Consultative Committee for Time and Frequency (CCTF), *UTCr* will become a routine weekly publication. About 50% of the laboratories in UTC participate to *UTCr*, representing more than 60% of the clock weight. *UTCr* has been published without interruption since 1 July 2013.

Results for UTC and *UTCr* are available at http://www.bipm.org/en/bipm-services/timescales/time-ftp/publication.html.

A considerable amount of effort has been put in contributing to the discussions on a redefinition of UTC without leap seconds at the International Telecommunication Union (ITU). In particular, the BIPM organized jointly with the ITU a workshop on the future of the international time scale on 19-20 September 2013.

The total number of publications of the Time Department staff during the period is around 75.

Activities

Coordinated Universal Time (UTC), rapid UTC (UTCr) and TT(BIPM)

The reference time scale Coordinated Universal Time (UTC), is computed from data reported regularly to the BIPM by about 75 timing centres that maintain a local UTC; monthly results are published in *Circular T*. The rapid solution UTCr is computed for about 40 laboratories contributing also to UTC, and published every Wednesday. The realization of terrestrial time TT(BIPMxy) is computed for the year 20xy, with monthly extrapolations that can be derived from TAI. The *BIPM Annual Report on Time Activities for 2011, 2012, 2013 and 2014* have been published in electronic version and are available on the BIPM website at http://www.bipm.org/en/bipm/tai/annual-report.html.

Algorithms

The algorithm used for the calculation of time scales is an iterative process that starts by producing a free atomic scale (*Échelle atomique libre* or EAL) from which TAI and UTC are derived.

EAL is optimized in frequency stability, but nothing is done for matching its unit interval to the second of the International System of Units (SI second). In a second step, the frequency of EAL is compared to that of the primary frequency standards, and the frequency accuracy is improved by applying whenever necessary a correction to the frequency of EAL. The resulting scale is TAI. Finally, UTC is obtained by adding an integral number of seconds (leap seconds). Research into time scale algorithms is conducted in the Time Department with the aim of improving the long-term stability of EAL and the accuracy of TAI/UTC.

Since August 2011 the clock frequency prediction model in the algorithm of calculation of TAI has been improved. The new algorithm uses the same quadratic model for predicting the frequency of all clocks (caesium and hydrogen-maser clocks). This model takes into account the drift of the hydrogen-masers frequency and the effects coming from the ageing of the caesium clocks. In consequence, the drift that had been observed in the frequency of EAL with respect to the primary frequency standards, amounting -1.3×10^{-17}/day has been completely removed.

The old frequency prediction model (linear) did not take into account the drift of the hydrogen-masers frequency, and consequently these clocks were not properly used. After the change in the prediction model, it was clearly necessary to make a revision of the clock weighting procedure so that all clocks could contribute in function of their quality. A new weighting algorithm has been implemented in the calculation of TAI since January 2014, based on the criteria that a good clock is a predictable one, instead of using the frequency stability as indicator of its quality.

Stability of TAI

About 450 clocks contribute as in April 2015 to the construction of TAI/UTC at the BIPM. Some 87 % of these clocks are either commercial caesium clocks 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. Until December 2013, the weighting procedure was based on clock stability and assigned the maximum weight to about 14 % of the participating clocks on average, per year; this process made the caesium clocks predominant. When the criteria for clock weighting is based on the predictability of the clock frequency, as from January 2014, the weight distribution is different; in average, over one year, about 10% of the participating clocks reach the maximum weight, including 38% of the hydrogen-masers, and less than 1% of caesium clocks. This procedure generates a time scale which relies mostly upon the best hydrogen-maser clocks.

The stability of EAL, expressed in terms of an Allan deviation, has been about 3×10^{-16} for averaging times of one month. Studies indicate that the changes introduced in the algorithm will improve both, the short- and long-term stability of TAI/UTC.

Accuracy of TAI

To characterize the accuracy of TAI, estimates are made of the relative departure, and its uncertainty, of the duration of the TAI scale interval from the SI second, as produced on the rotating geoid, by primary and secondary frequency standards. In the period of this report individual measurements of the TAI frequency have been provided by sixteen caesium and one rubidium fountains, this last one providing a secondary representation of the second. Reports on the operation of the primary and secondary frequency standards are regularly published in the *BIPM Annual Report on Time Activities* and on the BIPM website.

Monthly steering corrections can be applied if necessary to put the frequency of TAI as close as possible to that of the primary/secondary frequency standards. Corrections of maximum 0.5×10^{-15} were applied until October 2012. Until then, the global treatment of individual measurements has led to a relative departure of the duration of the TAI scale unit from the SI second on the geoid ranging from $+5.9 \times 10^{-15}$ in July 2011 to -0.99×10^{-15} in June 2014 with a standard uncertainty of less than 0.37×10^{-15}. As a consequence of the implementation of the quadratic frequency prediction model no steering corrections have been applied since November 2012.

BIPM realization of terrestrial time TT(BIPM)

Because TAI is computed in "real-time" and has operational constraints, it does not provide an optimal realization of Terrestrial Time (TT), the time coordinate of the geocentric reference system. The BIPM therefore computes an additional realization TT(BIPM) in post-processing, which is based on a weighted average of the evaluation of the TAI frequency by the primary frequency standards, and since July also the Rb secondary standard. The last updated computation of TT(BIPM), named TT(BIPM14), valid until December 2014, has an estimated accuracy of order 3×10^{-16}. Extrapolations over 2015 can be obtained from TAI from the equation
TT(BIPM14) = TAI + 32.184 s + 27697.0 ns.

Primary frequency standards and secondary representations of the second

Members of the BIPM Time Department are actively participating in the work of the CCL/CCTF Frequency Standards Working Group created jointly at the Consultative Committee for Length (CCL) and the CCTF, seeking to encourage knowledge sharing between laboratories, the creation of better documentation, comparisons, and the use of highly accurate primary frequency standards (Cs fountains) for TAI. A mission of this working group it to maintain a list of frequencies recommended for applications including the practical realization of the metre and secondary representations of the second. Updates of this list are proposed to the CCL and CCTF, and are finally recommended by the International Committee for Weights and Measures (CIPM).

Other microwave and optical atomic transitions have been approved and are recommended by the CIPM as secondary representations of the second. Frequency values and uncertainties for transitions in Rb, and various atom and single ion species have been included in the list of recommended frequencies as secondary representations of the second at its last update in September 2012. The list is available at http://www.bipm.org/en/publications/mises-en-pratique/standard-frequencies.html.

BIPM staff participates in the rapidly evolving field of optical frequency standards, addressing, for example, the issue of their comparison at the 10^{-17} uncertainty level or below.

Reports of frequency measurements of the Rb transition at the French national metrology institute are regularly submitted to the Time Department. Based on these reports, results of the comparison of the secondary standard with TAI are published in *Circular T* since the beginning of 2012. Starting in July 2013 Rb measurements have been officially used for the accuracy of TAI, and included in the computation of TT(BIPM13) and TT(BIPM14).

Clock comparison for TAI

TAI/UTC rely on about 75 participating time laboratories equipped with GNSS receivers and/or operating TWSTFT stations.

The GPS all-in-view method has currently been used taking advantage of the increasing quality of the International GNSS Service (IGS) products (clocks and IGS time). Most clock comparison links are based on GPS satellites observations. Data from multi-channel dual-frequency GPS geodetic-type receivers are regularly used in the calculation of time links. Single-frequency GPS data are corrected using the ionospheric maps produced by the Centre for Orbit Determination in Europe (CODE); all GPS data are corrected using precise satellite ephemerides and clocks produced by the International GNSS Service (IGS).

GPS links are computed using the method known as “GPS all in view”, with a non-redundant network of time links that uses a unique pivot laboratory for all the GPS links. Since September 2009, links equipped with geodetic-type receivers are computed with the “Precise Point Positioning” method GPS PPP.

Clock comparisons using GLONASS C/A (L1C frequency) satellite observations with multi-channel receivers have been introduced since October 2009. These links are computed using the “common-view” method; data are corrected using the IAC ephemerides SP3 files and the CODE ionospheric maps.

Combination of individual TWSTFT and GPS PPP links and of individual GPS and GLONASS links were introduced in January 2011 and are currently used in the calculation of TAI.

Results of time links and link comparison using GNSS and TW observations are published monthly on the ftp server of the Time Department (ftp://tai.bipm.org/TimeLink/).

Characterization of delays of time transfer equipment

The BIPM continuously organizes and runs campaigns for measuring the relative delays of GNSS (GPS and GLONASS) time equipment in laboratories which contribute to TAI. The BIPM supports the TWSTFT calibration trips organized by the contributing laboratories in the frame of the relevant CCTF Working Group. Collaboration with the regional metrology organizations has been established in 2014 for maintaining the GNSS calibrations up-to-date.

Advanced time and frequency transfer

In the frame of cooperation with the French space agency (CNES), frequency transfer with GPS has been achieved at the level of 1×10^{-16} with the integer ambiguities PPP solution (IPPP).

Another innovative activity of the BIPM in this field is related to the establishment of optical fibre links between certain laboratories which maintain local representations of UTC. A successful experiment was conducted using the BIPM GPS equipment in parallel with the optical fibre link regularly operated between two institutes that represent UTC in Poland. This experiment demonstrated excellent agreement (at the level of the GPS PPP uncertainty) between the GPS PPP link calculated with the BIPM equipment and the optical fibre link. The optical fibre link can be used to assess the calibration of a UTC link calculated with the current time transfer techniques as a result of the small (hundred picoseconds) and stable calibration uncertainty. This experiment enabled the validation of the new BIPM calibration system with u_B within 1 ns. It also allowed validation of the results of the newly developed IPPP processing technique. Several other fibre links between contributing laboratories are calculated on a regular basis and are anticipated to achieve a potential measurement uncertainty of about 100 ps in the future. In order to benefit from the quality of these links, the Time Department has initiated discussions with the laboratories that already implement time transfer via optical fibres with the aim of establishing standards for data transmission and to validate the compatibility of the different techniques.

Collaboration continues with the Observatoire Midi-Pyrénées (OMP), Toulouse (France), and other radio-astronomy groups observing pulsars and analyzing pulsar data to study the potential capability of using millisecond pulsars as a means of sensing the very long-term stability of atomic time. The Time Department provides these groups with its post-processed realization of Terrestrial Time TT(BIPM). The IAU Division A created in 2012 a working group on Pulsar-based timescales, to which staff of the Time Department contributes.

The BIPM shares with the US Naval Observatory the responsibility for providing the IERS Conventions Centre. Updates to the IERS Conventions (2010) are published since May 2011 at http://tai.bipm.org/iers/conv2010/conv2010.html. The text of the conventions, in IERS Technical Note N°36 is also available at (http://www.iers.org/nn_11216/IERS/EN/Publications/TechnicalNotes/tn36.html).

Activities related to the realization of reference frames for astronomy and geodesy are developing in cooperation with the IERS. In these domains, improvements in accuracy will enhance the need for a full relativistic treatment and it is essential to continue participating in international working groups on these matters; e.g. through the IAU Commission "Relativity in Fundamental Astronomy". Cooperation continues for the maintenance of the international celestial reference system. The IAU Division A established a working group for realizing the

3rd version of the international celestial reference frame, ICRF3. Staff of the Time Department contributes to this working group.

A change in the definition of UTC is under discussion at the ITU since year 2000, and the BIPM has permanently contributed as a Member of the ITU Radiocommunication Sector. Final decision on the adoption of a proposed recommendation of implementing a continuous time scale, namely stopping the insertion of leap seconds in UTC, will be taken at the World Radioconference in 2015. For complementing the effort of disseminating all relevant information, a workshop jointly organized by the ITU and the BIPM took place in Geneva in September 2013. Information on this event is provided at http://www.itu.int/ITU-BIPM_Workshop.

Activities in Frequency

Frequency comb, calibration and measurement service

The frequency comb activities are limited to the comb maintenance for BIPM internal applications. The combs are passively kept in running conditions and used when needs appear. The Department has provided calibration and measurement service for combs and reference lasers for internal needs only. This includes the periodic absolute frequency determination of our reference lasers, both at 633 nm and 532 nm, used for iodine cell quality testing lasers and for the calculable capacitor project at the BIPM. Support to the development of a watt balance is also provided with the construction of interferometers.

Gravimetry

Gravimetry for the BIPM watt balance project

At the International Comparison of Absolute Gravimeters in 2009, the very last one organized by the BIPM, the first measurements for determining the free-fall acceleration in the watt balance room were made with three absolute gravimeters participating to the comparison. The Consultative Committee for mass and related quantities (CCM) has required a total relative standard uncertainty of 2×10^{-8} (corresponding to 20 μGal) for the determination of the Planck constant *h* as a condition for the redefinition of the kilogram. Taking into account all effects that can be sources of uncertainty, the demonstrated uncertainty of the determination of the free-fall acceleration at the test mass centre is of 4.5 μGal. Studies made at the BIPM Time Department as a contribution to the watt balance project have been published.

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