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

http://www.bipm.org/en/scientific/tfg/

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Overview

The international time scales TAI and UTC have been regularly compute 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.

Eight primary frequency standards contributed during the period to improve the accuracy of TAI, all are caesium fountains developed and maintained in metrology institutes in France, Germany, Japan, the United Kingdom and the USA. The scale unit of TAI has been estimated to match the SI second to about 5×10^{-16}.

Routine clock comparison for TAI is undertaken using different techniques and methods of time transfer. All laboratories contributing to the calculation of UTC at the BIPM are equipped for GNSS 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. Thanks to this evolution, the statistical uncertainty of time comparisons is at the sub-nanosecond level for the best GNSS time links. Some laboratories are equipped of two-way satellite time and frequency transfer (TWSTFT) devices allowing time comparisons independent from GNSS through geostationary communication satellites. Combination of time links (TWSTFT/GPS PPP and GPS/GLONASS) is routinely used in the computation of TAI since 2011. The uncertainty of time comparison by GNSS is still limited by the hardware to 5 ns for the calibrated links whilst in the case of TWSTFT it is 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 (http://www.bipm.org/jsp/en/TimeFtp.jsp).

The section organizes and runs GNSS receiver round trips with the aim of characterizing the relative delays of time transfer equipment in contributing laboratories.

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. The procedure for establishing the clock weight is under revision.

Radiations other than the caesium 133, most in the optical wavelengths, have been recommended by the International Committee of 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.

Following the decision of the CIPM in October 2009, the BIPM stopped the activities in gravimetry, but the Consultative Committee for the Mass and Related Quantities (CCM) continues organizing the Working Group on Gravimetry (WGG), and thus cooperating with the IAG in providing support to the future International Comparisons of Absolute Gravimeters (ICAG). In the new scheme, the comparisons are organized in different regions, with a national metrology institute acting as the pilot laboratory.

The last campaign (ICAG 2009) at the BIPM gave the opportunity to make the first absolute measurements in the room prepared for the operation of the BIPM watt balance. Based on measurements, the value for g and its uncertainty have been evaluated.

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.

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). The BIPM Time Department is contributing to the preparation of a workshop on the future of the international time scale jointly organized by the ITU and the BIPM. The event will take place in Geneva, on 19-20 September 2013.

The total number of publications of the Time Department staff during the period is around 50.

Activities

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

The reference time scales, International Atomic Time (TAI) and Coordinated Universal Time (UTC), are computed from data reported regularly to the BIPM by the various timing centres that maintain a local UTC; monthly results are published in *Circular T*. The *BIPM Annual Report on Time Activities for 2011* and *for 2012* have been published in electronic version and are available on the BIPM website (http://www.bipm.org).

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 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. The studies on the weighting algorithm progressed. A new method has been developed based on the criteria that a good clock is a predictable one, instead of using the frequency stability as indicator of its quality. Tests on this new procedure are still on-going, and they prove that the procedure is efficient in increasing the weight of the hydrogen-masers in the clock ensemble. It is foreseen to implement the new procedure in the algorithm before the end of 2013.

Stability of TAI

About 420 clocks contribute as in April 2013 to the construction of TAI 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. About 14 % of the participating clocks have been at the maximum weight, on average, per year. This procedure generates a time scale which relies upon the best clocks.

The stability of EAL, expressed in terms of an Allan deviation, has been about 3×10^{-16} for averaging times of one month.

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 frequency standards. In the period of this report individual measurements of the TAI frequency have been provided by eight caesium fountains. Reports on the operation of the primary frequency standards are regularly published in the *BIPM Annual Report on Time Activities* and on the BIPM website.

A monthly steering correction of maximum 0.5×10^{-15} has been applied as deemed necessary to put the frequency of TAI as close as possible as that of the primary frequency standards until October 2012. As a consequence of the implementation of the quadratic frequency prediction model no steering corrections have been applied since November 2012. In the period of this report, 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 -0.7×10^{-15} in March 2013 with a standard uncertainty of less than 0.5×10^{-15}.

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. The last updated computation of TT(BIPM), named TT(BIPM12), valid until December 2012, has an estimated accuracy of order 3×10^{-16}. Extensions of TT(BIPM12) over 2013 are provided and are updated each month after the publication of *Circular T*.

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. The list containing 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. BIPM staff continues to participate 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 been 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. It is expected to use the Rb measurements in the current of 2013 for improving the accuracy of TAI.

Clock comparison for TAI

TAI relies at present on 72 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). Clock comparisons are possible with C/A code measurements from GPS/GLONASS single- frequency receivers (only 3% of the time links in TAI); with dual-frequency, multi-channel GPS geodetic type receivers (P3, 14%); with code and phase measurements (GPS PPP, 27%); and with two-way satellite time and frequency transfer through geostationary telecommunications satellites (TWSTFT, 18%). Single-frequency, multi-channel receivers still provide the majority of time links in TAI (30%).

Links calculated from a combination of individual techniques are regularly used in the computation of TAI and their number is increasing. At present, 7% of the links are from a combination of GPS and GLONASS observations, and 14% are obtained combining TWSTFT and GPS PPP.

All GNSS links are corrected for satellite positions using IGS and ESA post-processed, precise satellite ephemerides, and those links made with single-frequency receivers are corrected also for ionospheric delays using IGS maps.

Results of time links and link comparison using GNSS and TW observations are published monthly on the ftp server of the Time Department (*http://www.bipm.org/jsp/en/TimeFtp.jsp*).

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 is also taking part in the organization of TWSTFT calibration trips; these trips are supported with a GNSS receiver from our time laboratory. Collaboration of the regional metrology organizations is under implementation for supporting the campaigns.

In the frame of a PhD successfully concluded in 2011 in cooperation with the CNES, a facility for absolute calibration of GNSS equipment has been developed.

Other activities in the field of time and frequency

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 new 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. Technical documents for providing complete information to administrations member of the ITU are under preparation with the contribution of the BIPM. For complementing the effort of disseminating this information, a joint ITU/BIPM Workshop will take place in Geneva on 19-20 September 2013. Information on this event is provided at http://www.itu.int/ITU-R/index.asp?category=conferences&rlink=itu-bipm-workshop-13&lang=en.

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.

Iodine cells

The service for filling and testing iodine cells has been discontinued in 2009. The BIPM maintains a list of suppliers of this service that can be provided on request to the Department Director.

Gravimetry

The International Campaign of Absolute Gravimeters ICAG has been re-organized during the period of the present report.

Starting by ICAG 2013, the comparisons will be piloted by national metrology (and/or designated) institutes at the usual four-year frequency. The Working Group on Gravimetry (WGG) of the Consultative Committee for Mass and Related Quantities (CCM) keeps the responsibility for the general coordination of the campaigns.

ICAG 2013 will take place in Walferdange, under the auspices of the University of Luxembourg. The Federal Institute of Metrology (*METAS*, Switzerland) will act as the pilot laboratory.

Gravimetry for the BIPM watt balance project

At the ICAG 2009 at 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 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. These studies and results have been submitted for publication.

Staff of the Department

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Publications of the staff

Year 2011

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1. BIPM Annual Report on Time Activities for 2010, 2011, **5**

2. BIPM Annual Report on Time Activities for 2011, 2012, **6**

3. BIPM Annual Report on Time Activities for 2012, 2013, **7**

4. *BIPM Circular T* (monthly)

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