Bureau International des Poids et Mesures (BIPM) – Time Department[1] –

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

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Overview

The international time scales TAI and UTC have been regularly computed monthly 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.

Fourteen primary frequency standards contributed during the period to improve the accuracy of TAI, including ten caesium fountains developed and maintained in metrology institutes in France, Germany, Italy, 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. Since October 2009 a combination of code and phase measurements of geodetic-type receivers is used in the computation of TAI. Since the end of 2009 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. 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

Improvements to the algorithm for calculation of TAI and UTC contributed with the development of a new model for the clock frequency prediction. Initially thought for the hydrogen maser frequency prediction, we concluded that also the caesium clocks needed of a revision of the frequency prediction model. The new algorithm has been developed, based on a parabolic model for the clock prediction. With this new model, the drift observed in the atomic free scale (EAL) with respect to TAI disappears.

[1] The Time, Frequency and Gravimetry Section of the BIPM became the Time Department on 1 January 2011.

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, still unable to compare these standards at the level of their performances. Studies on the use of optical fibres show excellent results. The time community is engaged in a collective effort for solving this issue, since one of the interests is the possibility of redefining 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). A new version of the IERS Conventions (2010) has been published in the IERS Technical Note N°36, and is available on the internet (http://www.iers.org/nn_11216/IERS/EN/Publications/TechnicalNotes/tn36.html). 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 IAU and IVS activities.

The campaign of comparison of absolute gravimeters ICAG 2009 took place at the BIPM in October 2009, with the participation of 23 instruments. First measurements of the gravity on the site where the BIPM watt balance will be operated were made.

Following the decision of the CIPM in October 2009, the BIPM stop 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 ICAGs.

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

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 2007, 2008, 2009* and *for 2010* have been published. Starting by the report for 2009, this publication is only in electronic version, complemented by computer-readable files, and 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.

The effect of the linear prediction algorithm has been studied for different types of clocks in TAI. Until present the algorithm predicts the clock frequency with a linear model for the two types of industrial standards in TAI, caesium clocks and hydrogen masers. This model of prediction proved to be well adapted to the caesium clock behaviour not affected by ageing, and is not at all suitable for the hydrogen masers, whose frequency presents a short-term drift. A new mathematical expression for the prediction of the hydrogen maser frequency is proposed taking into account this drift. Also a mathematical expression has been developed to account for the effects (long-term) of the age of the caesium clocks. Tests have been performed applying a quadratic prediction to the clocks. The results indicate that non-modelling of the frequency drift of hydrogen masers could be responsible for 20% of the drift of EAL with respect to TAI observed in the past five years. Completed with the new modelling of the caesium clock frequency the drift of EAL disappears.

Stability of TAI

Some 87 % of the clocks used in the calculation of time scales 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 15 % 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. Slowly varying, long-term drifts limit the stability to around 2×10^{-15} for averaging times of six months.

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 fourteen primary frequency standards, including ten 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, a maximum, 0.7×10^{-15} is applied as deemed necessary to put the frequency of TAI as close as possible as that of the primary frequency standards. 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 $+2.6 \times 10^{-15}$ to $+6.9 \times 10^{-15}$, with a standard uncertainty of less than 1×10^{-15}.

To improve the performances of TAI, in term of accuracy, a study of the influence of different atomic clocks (caesium clocks, hydrogen masers, etc.) on the time scale algorithm has been conducted (see section "Algorithms").

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(BIPM10), valid until December 2010, has an estimated accuracy of order 3×10^{-16}. Starting with TT(BIPM09), an extrapolation for the current year of the latest realization TT(BIPMYY) is provided and is updated each month after the TAI computation.

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 Committees for Length and for Time and Frequency, seeking to encourage knowledge sharing between laboratories, the creation of better documentation, comparisons, and the use of high accuracy PFS (Cs fountains) for TAI.

Other microwave and optical atomic transitions are being proposed as secondary representations of the second by the CCL/CCTF Frequency Standards Working Group. The list containing frequency values and uncertainties for transitions in Rb, Hg^+, Yb^+, Sr^+ and Sr, recommended by the Consultative Committee for Time and Frequency (CCTF) has been updated in 2009. 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.

Clock comparison for TAI

TAI relies at present on 69 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; with dual-frequency, multi-channel GPS geodetic type receivers (P3); with code and phase measurements (GPS PPP); and with two-way satellite time and frequency transfer through geostationary telecommunications satellites (TWSTFT). Most of the old GPS single-channel single-frequency receivers had been replaced by either multi-channel single- or dual-frequency receivers. Ten TWSTFT links are officially used for the computation of TAI, representing 15% of the time links

Results of link comparisons by the different techniques and methods are made available on the BIPM website (http://www.bipm.org/jsp/en/TimeFtp.jsp). Testing continues on other time and frequency comparison methods and techniques.

All GNSS links are corrected for satellite positions using IGS (International GNSS Service) and ESA post-processed, precise satellite ephemeredes, and those links made with single-frequency receivers are corrected for ionospheric delays using IGS maps.

The TWSTFT technique is currently operational in twelve European, two North American and seven Asia-Pacific time laboratories. Ten TWSTFT links are routinely used in the computation 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 (*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 GPS receiver from our time laboratory.

Work on absolute calibration of GNSS receivers has been started by a PhD student trough a collaboration co-financed with the French space agency CNES, and also involving the French laboratory for time metrology LNE-SYRTE at the Paris Observatory. This work is close to conclusion, with excellent results.

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 BIPM shares with the US Naval Observatory the responsibility for providing the IERS Conventions Centre. The web and ftp site for the *IERS Conventions* established at the BIPM (http://tai.bipm.org/iers/) has been maintained. The version *Conventions* (2010) have been posted on the website and the printed version is expected soon.

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. Within the period of this report, the new conventional reference frame was submitted to the IAU and approved by a resolution in August 2009.

Activities in Frequency

Frequency comb

As the result of the reorganization of activities in the Section, the comb activities are limited to the comb maintenance for BIPM internal applications.

Calibration and measurement service

The section 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, for the calculable capacitor project and the gravimeter instrumentation at the BIPM. The combs are passively kept in running conditions and used when needs appear.

Iodine cells

Although the continuation of the iodine cell service was accepted in the frame of the 2009-2012 work program, the BIPM budget voted by the General Conference for Weights and Measures (CGPM) in 2007 led the CIPM to reconsider the BIPM work program and to take the decision to stop this activity by the end of July 2009.

Gravimetry

The activities on gravimetry were interrupted following a decision of the CIPM in 2009. We report here on those until the end of the service.

Gravimeter FG5-108

The laser head of the compact Nd:YVO_4/KTP/I_2 laser at 532 nm has been modified and the optical fibre system for the light delivery to the interferometer of FG5-108 has been tested. The gravimeter is out of use at the moment of concluding this report.

Truncation tests

The truncation tests, i.e. the study of the dependence of the results of *g* measurement on the choice of the initial and final interference fringes of the series of recorded fringes used in the data processing, were performed for the data obtained with the gravimeter FG5-108 during the comparison ICAG-2005.

Correction related to the distortion due to diffraction effects

The modern design of an absolute gravimeter is based on laser interferometers for the determination of the time-dependent position of the falling test mass. Ideally, the light field for such an interferometer is considered to be a monochromatic plane wave of infinite lateral extension. However, the fact that the laser sources most often used have a resonant cavity composed of spherical mirrors imposes broader conditions on the Helmholtz equation giving beam-like solutions with different spatial extensions. For each of these, minute corrections in the phase progression compared to the plane wave approximation are present. A study has been made in which expressions for these phase-corrections were derived for the case of a two-beam interferometer. The contribution from these diffraction-induced shifts to the *g* value determined in absolute gravimetry has been calculated.

Correction related to the finite speed of light

The existing methods for the evaluation of the correction to the results of *g* measurements related to the effects of the light propagation in the interferometer with the free-falling reflector are under analysis for the preparation of the recommendations by the Consultative Committee for the Mass and Related Quantities (CCM) Working Group on Gravimetry on the evaluation of such a correction for the absolute ballistic gravimeters.

The 8th International Comparison of Absolute Gravimeters, ICAG-2009

The evaluation of the results of the ICAG-2005 provided valuable input to the design and preparation of the 8th ICAG-2009.

Two meetings of the Steering Committee of ICAG-2009 were organized in November 2008 at the BIPM and on 11-12 May 2009 in Prague (Research Institute of Geodesy, Topography and Cartography). Twenty-three participated in the comparison. Of these, twelve gravimeters will took part in the Key Comparison CCM.G-K1 which is the part of ICAG-2009. The measurements of the remaining subset of gravimeters were organized as a Pilot Study but still being part of ICAG-2009.

The strategy of the absolute and relative measurements, the data processing and evaluation of the Comparison Reference Values with their uncertainties are defined in the Technical Protocols. Two different protocols are being developed for CCM.G-K1 part of the ICAG-2009 and for the whole ICAG-2009.

The final report of ICAG 2009 is under preparation. Results of the Key Comparison CCM.G-K1 will be published in the BIPM KCDB.

Preliminary study on the BIPM watt balance project in view of gravimetry

The watt balance requires an uncertainty of 10^{-8} in the absolute gravity value. Preliminary studies have been carried out on the equipment and the influence of local and global environment for accurate gravity measurements.

Staff of the Section

Dr Elisa Felicitas Arias, Principal Research Physicist, Director
Mr Raymond Felder, Physicist (Frequency), retired 09/2009
Ms Aurélie Harmegnies, Assistant (Time), since 11/2008
Dr Zhiheng Jiang, Principal Physicist (Time, Gravimetry)
Mrs Hawaï Konaté, Principal Technician (Time)
Mr Jacques Labot, Principal Technician (Frequency)[2], retired 07/2009
Dr Wlodzimierz Lewandowski, Principal Physicist (Time)
Dr Gianna Panfilo, Physicist (Time), since 08/2007
Dr Gérard Petit, Principal Physicist (Time)
Dr Lennart Robertsson, Principal Physicist (Frequency, Gravimetry)
Mr Laurent Tisserand, Principal Technician (Time) *
Dr Leonid Vitushkin, Principal Research Physicist (Gravimetry), retired 10/2009

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