

Bureau International des Poids et Mesures (BIPM) – Time, Frequency and Gravimetry Section –

<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, and in the updates of the key comparison CCTF-K001.UTC. The frequency stability of TAI, expressed in terms of an Allan deviation, is estimated to be at or below 0.4×10^{-15} for averaging times of one month.

Twelve primary frequency standards contributed during the period to improve the accuracy of TAI, including eight caesium fountains developed and maintained in metrology institutes in France, Germany, Italy, Japan and the USA. The scale unit of TAI has been estimated to match the SI second to about 1×10^{-15} .

Routine clock comparison for TAI is undertaken using GPS C/A observations from time and geodetic-type receivers operated in laboratories. Some laboratories are equipped of two-way satellite time and frequency transfer (TWSTFT) devices allowing time comparisons independent from GPS through geostationary communication satellites. The uncertainty of time comparison by GPS is limited by the hardware to 5 ns for the best dual-frequency links whilst in the case of TWSTFT it is at the nanosecond order.

Studies on the use of phase measurements along with the code measurements of geodetic-type GPS receivers were performed in 2007 by using the Precise Point Positioning method (PPP). In April 2008, a pilot experiment started with the participation of 25 laboratories for studying the introduction of PPP links in TAI. The successful results of the pilot experiment were presented to the Consultative Committee for Time and Frequency (CCTF) in June 2009, which approved the inclusion of this method in clock comparison for TAI. The solutions based on this method (TAI PPP) will be used in the routine computation of Circular T starting from October 2009.

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 GPS receiver round trips with the aim of characterizing the relative delays of time transfer equipment in contributing laboratories. In 2009 the first measurements of relative delays of GLONASS equipment have been made, and more are under organization. A pilot experiment to study the possibility of including GLONASS time transfer in the calculation of TAI is planned to start by the end of 2009.

Improvements to the algorithm for calculation of TAI and UTC are on the way; a new model for the hydrogen maser clock frequency prediction has been tested, providing a partial justification to the drift observed between the industrial clocks and the caesium primary standards.

Radiations other than the caesium 133 have been recommended by the International Committee of Weights and Measures (CIPM) as secondary representations of the second. One is in the microwave frequencies (Rubidium) and the other in the optical frequencies (ytterbium, strontium, mercury, aluminium). These frequency standards are at least one order of magni-

tude more accurate than the caesium, but by the moment their use for time metrology is limited due to the state of the art of frequency transfer, still unable to compare these standards at the level of their performances.

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 Workshop on the IERS Conventions took place at the BIPM in September 2007. Updates to the Conventions (2003) have been posted on the website. Concerning the realization of reference frames for astrodynamics, section staff has participated to the construction of the new international celestial reference frame in the scope of IAU and IVS activities.

The work on the gravimeter FG5-108 being made in cooperation with the VNIIM has concluded with a system for delivering the laser light to the interferometer. Some theoretical investigations have been conducted with the aim of obtaining better corrections to the position of the free-falling mass in the gravimeter. The preparation of the ICAG-2009 and of the technical protocol of the key comparison of absolute gravimeters concluded. About 25 absolute gravimeters will participate to the international comparison between September and October 2009, from which 17 will provide results for the key comparison. A campaign of measurements with about ten relative gravimeters started in July 2009 to provide support to the absolute measurements. Some measurements will be made also on the new site at the BIPM where the watt balance will be operated in the future.

The total number of publications of the section during the period is 53.

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 2006, for 2007 and for 2008* volume **3**, complemented by computer-readable files on the BIPM website (<http://www.bipm.org>), provides the definitive results for at the end of each year.

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. Research into time scale algorithms is conducted in the Section with the aim of improving the long-term stability of EAL and the accuracy of TAI.

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 is well adapted to the caesium clock behaviour, but not for the hydrogen maser, whose

frequency presents a drift. A new mathematical expression for the prediction of the hydrogen maser frequency is proposed taking into account the drift. Tests over a 3-year period have been performed applying the linear prediction to the caesium clocks and the quadratic prediction to the H-masers. The results seem to indicate that non-modelling of the frequency drift of H-masers could be responsible for 20% of the drift of EAL with respect to TAI observed in the past five years. EAL still shows a significant drift; further work needs to be done in the next period.

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, during 2008. 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 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.

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 triennium, individual measurements of the TAI frequency have been provided by twelve primary frequency standards, including 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, 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 year preceding 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 $+5.7 \times 10^{-15}$, 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 initiated (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. We have provided an updated computation of TT(BIPM), named TT(BIPM08), valid until December 2008, which has an estimated accuracy of order 0.5×10^{-15} . Studies aiming at improving the computation of TT(BIPM) have been undertaken, in order to keep it in line with improvements in primary frequency standards.

Primary frequency standards and secondary representations of the second

Members of the BIPM Time, Frequency and Gravimetry section 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 continue 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 68 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 single-frequency receivers; with dual-frequency, multi-channel GPS geodetic type receivers (P3); and 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, and they represent today only 6% of the total number. Ten TWSTFT links are officially used for the computation of TAI, representing 15% of the time links. More TW links exist in the Asia-Pacific region, not already officially introduced in the calculation, and some European laboratories are close to contributing.

Following the recommendation of the CCTF in 2006 the section started in April 2008 a pilot experiment, TAIPPP, where time laboratories contribute GPS phase and code data and where the BIPM uses the Precise Point Positioning technique to generate monthly solutions, in slightly deferred time after the regular TAI computation. The CCTF, at its last meeting in June 2009 approved the report on the pilot experiment, and agreed on the introduction of TAIPPP links in the calculation of time links for TAI. The number of laboratories regularly participating today is 25. Comparison of the TAIPPP links with others obtained by TWSTFT and P3 are published monthly on the ftp server of the section. Plans exist for starting processing TAIPPP links officially in Circular T in October 2009.

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 GPS links are corrected for satellite positions using IGS (International GNSS Service) post-processed, precise satellite ephemerides, 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; four others are in preparation for their introduction or re-introduction into TAI, or are used for particular studies as the T2L2 experiment. The TWSTFT technique

applied to clock comparison in TAI is reaching its potential capabilities with the sessions scheduled every two hours.

Results of time links and link comparison using GPS single-frequency, dual-frequency and TW observations are published monthly on the ftp server of the TFG section (<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 GPS time equipment in time 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.

Progress has been possible on the measurement of relative delays of GLONASS equipment thanks to the cooperation with the Space Research Centre in Warsaw (Poland). The measurements have already started with a TTS-3 receiver having visited in the third trimester of this year the national metrology institute of the Russian Federation, VNIIFTRI.

Work on absolute calibration of GNSS receivers has been started by a PhD student through a collaboration co-financed with the French space agency CNES, and also involving the French laboratory for time metrology LNE-SYRTE.

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, Frequency and Gravimetry section 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. Updates to the *Conventions* (2003) have been posted on the website (<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 are 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. Following the conclusions of the Workshop on the IERS Conventions, held at the BIPM on 20 – 21 September 2007, a new registered edition of the IERS Conventions is now planned to be assembled within one year.

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, and work has progressed in the framework of the IAU, IVS and IERS for the construction of a new conventional reference frame to be submitted to the IAU 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.

At present, preparations are in full progress for the ICAG2009 in which some 20 lasers are supposed to be measured. As a consequence of the prioritization of activities of the BIPM by the CIPM, modifications occurred in the section staff, and at the moment of elaborating this report there are doubts on the possibility of making these measurements. Furthermore, a study of beam characteristics for the beams in the interferometer of the participating gravimeters was planned in order to account for small corrections related to diffraction effects.

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 of July 2009.

Gravimetry

Gravimeter FG5-108

The laser head of the compact Nd:YVO₄/KTP/I₂ 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 broken motor of the dropping chamber is replaced and the re-adjustment of dropping controller is in progress.

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 com-

posed 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 has been completed and provides 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). At present, twenty seven absolute gravimeters have announced their participation in the comparison. Of these, seventeen gravimeters will take part in the Key Comparison CCM.G-K1 which is the part of ICAG-2009. The measurements of the remaining subset of gravimeters will be 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. All the results of the participating gravimeters will be included in the evaluation of the results of the KCD for CCM.G-K1 and as the result of ICAG2009 as a whole while only the results of the gravimeters from KC subset will be submitted to KCDB of the BIPM.

Preliminary schedules for the absolute and relative measurements have been prepared and distributed among participants. It is estimated that five gravity stations of the microgravity network at the BIPM is a suitable number for their homogeneous measurement and optimal adjustment.

The BIPM is at present working with the preparation of the verification of the laser frequencies of the lasers used in the interferometric measurement of the displacement of the falling test body and the frequencies of the reference Rb clocks of the absolute gravimeters. It is planned to monitor the stability of the gravity field at the BIPM using the gravimeter FG5-108 belonging to BIPM.

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 Physicists, Head
Mr Raymond Felder, Physicist (Frequency), retiring 09/2009
Ms Aurélie Harmegnies, Assistant (Time), since 11/2008
Dr Zhiheng Jiang (Time, Gravimetry)
Mrs Hawai Konaté, Principal Technician (Time)
Mr Jacques Labot, Principal Technician (Frequency)*, retiring 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, Physicist (Frequency, Gravimetry)
Mr Laurent Tisserand, Technician (Time)¹
Dr Leonid Vitushkin, Principal Research Physicist (Gravimetry)

Publications of the staff

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¹ Also cooperating with Gravimetry

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