BIPM TIME ACTIVITIES UPDATE

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Abstract

This paper describes BIPM time activities related to the calculation of international reference time scales: UTC and TAI. Monthly, TAI and UTC are computed from clock data (representing 350 clocks coming from 69 institutes) and time transfer data used to compare clocks. Results are published each month in BIPM Circular T.

Due to the evolution of time transfer techniques and clock types, the process of evaluation of TAI has to be regularly updated with newer and better techniques to improve the frequency stability and the frequency accuracy of TAI.

Part of the improvements concerns clock comparisons:

- introduction of new time transfer technique as GPS PPP and GLONASS Common View,

- creation of new statistical tools in order remove outliers in TWSTFT time links, making the best use of time transfer results,

- another improvement is a study on clock frequency prediction in ALGOS, which deals with H-maser clock properties, in order to well understand their impact on generated time scales.

This publication reports on the work of the whole staff of the BIPM dedicated to time activities.

1 INTRODUCTION

The international reference time scales International Atomic Time (TAI) and Coordinated Universal Time (UTC) are calculated at the International Bureau of Weights and Measures (BIPM) on the basis of clock and time transfer data contributed, at the end of 2009 by 69 laboratories distributed worldwide.

The interval unit of TAI and UTC is the second of the International System of Units (SI); the BIPM thus provides traceability to the SI for the laboratories participating in the formation of UTC. The applications of these time scales range from civil timekeeping up to those requiring the highest level of accuracy, such as global navigation satellite systems (GNSS).

Current clock comparisons for the generation of TAI are based mostly on GPS satellite all-in-view **[1]** using single- and dual-frequency receivers and TWSTFT links **[2-4]**. Significant progress has been made in time transfer for clock comparison at the BIPM in 2009, either in the routine calculation of *Circular T* **[5]** or in studies tending to enhance the quality of the reference time scales. In September 2009, the new technique based on the carrier phase combined with the code of the GPS signal (Precise Point Positioning GPS PPP **[6]**) has been introduced in *BIPM Circular T*. In November 2009, one link by GLONASS Common View has been introduced in *BIPM Circular T* **[7]**, making use of differentially calibrated GLONASS receivers **[8]**. TWSTFT links are often affected by outliers which are difficult to remove; for safe handling, a new cleaning technique **[9]** has been developed at the BIPM and has been incorporated in the software dedicated to the time link computation.

The clock frequency prediction algorithm has been studied for different types of clocks in TAI, making a step forward in the understanding of the drift observed between the free atomic scale (EAL) and the BIPM realization of Terrestrial Time TT (BIPM) **[10,11]**.

2 THE CHARACTERISTICS OF UTC AND TAI

At the end of 2009, UTC is calculated from about 350 atomic clocks operated in the 69 contributing institutes. The principal types of participating clocks are industrial cesium clocks and hydrogen masers, which confer high frequency stability to the EAL; in 2009, they represented respectively 26% and 60% of the participating clocks. The frequency accuracy is achieved by the introduction of measurements of primary frequency standards, numbering 13 over 2009; among these, nine cesium fountains provided the best representation of the SI second. In a monthly process, designed to improve the frequency accuracy without degrading the stability, the frequency of EAL is steered to obtain TAI.

The algorithm ALGOS uses clock differences as the basic data. In the case of time comparisons between remote sites, the algorithm is strongly dependent on the quality of the time transfer, and it imposes constraints on the stability and accuracy of the scale. To calculate UTC, the laboratories submit two different types of data: the clock data and time-transfer data.

Three independent time-transfer techniques are used today for remote clock comparison: two-way satellite time and frequency transfer (TWSTFT), making use of telecommunication satellites **[2-4]**, GPS satellites **[1]**, and GLONASS satellites for the link between VNIIFTRI and the PTB **[7]**. GPS time transfer represents today about 85% of the time links for TAI; in this technique, we make use of different types of signal depending on the characteristics of the GPS equipment: single- or multi-channel receivers; single- or dual-frequency information. There are also a variety of methods of dealing with the data, either making use of the code of the carrier, or of a combination of the code and the phase. The best performing example of the first method is so-called GPS P3 **[12,13]** for multi-channel dual-frequency reception using the code of the carrier (statistical uncertainty is less than 1 ns). Following a successful pilot experiment for testing the use of the carrier phase combined with the code of the GPS signal, the method has been officially introduced in the calculation of *BIPM Circular T* in August 2009 and named GPS PPP **[6]**. As of December 2009, 21% of the links in TAI are calculated with GPS PPP.

UTC is endorsed with the metrological qualities required by a time scale used as reference: frequency stability better than 0.4 parts in 10^{15} for averaging times of about 1 month, and frequency accuracy at the level of one part in 10^{15}. For scientific applications requiring a time reference stable in the long term, the BIPM fabricates on a yearly basis TT (BIPMYY) **[10,11]**, which is free of the short-term instabilities of TAI.

3 GNSS TIME LINKS

Among GPS processing techniques, Precise Point Positioning (PPP) appears as a natural choice for TAI computation needs because it is particularly adapted to a global, but sparse, network of stations and because its processing is flexible and easy to implement. Following the recommendation of the Consultative Committee for Time and Frequency (CCTF) in 2006, the Section started in April 2008 a pilot experiment where time laboratories contributed 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 number of laboratories regularly participating to this experimental phase was 25. Six of these stations also participate to the network of the International GNSS Service (IGS) **[14]** and clock solutions for these stations are also generally available from the IGS. The software used in the analysis is the GPS PPP software developed by Natural Resources Canada **[15]**.

The CCTF, in its meeting of June 2009, approved the report of the BIPM on the results of a 1-year pilot experiment, and we have started the implementation of its use for routine time comparisons in August 2009. As of December 2009, 15 links are calculated with GPS PPP. The PPP results have been included in the regular link comparisons associated with the TAI computation and the results are available in the corresponding Web page **[16]**. They are provided as monthly plots of the difference between two techniques; specifically, they are shown for all links where TW data are available.

The PPP link results are superior to code-only P3 links and have a short-term (below 1 month) stability comparable to or sometimes lower than TW.

The quality of PPP time links is such that TAI would already benefit from its introduction (PPP would then replace the presently used code-only P3 links). Because PPP and TW have different features, the situation is not as straightforward to choose between them.

Link and link comparison results are monthly updated and published on the ftp server of the Time, Frequency, and Gravimetry Department of the BIPM **[16]**.

With the aim of introducing GLONASS observations for clock comparison, the Section has started the characterization of relative delays of GLONASS equipment in participating laboratories. A travelling GPS/GLONASS BIPM receiver is in use for measuring the relative delays taking as reference that in Paris Observatory (LNE-SYRTE). The first calibration campaign visited the PTB, the VNIIFTRI, and the AOS **[8]**. Already in 1996, the use of GLONASS in standard CGGTTS Common-View mode was proposed, but only now the GLONASS constellation is at the final stage of its construction and it can be considered for operational international time transfer. The GLONASS P-code has advantages for high-precision time transfer **[7]**. At least 12 national time laboratories are equipped with most recent GPS/GLONASS time receivers. BIPM collects data from these receivers and started to compute regularly related time links, using IGS products. GLONASS links are compared on regular basis to GPS and TWSTFT methods **[16]**. Also, with the agreement of the CCTF (2009), the link between the PTB and VNIIFTRI has been calculated with Common Views of GLONASS satellites since November 2009 and published in *BIPM Circular T*.

Information on calibration of time transfer equipment (GPS, GLONASS, and TWSTFT) is provided at the BIPM Web site **[17]**.

4 DETECTION OF TWSTFT OUTLIERS

A filtering technique has been developed at the BIPM for detecting and, thus, eliminating outliers in TWSTFT time links. Although the data-cleaning technique has been developed for application to TWSTFT links, it could be adapted to other kinds of time links. Removing the outliers on TWSTFT links is a challenge for different reasons: it is not obvious to identify outliers from useful data; the slope some TWSTFT links may show renders the standard treatment difficult; and finally, the number of TWSTFT data points is rather poor. TWSTFT time links routinely provide 12 data points per day (24 in the case of Asia-Europe time links); this number is rather poor compared to the number of measurements for GPS time links (about 100 measurements per day).

The new technique implemented at the BIPM to clean TWSTFT links has been set up with the aim of detecting outliers avoiding the deletion of useful data. Using phase and frequency filtering techniques, a new way to detect outliers with high conservative properties has been issued.

The filter consists in a combination of two different mathematical methods to detect outliers; in a first step a rough cleaning is applied on phase data to eliminate large outliers that could affect the efficiency of a more refined filter; in the second step, two filtering techniques are applied separately on frequency and phase data. A point is considered as an outlier, and consequently eliminated only in the case when both techniques detect it is as such.

This filtering for outliers' removal in TWSTFT links has been implemented for the calculation of time links in the BIPM Time, Frequency, and Gravimetry Department in order to improve and refine TAI calculation. For a complete description of the method, refer to **[9]**.

5 STUDIES ON CLOCK FREQUENCY PREDICTION IN ALGOS

In the present version of the BIPM algorithm ALGOS **[18-20]**, the clock frequency prediction is considered constant during a month for all type of clocks, a procedure which is considered adequate for caesium standards. This simple approach does not take into account the frequency drift of the H-masers, which could be significant in a 1-month interval. The frequencies of EAL are compared to those of TT (BIPM), a time scale optimized for frequency accuracy, and a frequency drift is clearly detected **[21]**. The first analyses have addressed understanding the reasons of this drift. In particular, the effect of the H-masers on the frequency drift of EAL has been evaluated. In the second part, a new mathematical model for the prediction algorithm was presented. This model takes in to account the frequency drift of the H-masers.

A test version of EAL without H-masers has been calculated to evaluate the effects of the equal modelling of the clock frequencies. From the results it was evident that the 40% percent of the frequency drift on EAL is due to H-masers. The consequence is that it also looks like the cesium standards are playing a major role. A drift correction term also seems to be needed for the cesium standards, though this is more difficult to accomplish, due to the much large white FM noise level of the cesium standards. A new mathematical expression for the prediction of the H-maser frequency is proposed taking into account the drift. Tests over a 3-year period have been performed applying the linear prediction to the cesium clocks and the quadratic prediction to the H-masers. A version of EAL on the basis of the proposed frequency prediction for H-masers, but with the classical clock weighting, has been evaluated. 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. In this test, 1 month of past data has been used to evaluate frequency drift, but a longer period could be tested. EAL still shows a significant drift; further work needs to be done on EAL weighting algorithm.

6 CONCLUSIONS

The reference time scales TAI and UTC are calculated at the BIPM each month. Comparison between UTC and the local time scales UTC (*k*) are published in the monthly document called *Circular T*. Clock data and time links are the main ingredients used to calculate UTC and TAI.

Significant progress has been made in time transfer for clock comparison (GPS PPP and GLONASS time links) at the BIPM in 2009, either in the routine calculation of *Circular T* or in studies tending to enhance the quality of the reference time scales. A new cleaning technique has been developed at the BIPM and has been incorporated in the software dedicated to the time link computation to remove outliers from TWSTFT links. The clock frequency prediction algorithm has been studied for different types of clocks in TAI, making a step forward in the understanding of the drift observed between the free atomic scale (EAL) and the BIPM realization of Terrestrial Time TT (BIPM).

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