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Report of the BIPM Time section 1999-2000

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This report covers the period elapsed since the 14th meeting of the Consultative Commitee for Time and Frequency. Much progress has been done in the field of time transfer techniques used in the computation of TAI; the inclusion of multichannel GPS and two way links increased the robustness of TAI. In parallel, research work and experiences are in development concerning the utilisation of phase measurements for accurate time and frequency comparisons. An improved method of evaluation of the primary frequency standards and of their uncertainties has been put into practice by the section in cooperation with time laboratories.

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

Reference time scales TAI and UTC have been computed regularly and have been published in the monthly *Circular T*. Definitive results for 1999 and 2000 have been available in the form of computer-readable files in the BIPM home page and on printed volumes of the *Annual Report of the BIPM Time Section* (Volume 12 for 1999 and Volume 13 for 2000). Changes have been introduced in this publication since 1999 to make more suitable to the needs of users. Some tables that traditionally appeared in the printed version are only accessible through the internet and ftp sites. With the aim of improving the dissemination of information and of taking advantage of electronic facilities, a questionnaire has been addressed to the users with *the Annual Report for 2000.*

Following the 4th meeting of representatives of laboratories contributing to TAI and the 14th CCTF meeting held at the BIPM in April 1999, changes have been implemented to render the data used in TAI, as well as the results, more accessible to the users and to make the procedures of calculation even more transparent and traceable. Work is in progress to automate the calculation of TAI and UTC, thus allowing a shorter delay in the publication of *Circular T* and providing an increased reliability for the system.

Research concerning time scale algorithms included studies which aim to improve the long-term stability of the free atomic time scale EAL and the accuracy of TAI. Studies are undertaken within the section to evaluate the feasibility of providing a quasi-real time prediction of TAI and UTC.

1.1. EAL stability

Some 80 % of the clocks are now either commercial caesium clocks of the type HP5071A or active, auto-tuned active hydrogen masers, and together they contribute 86 % of the total weight with consequent improvement in the stability of EAL.

In January 1998 the weighting procedure applied to clocks in TAI had been shifted to the assignation of an upper limit to relative weights, instead of the previous absolute weighting procedure. Analysis of the distribution of the relative weights attributed to clocks by the end of 2000 indicated that the maximum relative weight which has been fixed to 0.007 was no longer appropriate, since about 80% of high performance caesium clocks reached this value. Since January 2001 the procedure of establishing the maximum relative weight has been improved [33]; this value is fixed each month depending on the number of clocks participating in the calculation. By doing this, EAL relies on the best clocks, and the stability of TAI is improved.

The medium-term stability of EAL, expressed in terms of an Allan deviation, is estimated to be 0.6×10^{-15} for averaging times of twenty to forty days over the period. This improves the predictability of UTC for averaging times of between one and two months.

1.2. TAI accuracy

Progress has been done in the evaluation of the accuracy of the primary frequency standards at the time laboratories, which made efforts to get aligned to the CCTF recommendations. The BIPM time section has developed new procedures for using primary frequency standards to ensure the accuracy of TAI and for reporting the results, with the aim to provide more detailed information and ensure better traceability for the users. The development of these new procedures has been done in collaboration with the laboratories operating primary frequency standards and has been largely discussed before its implementation. Recommendation S 3 (1999) also asked these laboratories to regularly publish the results of the bilateral comparisons with TAI [20, 34]. This has been put in practice by the PTB through a common publication with the BIPM . The new procedures have been put in regular use starting *Circular T 148* issued in May 2000.

Since 1999, individual measurements of the TAI frequency have been provided by nine primary frequency standards, including two Cs fountains (NIST-F1 and PTB CSF1):

- CRL-O1, which is the optically pumped primary frequency standard developed and evaluated at the NIST for the CRL, Tokyo (Japan). In the period covered by this report, it provided four measurements covering a 10-day period each between April and October 2000. The type B relative standard uncertainty of CRL-O1 are stated by the CRL as 0.3×10^{-14}, 0.5 x 10-14, 0.5 x 10-14, and 0.4 x 10-14 respectively.
- NIST-7, which is the optically pumped primary frequency standard developed at the NIST, Boulder (Colorado, United States). In the period covered by this report, it provided 30-day period measurements almost every two months up to September 2000. The type B relative standard uncertainty is stated by the NIST-7 as 1×10^{-14} at the beginning of the period and 0.5×10^{-14} at its end.
- NIST-F1, which is the caesium fountain developed at the NIST. In the period covered by this report, it provided five measurements covering a 20-day period centred in November 1999 and a 30-day period for the other four measurements (March, May, September 2000 and March 2001). The Type B uncertainty of NIST-F1 are stated by the NIST as 1×10^{-15} and 2×10^{-15} for the last two periods.
- NRLM-4, which is the optically pumped primary frequency standard developed at the NRLM, Tsukuba (Japan). It provided measurements covering 10-day periods quite regularly until October 2000. The type B relative standard uncertainty of NRLM-4 is stated by the NRLM as 2.9×10^{-14}.

- PTB CS1, CS2 and CS3 are classical primary frequency standards operating continuously as clocks at the PTB, Braunschweig (Germany). After an interruption in July 1999, PTB CS1 restarted providing measurements since April 2000 over periods of 20-30 days; the type B relative standard uncertainty is stated as 0.8 x 10^{-14}. Frequency measurements for PTB CS2 have been taken continuously, over periods ranging from 25 to 35 days. The published evaluation of its type B relative standard uncertainty is 1.2×10^{-14} for the period. Two measurements were provided for PTB CS3 covering 30-day periods until October 2000. The Type B relative standard uncertainty of PTB CS3 is stated by the PTB as 1.4 x 10^{-14}.
- PTB CSF1 is the caesium fountain developed at the PTB. It started providing measurements in August 2000, since then five reports have been provided. The type B relative standard uncertainty of PTB CF1 is stated by the PTB as 0.1-0.2 x 10^{-14}.
- LPTF-JPO, is the optically pumped caesium standard operated at the LPTF (Paris). It provided three measurements in the last semester of 1999 and two in 2001. The type B relative standard uncertainty of LPTF-JPO, is stated by the LPFT as 0.6 x 10^{-14}.

The global treatment of individual measurements led to a relative departure of the duration of the TAI scale unit from the SI second on the geoid ranging since October 1999 from $+0.2 \times 10^{-14}$ to $+0.7 \times 10^{-14}$, with an uncertainty of 0.2×10^{-14}.

2. Time links

For many years, the sole means of time transfer used for TAI computation at the BIPM has been the classical GPS common-view technique based on C/A-code measurements obtained from one-channel receivers. The combined standard uncertainty of one 13-minute comparison between remote clocks is about 3 ns for continental distances and 5 ns for intercontinental distances, provided that the GPS receivers involved are differentially calibrated. The commercial availability of newly developed receivers has stimulated interest in extending the classical common-view technique for use of multichannel dual-code dual-system (GPS and GLONASS) observations, with the aim of improving the accuracy of time transfer. Three links are at present calculated using GPS multichannel observations (AOS/NPL, GUM/NPL and CSIR/NPL. Following a decision of 14th CCTF in April 1999, several TWSTFT links were introduced into TAI. Three TWSTFT links are currently used in the construction of TAI: USNO/NPL, VSL/PTB and NPL/PTB. For these the corresponding GPS C/A-code common-view links are also computed as back-up data and occasionally used. The TWSTFT links used for TAI are calibrated by GPS common-view. An ongoing calibration of the TWSTFT links is being carried out between the USNO and various European laboratories using a US X-band geostationary satellite.

The TUG/PTB TWSTFT link was used in the computation of TAI from July 1999 to June 2000, when the TUG time laboratory ceased regular operations. This TWSTFT link was calibrated differentially by transportation of a portable TWSTFT station in May-June 1998.

In March 2001 the TWSTFT link between the NIST and the PTB was temporarily suspended as primary link due to changes of the INTELSAT 307° E transponders. For the time being GPS data are being used for the computation of TAI, and the corresponding TWSTFT data are being computed as back-up.

Several other TWSTFT links in Europe and the Pacific Rim are being prepared for introduction into the construction of TAI.

In addition, the BIPM Time section develops activities to implement other time and frequency comparison methods, such as phase and code measurements

2.1. Global Positioning System (GPS)

For the organisation of GPS satellite common views performed with single-channel receivers, the BIPM Time section issues, twice a year, GPS international common view schedules. This schedules are not necessary in the case of satellite tracking with GPS multichannel receivers. The international network of GPS time links used by the BIPM is organized to follow a pattern of local stars within a continent. During the period 1 July 1999 – 1 May 2000, ionospheric corrections had been computed for long-distance links using the total electronic content maps produced by the International GPS Service (IGS). Starting from May 2000, all GPS links are corrected by using the IGS ionospheric maps and precise operational setellite ephemerides.

The BIPM publishes an evaluation of the daily time differences [*UTC – GPS time*] in its monthly *Circular T*. These differences are obtained by smoothing GPS data, taken at the OP from a selection of satellites at high elevation. The standard deviations characteristic of daily GPS results are respectively was about 10 ns; since 1 May 2000 when the intentional degradation of the signal by Selective Availability of GPS was stopped, the standard deviation became less than 2ns.

An important part of our work is to check the differential delays between GPS receivers which operate on a regular basis in collaborating timing centres. Differential delays may be applied in the regular TAI computation if its value is found to be significant and consistent over different evaluations. Alternative, the internal delay of a receiver may be changed by a laboratory. Although the differential calibration method is, in principle, perfectly suited to maintain consistency, absolute calibrations should provide an independent check of the consistency of the TAI links. It is also desirable to obtain new measurements of receiver delays absolutely calibrated in the past.

The first multichannel GPS links have been introduced into TAI at the beginning of 2000 [38]. Besides the improvement of TAI robustness, the introduction of this technique will allow to suppress the need of the common view schedules and facilitates the operation at the BIPM and in laboratories.

GPS time and frequency transfer may also be carried out using dual-frequency carrier-phase measurements rather than code measurements. This technique, already in common use for GPS in the geodetic community, can be adapted to the needs of time and frequency transfer. An Ashtech Z12-T GPS receiver has been in operation at the BIPM since December 1997 and a new JPS Legacy GPS/GLONASS receiver has been acquired in 2000. Studies using the Ashtech receiver have been conducted in close collaboration with the BNM-LPTF [21], which owns a similar receiver. A method has been developed to perform the absolute calibration of the Z12-T hardware delays and to use it to perform differential calibration of similar receivers [24, 28, 39]. Two absolute calibration measurements of the Z12-T have been carried out at the US Naval Research Laboratory in May-June 2000 and April-May 2001 and the results are being compared. A calibration trip was started in January 2001 in order to differentially calibrate all similar receivers in time laboratories world-wide. The JPS Legacy GPS/GLONASS receiver also serves as a reference to which the Z12-T is compared while at the BIPM. These studies are being conducted in the framework of the IGS/BIPM Pilot Project with a view to providing accurate time and frequency comparisons using GPS phase and code measurements.

The construction of low-cost Motorola Oncore 8-channel receivers has been achieved with the cooperation of the BIPM; software fulfils all standards agreed for accurate time transfer. These multichannel receivers are assembled on request by the Polish Academy of Sciences.

2.2. Global Navigation Satellite System (GLONASS)

GLONASS international common-view schedules are also issued twice a year by the time section. GLONASS data taken by time laboratories are collected and studied at the BIPM, but not yet used in the current TAI computation.

The BIPM publishes an evaluation of the daily time differences [*UTC – GLONASS time*] in its monthly *Circular T*. These differences are obtained by smoothing GLONASS data, taken at the NMi-VSL, from a selection of satellites at high elevation. The standard deviations characteristic of daily results is about 3 ns. The combined standard uncertainty of the daily GLONASS values is, however, not better than several hundred nanoseconds, because no absolutely calibrated GLONASS time receivers are available.

Introduction of multichannel GPS+GLONASS links into TAI is also studied. Procedure for the use of multichannel GLONASS P-code [19] and GLONASS precise ephemerides were established [36]. A series of differential calibration of GPS/GLONASS multichannel dual-code receivers was started in December 1998 and is been carried at present. This involves six laboratories in Europe, three in the United States and one each in South Africa, Australia and Japan.

The BIPM is currently equipped with four GPS/GLONASS or GLONASS-only time receivers from the 3S Navigation Company.

The staff of the BIPM Time section is actively involved in the work of the CCTF sub-group on GPS and GLONASS time transfer standards, and several decisions made by the sub-group have their origins in studies initiated at the BIPM.

The 3S Navigation receivers in operation at the BIPM have the capability to provide GLONASS phase measurements and software has been installed to allow automatic data retrieval. With this set-up, one 3S receiver has been collecting data for the International GLONASS Experiment, IGEX'98, organized by the IAG, the IGS and the ION, since its inception in October 1998. This experiment ended in 1999 and has been continued by the International GLONASS Service Pilot Project (IGLOS-PP) sponsored by the IGS, in which the BIPM participates.

2.3. Two-way time transfer

The TWSTFT technique is currently operational in seven European, three North American and five Pacific Rim time laboratories. Some other laboratories have reached pre-operational status.

Analysis of the performance of TWSTFT, which is now in use for several TAI links, shows that clocks located on different continents can be compared by this technique at five-day intervals at their full level of performance, without being affected by time-transfer measurement noise. The introduction of TWSTFT into TAI has brought about another important change; TAI is no longer reliant on a single technique, because TWSTFT links are backed up by GPS links and vice versa. Also, for the first time, two transatlantic links are used in its construction, and each of these links is performed by two independent techniques. This very new situation increases the robustness of the construction of TAI.

Starting in May 1999 the BIPM Time Section publishes regular BIPM TWSTFT Reports in which selected TWSTFT links through INTELSAT 307° E are computed and compared with the corresponding GPS links. Eighteen reports have been published to date.

3. Other research studies

3.1. Space-time references

The BIPM/IAU Joint Committee on General Relativity for Space-time Reference Systems and Metrology (JCR) has worked in collaboration with the IAU Working Group on relativity for celestial mechanics and astrometry (RCMA) on the problems of astronomical relativistic space-time reference frames. The website (http://www.bipm.org/WG/CCTF/JCR) provides general information on the JCR. The Resolutions prepared by the JCR were adopted at the 24th IAU General Assembly in August 2000 as Resolution B1.5 " Extended relativistic framework for time transformations and realisation of coordinate times in the solar system" and Resolution B1.9 "Re-definition of Terrestrial Time TT" [25]. The adoption of the new Resolutions by the IAU completes an important part of the original objectives of the JCR, concerning time and frequency applications. Therefore the BIPM and the IAU decided in January 2001 to terminate the Joint Committee and to continue to collaborate in the framework of the RCMA working group, renamed RCMAM where the final M stands for metrology.

Uniformity in the definition of space reference systems is becoming of importance to basic metrology. Such uniformity is essential for activities that use sets of measurements that are not local, as is the case of the astro-geodetic techniques contributing to the International Earth Rotation Service (IERS). In response to a call for participation of the IERS, the BIPM and the U. S. Naval Observatory (USNO) have been working together to provide the Conventions Product Centre (CPC) of the IERS since 1 January 2001.

3.2. Pulsars

Because millisecond pulsars have the potential to sense the very long-term stability of atomic time, collaboration is maintained with radio-astronomy groups observing pulsars and analysing pulsar data. The Time section provides these groups its post-processed realization of Terrestrial Time TT(BIPMxx), where xx stands for the last two digits of the year. A small collaboration is continuing with the Observatoire Midi-Pyrénées (OMP) in Toulouse to complete the processing of a small programme of survey observations carried out in past years[26].

3.3. Atom interferometry

More generally the active field of atomic interferometry using laser cooled atoms (as applied in e.g. Cs fountain primary frequency standards, gravimeters, gyroscopes) on the ground as well as onboard satellites has stimulated collaboration between BIPM time section staff and laboratories involved in these developments (BNM-LPTF, University Paris VI). As a consequence a member of the time section has been on a one-year leave on a CNES (Centre National des Etudes Spatiales) grant to study possible applications of this technology in fundamental physics and metrology. The work has been carried out at the BNM-LPTF in collaboration with one of the most active groups in the field from May 1 2000 until April 30 2001.

3.4. Clocks in space

Scientists of the Time section are involved, in collaboration with the BNM-LPTF, in the evaluation of the possible use for international time keeping, and in particular TAI, of highly stable and accurate space clocks, in particular those that will be operated within the ACES (Atomic Clock Ensemble in Space) experiment on board the international space station in 2003. Because of the micro-gravity environment such laser-cooled clocks are expected to reach relative accuracies in the low 10^{-16} region, hence presenting an improvement by at least one order of magnitude with respect to current primary standards. They will therefore be of primordial interest for the establishment of TAI accuracy. Within this work an important part concerns the calculation, at the required accuracy, of relativistic corrections affecting the clocks themselves as well as the time transfer between the space and ground clocks. Detailed such calculations were carried out in collaboration with colleagues from the Observatoire de Paris and the ENS (Ecole Normale Supérieure) .

4. Publications

4.1. External publications

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4.2. BIPM publications

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