UPDATE ON TIME AND FREQUENCY ACTIVITIES AT PTB

Peter Hetzel and Andreas Bauch
Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig, Germany

Abstract

The activities in the field of time and frequency metrology pursued at PTB are reviewed. Among the recent milestones have been the development and quasi-continuous operation of a cesium fountain frequency standard, the realization of a free atomic time scale TAF (PTB) based on the fountain results, and the cooperation in international time comparison projects using GPS carrier-phase receivers and TWSTFT in Ku-band and X-band.

INTRODUCTION

Time and frequency activities are pursued in different sections of PTB within the Division Length and Time. In this contribution we report on some recent achievements related to the activities of the Time Unit Section and the Time and Frequency Dissemination Section which are listed below:

- Operation of primary clocks and realization of UTC (PTB) and TA (PTB)
- Development of cesium fountain frequency standard
- Development of single trapped-ion optical frequency standard
- Experimental realization of TAF (PTB)
- Participation in Two-Way Satellite Time and Frequency Transfer (KU-band and X-band)
- Participation in GPS carrier-phase frequency comparison projects (NIST-PTB, IGS, GeTT until March 2001)
- Time dissemination via LF broadcast (DCF77), public telephone network, Internet (NTP).

Other activities pursued in the Division are the development of optical frequency standards in the context of realization of the meter, the development of optical frequency standards based on laser-cooled atoms, atom optics, and optical frequency measurement. The interested reader is referred to the Proceedings of the 6th Symposium on Frequency Standards and Metrology, St. Andrews, Scotland, 2001, to be published in 2002, for records of the achievements in these fields.

PRIMARY TIME AND FREQUENCY REFERENCES

PTB has continued to operate three primary frequency standards (PFS) as clocks with a thermal atomic beam. We look back now on more than 30 years of operation of CS1. After a substantial refurbishment, a new detailed uncertainty evaluation was made and the relative CS1 standard uncertainty was stated as $u_B = 7\cdot10^{-15}$ [1]. The CS2 has been in continuous operation since 1986 and has been the source of TA (PTB) since 1991. Currently its uncertainty is estimated as $u_B = 12\cdot10^{-15}$. The CS3 performance was in some disagreement with the stated uncertainty of $14\cdot10^{-15}$. Clock operation was stopped in December 1999 as one oven had run out of cesium. Stable operation could not be resumed before March 2001, and the clock uncertainty is being currently reevaluated.

As an outcome of the 14th Session of the CCTF in March 1999, it was recommended that the results of the PFS should be published in a more detailed way than it had been common practice. Up to last year, a single line of data for each month or for each time interval during which the standard was operated was published in the Circular T, issued by the BIPM Time Section, and later published in the Annual Report of the BIPM Time Section. This practice was suspected not to fulfill the need of users. The information provided to the user should contain the following components:

- a component u_B which reflects the combined uncertainty from systematic effects,
- a component u_A which originates in the instability of the PFS,
- a component $u_{link/lab}$ which reflects the link between the PFS and the clock whose data are communicated to the BIPM and are processed in the ALGOS formalism,
- a component $u_{clock\text{-}TAI}$ reflecting the uncertainty in the link to TAI of this contributing clock, and
- information on the instability $\sigma_{TAI}(\tau)$ of TAI itself.

In fulfillment of these recommendations, two papers were written jointly with colleagues from BIPM, one for the clock results in 1999 and one for 2000 [2,3].

The development of CSF1, a fountain frequency standard using laser-cooled cesium atoms, shown in Figure 1, lasted from 1995 to 1999, when the first frequency measurements were made. In early 2000, the type B uncertainty of CSF1 was estimated to be $1.4\cdot10^{-15}$ [4,5]. Since the beginning of the year 2001, CSF1 has been in operation, launching atoms in the state (F=3, m_F = 0) only and discarding the others. Thereby several uncertainty contributions could be reduced so that the standard uncertainty in the so-called routine operation mode is now $1\cdot10^{-15}$ [6] and a relative frequency instability of $2\cdot10^{-13}\cdot(\tau/\mathrm{s})^{-1/2}$ is achieved. CSF1 was operated quasi-continuously during eight intervals, each of at least 15 days duration, for which data were submitted to the BIPM. Thus, the TAI scale unit could be compared eight times to the SI second as realized in CSF1, with a combined uncertainty of about $2.5\cdot10^{-15}$, documented in BIPM Circular T issues. In Figure 2, the results of comparisons between the primary clocks CSF1, CS1, and CS2 and a hydrogen maser of PTB is shown. One may notice that CS2 and CSF1 agree well within the overlap of the 1 σ error bars, representing the combined standard uncertainty and relative frequency instability over the averaging interval. The CS1 frequency was occasionally found slightly too low so that the error bars do not overlap. To conclude this section, in Figure 3 all measurement results of the TAI scale interval with respect to PFS during the last 12 months have been compiled, showing also the results from primary standards in the US, in France, and in Japan.

PTB TIME SCALES

PTB continues to realize a free atomic time scale TA (PTB) directly from the 1 PPS output of the CS2. UTC (PTB) had differed from TA (PTB) only by a constant time offset until Jan 1st, 1998 (MJD 50814). Then a time step of +1900 ns was introduced to UTC (PTB) and steering was started, in order to minimize the difference UTC–UTC (PTB). The steering is effected on a monthly basis, with maximum rate changes equal to ±0.5 ns/day. The steering corrections are published in PTB's Time Service Bulletin.

Since November 2000 a time scale provisionally named TAF (PTB) whose scale unit shall represent the SI second as realized with CSF1 (on the rotating geoid) has been realized. Its hardware realization is depicted in Figure 4. It is based on the 5 MHz output signal of an active hydrogen maser HM. Frequency steering by a microphasestepper (MPS) reflects the results of frequency comparisons CSF1-HM. The MPS output is fed to a divider generating 1 PPS, which is continuously monitored in PTB's clock comparison routine. For some time, the frequency steering was predicted for a week n based on a linear least-squares fit to the frequency data during the weeks $n-4$ to $n-1$. This practice had to be given up because of a deterioration of the maser performance for several weeks, which is apparent from Figure 5, showing the CSF1-HM data. Steering was then done based on visual judgment of the data. Nevertheless, a comparison of TAF (PTB) with TAI on one hand, and the maser ensemble time scale AT1E of NIST **[7]** using GPS carrier-phase receivers **[8]**, and UTC (NIST) and UTC (USNO) using TWSTFT, revealed the improved stability of TAF (PTB) compared to UTC (PTB). The respective modσ_y data for the four comparisons have been compiled in Figure 6. For the time being, it is premature to state an accuracy for the scale unit of TAF (PTB). Further studies and a more reliable hardware configuration would first be required to develop an optimum strategy for the steering of the maser in order to transfer the intrinsic stability and accuracy of CSF1 to TAF (PTB).

TIME AND FREQUENCY COMPARISONS

PTB operates a TurboRogue SNR 12 RM (on loan from NIST) to study the link NIST - PTB using the GPS carrier-phase method. It has been employed up to now to compare the primary clocks **[8]**, and in particular the fountain frequency standards of NIST and PTB **[9]**. The most recent comparison was just finished, and a preliminary evaluation confirmed that any deviation between the two fountains is within the combined uncertainty of the fountains and the frequency comparison, usually $\leq 2\cdot10^{-15}$ (1σ). In April 2000 the German Federal Agency for Cartography and Geodesy (BKG) in Wettzell created a permanent EUREF station at PTB using up to now a TurboRogue SNR-8000 receiver. This receiver (acronym PTBB) has recently been included in the network of the IGS. It will be replaced by an Ashtec Z12T receiver in December 2001.

PTB continues to perform TWSTFT routinely with European and US institutes using an INTELSAT geostationary satellite at 307°E. The TWSTFT data are made available on PTB's ftp-site and contribute to the calculation of the time links between the laboratories contributing to TAI. In Figure 7, the double differences of time scale comparisons using TWSTFT and GPS Common View are depicted for the links NPL - PTB and NIST-PTB. One can clearly identify the disturbed period of TWSTFT operations during the partial eclipse of the satellite around the vernal equinox in 2001. Apparently, a delay change occurred in the transatlantic transponder after that epoch.

At present PTB is establishing an X-band ground station to create a permanent two-way link via a U.S. X-band satellite between PTB and USNO, in parallel to the recently established link between NPL and USNO. USNO has offered satellite transponder time for such a transatlantic link. The first results, depicted in Figure 8, have been very encouraging. It is planned to obtain an absolute calibration of this link during the year 2002 which would at the same time allow the calibration of the TWSTFT link in the KU-band and the GPS CV link between UNSO and PTB.

OUTLOOK

It is intended to continue the development of atomic frequency standards and their application in the realization of atomic time scales in PTB's Length and Time Division. Both kinds of activities are dependent on each other to a large extent. The development of a second cold-atom clock is planned for the next 2 years, in parallel with the development and local comparison of all-optical frequency standards. Besides the research and development of atomic clocks, PTB will continue to improve its time transfer techniques. It may be envisaged that PTB's time scale could be used as one of the references for the realization of the system time of the future European satellite navigation system GALILEO.

REFERENCES

[1] A. Bauch, B. Fischer, T. Heindorff, and R. Schröder, 1998, *"Performance of the PTB reconstructed primary clock CS1 and an estimate of its current uncertainty,"* **Metrologia, 35,** 829-45.

[2] A. Bauch, B. Fischer, T. Heindorff, P. Hetzel, G. Petit, R. Schröder, and A. Wolf, 2000, *"Comparisons of PTB's Primary Clocks to TAI in 1999,"* **Metrologia, 37**, 683-692.

[3] T. Heindorff, A. Bauch, P. Hetzel, G. Petit, and S. Weyers, 2001, *"PTB primary clocks: Performance and comparison with TAI in 2000,"* **Metrologia, 38,** in press.

[4] S. Weyers, U. Hübner, B. Fischer, R. Schröder, C. Tamm, and A. Bauch, 2000, "Investigation of contributions to the stability and uncertainty of the PTB atomic caesium fountain CSF1," in Proceedings of the. 14th European Frequency and Time Forum, 14-16 March 2000, Torino, Italy, pp. 480-483.

[5] S. Weyers, U. Hübner, R. Schröder, C. Tamm, and A. Bauch, 2001, *"Uncertainty evaluation of the atomic caesium fountain CSF1 of PTB,"* **Metrologia, 38,** in press.

[6] S. Weyers, A. Bauch, R. Schröder, and C. Tamm, 2002, *"The atomic caesium fountain CSF1 of PTB,"* Proceedings of the 6th Symposium on Frequency Standards and Metrology, 9-14 September 2001, St. Andrews, Scotland, UK, to be published.

[7] T. E. Parker, 1999, *"Hydrogen maser ensemble performance and characterization of frequency standards,"* Proceedings of the 1999 Joint Meeting of the European Frequency and Time Forum and the IEEE International Frequency Control Symposium, 13-16 April 1999, Besançon, France (IEEE Publication 99CH36313), pp. 173-176.

[8] L. Nelson, J. Levine, T. Parker, K. Larson, P. Hetzel, and J. Becker, 2000, *"Comparison of Atomic Frequency Standards at NIST and PTB Using Carrier-Phase GPS,"* in Proceedings of the 31st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 7-9 December 1999, Dana Point, California, USA (U.S. Naval Observatory, Washington, DC), pp. 449-459.

[9] T. Parker, P. Hetzel, S. Jefferts, S. Weyers, L. Nelson, A. Bauch, and J. Levine, 2001, *"First Comparison of Remote Cesium Fountains,"* in Proceedings of the 2001 IEEE International Frequency Control Symposium and PDA Exhibition, 7-9 June 2000, Kansas City, Missouri, USA (IEEE Publication 00CH37052), pp. 63-68.

[10] P. Wolf and G. Petit, 2000, *"Use of IGS ionosphere products in TAI,"* in Proceedings of the 31st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 7-9 December 1999, Dana Point, California, USA (U.S. Naval Observatory, Washington, DC), pp. 419-430.

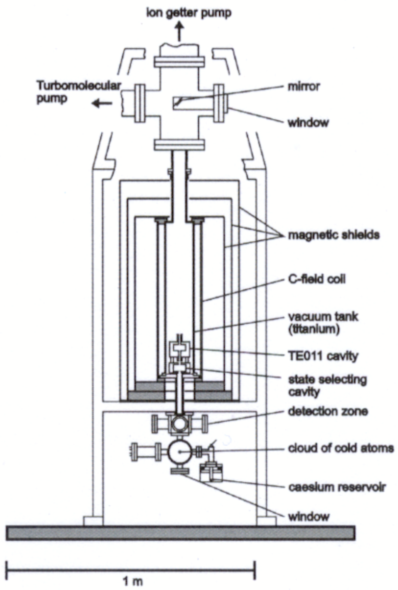

Figure 1. Scheme of the atomic cesium fountain frequency standard CSF1 of PTB.

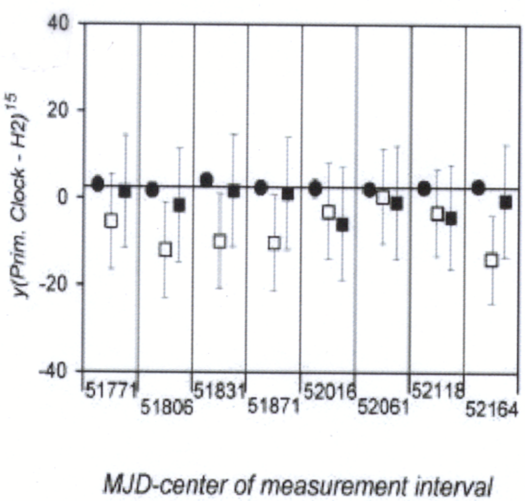

Figure 2. Results of comparison between the primary clocks CSF1 (●), CS1 (□), CS2 (■) and a hydrogen maser. Each data point represents 15-day or 20-day averages of measurements during which CSF1 was in operation in more than 98.5% of the total time. The label on the horizontal axis represents the mid-point of the measurement interval. Here, and in all other figures, MJD designates Modified Julian Day. MJD 52164 corresponds to 2001-09-12. Error bars (1 σ) reflect the combined uncertainty u_B of the standards and the uncertainty due to white frequency noise dominated performance at the respective averaging time.

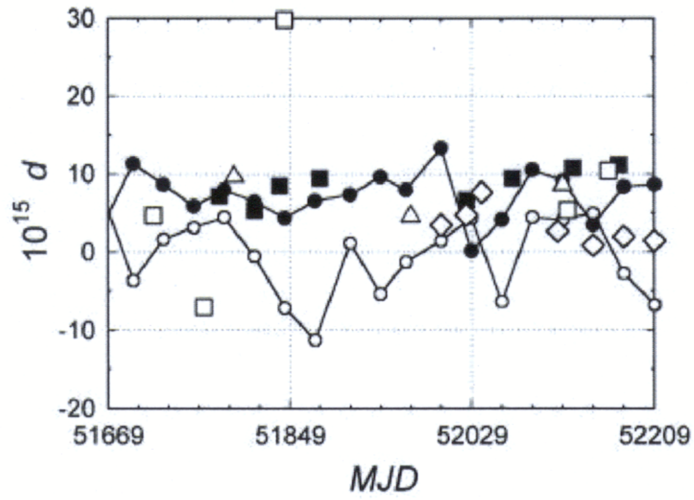

Figure 3. Fractional deviation *d* of the duration of the TAI scale interval from the SI second as realized by the individual primary clocks CSF1 (■), CS1 (O) and CS2 (●) of PTB, NIST-F1 (Δ), CRL-01 ( ) (CRL, Japan), and JPO (◊) (LPTF, France) during the period MJD 51669 – 52209, Source: BIPM Circular T. MJD designates the Modified Julian Date; MJD 52209 corresponds to 27th October 2001. Data points from PTB's primary clocks were connected for periods during which the clocks were operated continuously. "Error bars" (one representative for each clock) indicate the combined uncertainty in the determination of *d*.

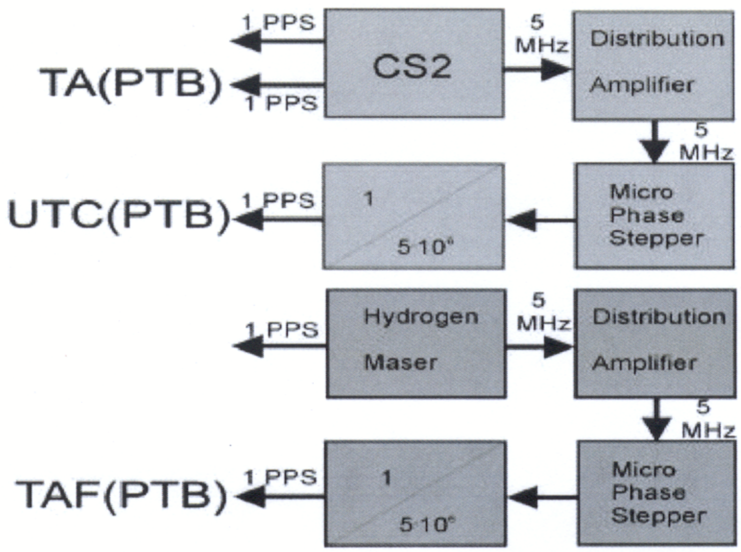

Figure 4. Schematic representation of the generation of UTC(PTB), TA(PTB) and the fountain time scale TAF(PTB)

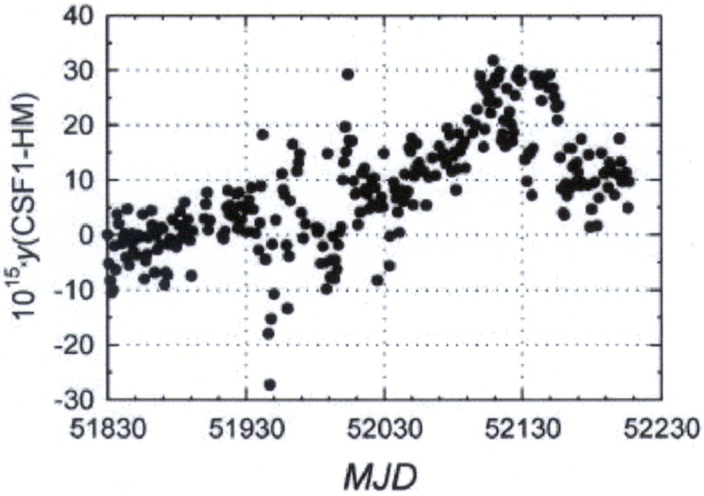

Figure 5. Results of comparisons of a hydrogen maser HM with respect to CSF1 expressed as relative frequency difference as a function of time.

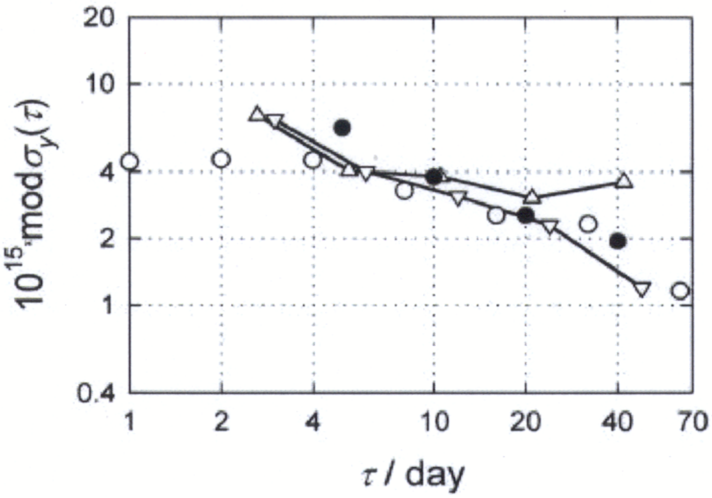

Figure 6. Frequency instability mod$\sigma_y(\tau)$ observed in the comparison between TAF(PTB) and TAI (●), TAF(PTB) and UTC(USNO) using TWSTFT (Ξ), TAF(PTB) and UTC(NIST) using TWSTFT (Δ), TAF(PTB) and NIST AT1E (O) using GPS carrier-phase results provided by L. Nelson, USNO (previously NIST). TWSTFT data were rearranged as if they were taken at regular intervals.

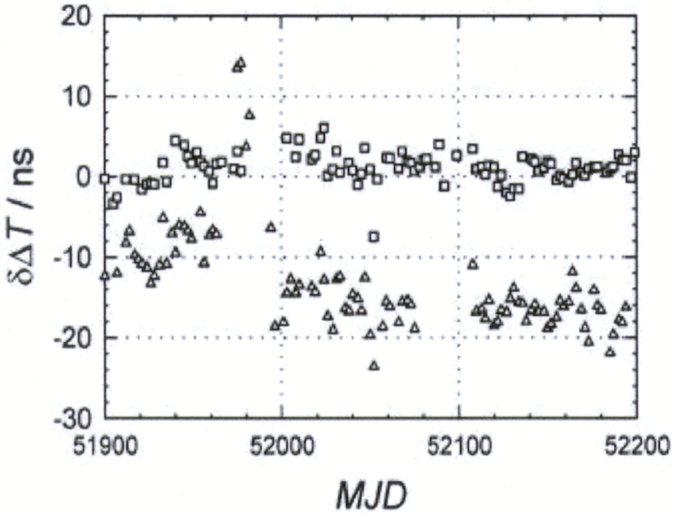

Figure 7. Results of time scale comparisons using two different techniques, TWSTFT and GPS Common View. Plotted are the differences $\{UTC(PTB){-}UTC(k)\}_{TWSTFT} - \{UTC(PTB){-}UTC(k)\}_{GPS}$; k: NPL ( ), and k: NIST (Δ), offset by −10 ns. GPS data for the transatlantic link were corrected using IGS ionosphere maps [10].

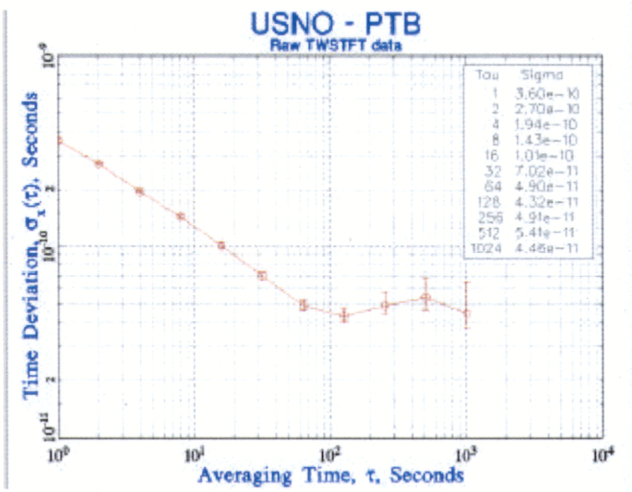

Figure 8. Time instability $\sigma_x(\tau)$ observed in the TWSTFT comparison using X-Band between USNO and PTB