OPERATIONAL USE OF PTB'S ATOMIC CAESIUM FOUNTAIN CSF1

S. Weyers, P. Hetzel, A. Bauch

Physikalisch-Technische Bundesanstalt, Bundesallee 100, D-38116 Braunschweig (Germany)

ABSTRACT

The atomic fountain frequency standard CSF1 of the Physikalisch-Technische Bundesanstalt (PTB) has matured to a regularly operated primary frequency standard. During 2001, CSF1 was used to measure the TAI scale unit during five intervals of 15 or 20 days duration, showing a departure of the TAI scale unit from the SI second of a few parts in 10^{15}. During three periods of simultaneous operation, CSF1 was compared to NIST-F1 of the US National Institute of Standards and Technology using GPS carrier phase technique and TWSTFT. In one case, the difference between the standards slightly exceeded the combined 1σ - measurement uncertainty, in two cases the disagreement was less significant.

A free atomic time scale, TAF(PTB), has been realised since summer 2000. Its physical realisation is based on a hydrogen maser and a subsequent microphase stepper (MPS). The MPS steers the frequency of TAF(PTB) to that of CSF1. With reference to the hydrogen maser based time scale AT1E of NIST, a relative frequency instability of $1.5 \cdot 10^{-15}$ at τ = 30 days was verified. Real time prediction of the difference TAI-TAF(PTB) has been shown to be possible with a 1σ - standard deviation of 12 ns.

Keywords: atomic frequency standard, caesium fountain, TAI, time comparison, GPS, TWSTFT

1. INTRODUCTION

The use of atomic fountain frequency standards based on laser-cooled caesium atoms has paved the way for an improvement of the realisation of the SI second by almost one order of magnitude compared to clocks using thermal atomic beams. In this contribution we discuss the use of such a fountain in "classical" time-keeping applications, namely the realisation of atomic time scales. In another contribution to this conference we discuss its use as a frequency reference for a test of Local Position Invariance [Ref. 1].

After a brief description of PTB's fountain CSF1 we report on recent local comparison results. In section 5 we present the current performance of PTB's free atomic time scale TAF(PTB) whose physical realisation is based on a hydrogen maser and a subsequent microphase stepper (MPS) steering the frequency to that of CSF1. This activity finally aims at a future realisation of UTC(PTB) with improved stability compared to the current situation. This is mandatory for facilitating the real-time prediction of UTC-UTC(PTB) with nanosecond accuracy.

2. CURRENT STATUS OF CSF1

The development of CSF1, a fountain frequency standard using laser-cooled caesium atoms 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 $1.4 \cdot 10^{-15}$ [Refs. 2, 3]. Since the beginning of 2001, CSF1 has been operated launching atoms in the state (F=3, m_F = 0) only and discarding the others. Thereby several uncertainty contributions have been reduced. As described in Ref. 4, the standard uncertainty u_B in the so-called routine operation mode is now $1 \cdot 10^{-15}$, and a relative frequency instability of $2 \cdot 10^{-13} \cdot (\tau/s)^{-1/2}$ is achieved. The actual u_B contributions are given in Table 1. All uncertainty contributions are less than $1 \cdot 10^{-15}$ and are considered to be linearly independent. Therefore the resulting standard uncertainty is the square root of the sum of squares of the individual components. During 2001 CSF1 was operated during more than 300 days for at least 16 hours.

Physical origin	Correction [10^{-15}]	Uncertainty [10^{-15}]
C-field	-46.4	< 0.1
Collisional shift	2.5	< 0.7
Blackbody shift	16.6	0.2
First-order Doppler effect	-	0.5
Majorana transition	-	< 0.1
Rabi-pulling	-	< 0.1
Ramsey-pulling	-	< 0.1
Microwave leakage	-	0.2
Microwave spectral impurities, Electronics	-	0.2
Light shift	-	0.2
Other collisions	-	0.1
Total 1σ uncertainty u_B		1.0

Table 1. Relative frequency corrections and uncertainty budget of CSF1 in the routine operation mode [Ref. 4].

3. LOCAL CSF1 FREQUENCY COMPARISONS

In Fig. 1, the results of comparisons between CSF1, PTB's primary clocks CS1 and CS2, and a hydrogen maser are shown, representing nine intervals of 15 days or 20 days, respectively, during which CSF1 was operated in the routine configuration. The last five data were taken in 2001. It can be seen that agreement between CS2 and CSF1 was always well within the overlap of the 1σ - error bars, representing the combined standard uncertainty and relative frequency instability over the averaging interval. The CS1 frequency

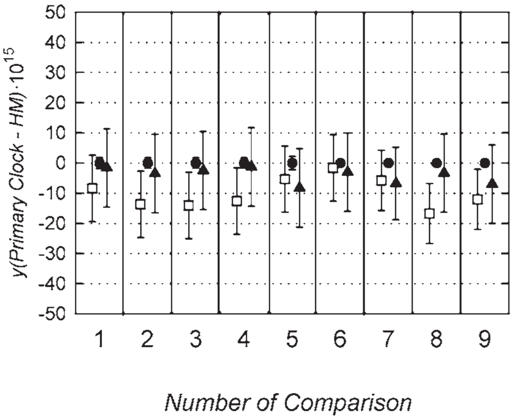

Figure 1. *Results of simultaneous comparisons between the primary clocks CSF1 (●), CS1 (□), CS2 (▲) and a hydrogen maser, displayed in bins identified by a number. Each data represents 15-day or 20-day averages of measurements during which CSF1 was in operation more than 98.5% of the total time. The mid points of the measurement intervals were at MJD 51771, 51806, 51831, 51871, 52016, 52061, 52118, 52164, and 52219, respectively. Here, and in all other figures, MJD designates Modified Julian Date. MJD 52219 corresponds to 2001-11-06. 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. CSF1-HM differences were set to zero individually in each bin.*

was occasionally found slightly too low.

Terrestrial Time TT has been defined by the International Astronomical Union as a coordinate time for the geocentric reference system, such that its scale interval agrees with the SI second on the geoid. International Atomic Time TAI is a realisation of TT, apart from a constant offset in time. TAI is realised by the BIPM, based on about 200 clocks, giving stability and reliability, and a few primary clocks, giving the accuracy [Refs. 5, 6]. During 2001 two fountains, NIST-F1 and CSF1, and four caesium clocks with a thermal atomic beam, CRL_01 of the Japanese Communication Research Laboratory, JPO of the French Laboratoire primaire du temps et des fréquences, and PTB CS1 and CS2 provided evaluations of the TAI scale unit. The data are compiled in Fig. 2. CSF1 data were obtained by frequency comparisons using a hydrogen maser as local reference. The maser in turn was compared with UTC(PTB), and the results were reported to the BIPM. In this way the maser frequency was known with respect to TAI for standard 5-day intervals. CSF1 was compared with the maser following the same time schedule. Thus the TAI scale unit could be measured with respect to the SI second as realised with CSF1.

Whereas both fountains point to a slight departure between the TAI scale interval and the SI second, this seems not the case for the JPO and the CS1, two clocks for which a similar relative uncertainty u_B

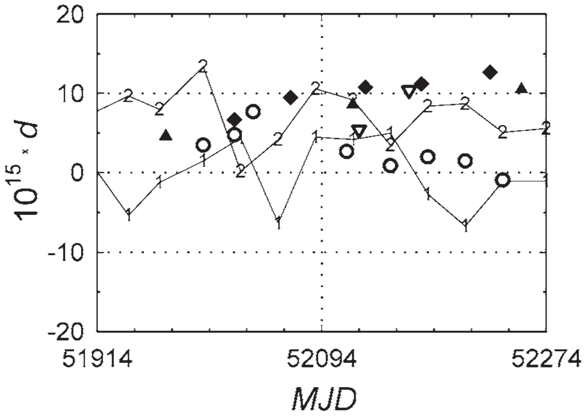

Figure 2. *Fractional deviation d of the duration of the TAI scale interval from the SI second as realised by the individual primary frequency standards CRL-01 (∇), NIST-F1 (▲), LPTF-JPO (o), CSF1 (◆), CS1 (1), CS2 (2), during the period MJD 51914–52274. MJD 52274 corresponds to 2001-12-31. The lines indicate that the clocks were operated continuously, the symbols are placed at the end of the measurement interval. Data were taken from Circular T of the BIPM Time Section.*

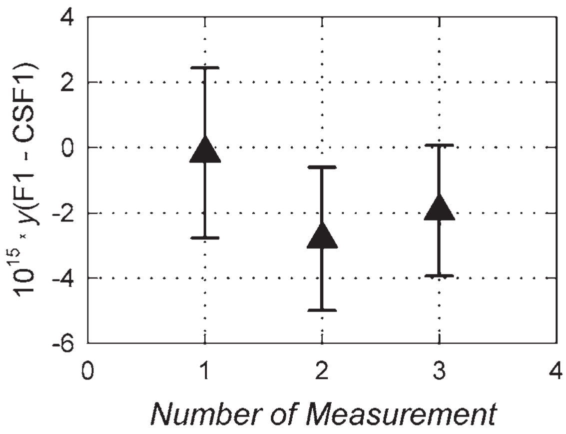

Figure 3. *Relative frequency difference between NIST-F1 and PTB CSF1 [Ref. 7,8]; "error bars" reflect the combined uncertainty due to the u_B values of both fountains, and the measurement uncertainty. For details of the comparison and evaluation see [Ref. 7]. The comparisons took place in August 2000, July 2001 and November 2001.*

(≈ $7{\cdot}10^{-15}$) was estimated. Steering of TAI has been affected to counteract the offset and the apparent drift. With the availability of fountain data the steering of TAI can be based on more accurate data than before.

To compare NIST-F1 and CSF1, two high precision transfer techniques were used. Continuous frequency comparisons between UTC(NIST) and a hydrogen maser (HM) at PTB were performed using the GPS carrier phase as obtained from two geodetic receivers operated at NIST and PTB [Ref. 9]. In parallel, UTC(PTB)-T(HM) was compared by TWSTFT (Two-Way Satellite Time and Frequency Transfer) via a Ku-band satellite typically three times per week. Thus, UTC(NIST) and the maser at PTB served as intermediate frequency references for the comparisons of NIST-F1 and CSF1. In Fig. 3 the evaluated frequency differences are compiled [Ref. 8].

4. REALISATION OF TAF(PTB)

Since November 2000 a time scale, provisionally named TAF(PTB), whose scale unit is intended to represent the seconds of CSF1 has been realised. Its hardware realisation is depicted in Fig. 4. It is based on the 5 MHz output signal of an active hydrogen maser HM. Frequency steering by a microphase stepper (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. Temporarily, 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 could not be continued because of unpredictable maser performance for several weeks. In Fig. 5, the CSF1-HM data and the applied steering is shown. Steering was partially based on visual judgement of the data.

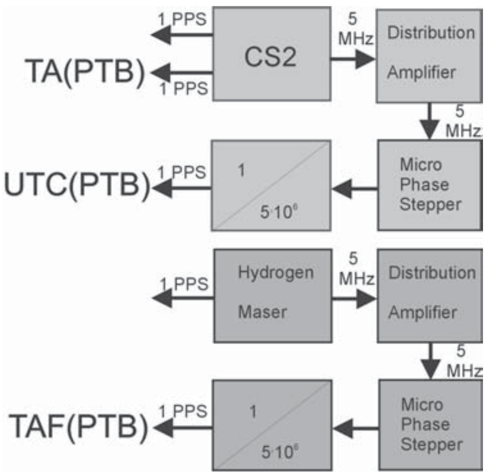

Figure 4. *Schematic representation of the generation of UTC(PTB), TA(PTB) and the fountain time scale TAF(PTB)*

Although we did not achieve a perfectly stable and reliable realisation of TAF(PTB) yet, it may be interesting to report on the instability and predictability of the new time scale. The modσ_y data of four different comparisons are compiled in Fig. 6. Data points (•) reflect the comparison TAI - TAF(PTB) which is based on TAI - TA(PTB) data published in the BIPM Circular T and an internal comparison (see Fig. 4). Comparisons with the maser ensemble time scale AT1E of NIST [Ref. 10] were performed using GPS carrier phase receivers

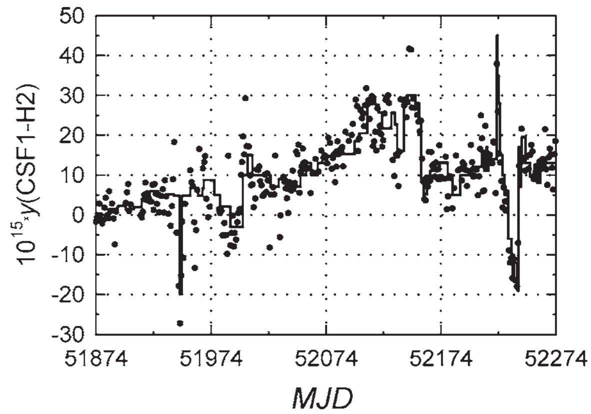

Figure 5. *Dots: Results of comparisons of a hydrogen maser HM with respect to CSF1 expressed as relative frequency difference as a function of time; stepped solid curve: frequency steering applied in the realisation of TAF(PTB).*

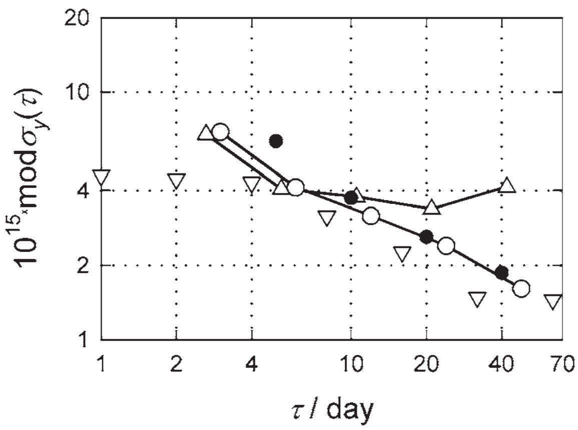

Figure 6. *Frequency instability mod$\sigma_y(\tau)$ observed in the comparison between TAF(PTB) and TAI (●), TAF(PTB) and UTC(USNO) using TWSTFT (o), TAF(PTB) and UTC(NIST) using TWSTFT (Δ), and TAF(PTB) and NIST AT1E (Ξ) using GPS carrier phase; many details of the data treatment are given in the text.*

(symbol ∇), as mentioned above, yielding daily mean frequency differences. TWSTFT was used for comparisons with UTC(NIST) (symbol Δ) and UTC(USNO) (symbol O). In our instability analysis we assumed that the 156 (132) measurements made with NIST (USNO) during the in total 402 days of the comparisons were equally spaced in time, which leads to mean frequency differences at averaging intervals of 2.59 d (3.07 d), respectively.

During 2001, TWSTFT between Europe and the US was for some weeks deteriorated by a reduced availability of the employed satellite and changes of downlink frequencies. Before calculating the frequency differences, we decided to remove some steps in the time scale differences which could unambiguously be identify as due to such problems. It may be the case that this data treatment was not done perfectly. Despite of these problems, the comparisons indicated an improved stability of TAF(PTB) compared to UTC(PTB).

In view of the potential use of PTB's time scales as a time reference for the establishment of the system time of the future European Navigation Satellite System Galileo, we started to study the real-time predictability of the time difference TAI - TAF(PTB). In our prediction strategy we assumed that Circular T, reporting data TAI - TA(PTB) including that for date D_E, is available between 15 and 20 days after D_E. The prediction was done for a period spanning five 5-day intervals starting with day D_E+20 and combined the Circular T data with internal comparisons TAF(PTB) - TA(PTB). In our first approach the prediction was based on a linear fit to the last 7 time differences, including D_E, and projecting into the future. An example of one fit is given in Fig. 7 for illustration.

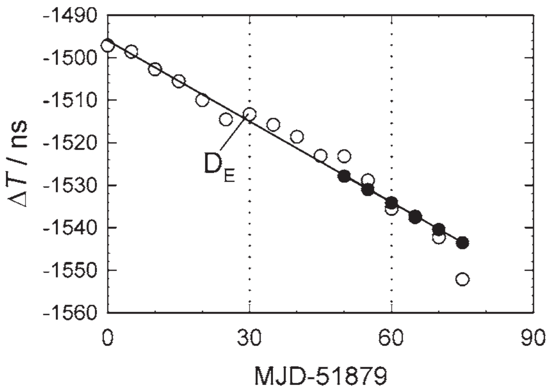

Figure 7. *Illustration of the strategy used to predict time differences ΔT:= TAI-TAF(PTB). The real data (o) are available on days with MJD ending in 4 and 9 and are based on Circular T plus internal comparisons. The predicted time differences (•) are derived from a linear fit to seven data points up to date D_E. The gap between D_E and D_E+20 reflects the delayed availability of Circular T. MJD 51879 corresponds to 2000-12-01.*

The deviations between predicted and documented time scale differences are shown in Fig. 8. Whenever the deviations show a large excursion this can be related to an unexpected behaviour of the hydrogen maser which we were unable to correct for in real time. It should be emphasised that TAF(PTB) was not post-processed, which would have been possible based on the data shown in Fig. 5. The mean of the differences shown in Fig. 8 is 0.7 ns and the 1σ -standard deviation amounts to 12.4 ns. In the future we plan to test different strategies for steering and prediction.

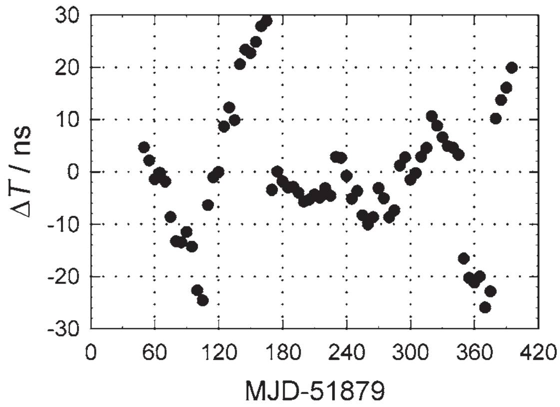

Figure 8. *Differences between predicted and documented differences TAI - TAF(PTB).*

ACKNOWLEDGEMENT

We gratefully acknowledge the support of NIST, providing the geodetic GPS receiver. Tom Parker, NIST, and Lisa Nelson, now at United States Naval Observatory, Washington DC, analysed the data and made them available to us. Their efforts are highly esteemed. We owe thanks to Jürgen Becker and Thomas Polewka of PTB for careful supervision of the local time comparison equipment and for data analysis.

REFERENCES

[1] Bauch A., Weyers S., this proceedings

[2] Weyers S., Hübner U., Schröder R., Tamm Chr., Bauch A., *Metrologia* **38,** 343-352, (2001)

[3] Weyers S., Hübner U., Fischer B., Schröder R., Tamm Chr., Bauch A., *Proc. 14th Europ. Freq. Time Forum (EFTF),* , 53–57 (2000)

[4] Weyers S., Bauch A., Schröder R., Tamm Chr., to be published in *Proc. of Symp. Frequ. Stand. and Metrol., St. Andrews, Sept. 2001*, World Scientific (2002)

[5] Thomas C., Wolf P., Tavelle P., *Time Scales*, BIPM Monographie 94/1 (1994)

[6] Bauch A., Fischer B., Heindorff T., Hetzel P., Petit G., Schröder R., Wolf P., *Metrologia* **37**, 683-692 (2001)

[7] Parker T., Hetzel P., Jefferts S. R., Weyers S., Nelson L., Bauch A., Levine J., *Proc. 2001 IEEE Frequency Control Symposium,* 63-68,(2001)

[8] Parker, T., NIST, private communication, Jan. 2002

[9] Nelson L. M., Levine J., Hetzel P., *Proc. IEEE/EIA Intern. Frequ. Contr. Symp.,* 622-628 (2000)

[10] T. E. Parker, *Proc. 1999 Joint Meeting of the Europ. Freq. and Time Forum and the IEEE International Freq. Contr. Symp*, 173-176 (1999)