Physikalisch-Technische Bundesanstalt, Germany

Report on Activities to the 16th Session of the Consultative Committee for Time and Frequency, April 2004

This report covers the activities pursued in PTB's Time and Frequency Department concerning

1. primary clocks
2. atomic-time scales
3. time and frequency comparisons.

In preparation of the meeting of the CCTF/CCL Joint Working Group on Secondary Representations of the second a separate document dealing with optical frequency standards and optical frequency measurement is made available.

1. Primary clocks

1.1 Fountain clock CSF1
CSF1 is a caesium fountain clock based on the (100)-geometry of the laser beams for the capture of caesium atoms in a magneto-optic trap. The atoms traverse a state-selection cavity before reaching the main microwave cavity and the free-flight region. CSF1 has been operated almost every day over the last three years [1], with the longest interruption (one week) due to the failure of a laser diode in summer 2003.

Most of the time CSF1 was run under a variety of operating conditions, with the goal of investigating possible systematic effects and of optimisation and modernisation of the control and detection electronics. Further developments included the partial automation of the data analysis. All this work is still on-going. One potential problem was encountered when the main cavity was operated at higher microwave power: applying $3\pi/2$-pulses or $7\pi/2$-pulses to the atoms instead of $\pi/2$-pulses leads to a shift of the fountain output frequency exceeding the stated type-B uncertainty, a shift not present when $5\pi/2$-pulses are used. Investigation of the roots of this effect and whether it might be a problem under normal operating conditions have been seriously hampered by the lack of a suitably stable frequency reference (better than the hydrogen masers currently available) and have therefore been postponed until a better reference becomes available with the second PTB fountain (see below).

Since CSF1 became operational, it was run 15 times under routine operating conditions for periods of 15-25 days each, the results were submitted to BIPM and served for the measurement of the TAI scale unit. When these operating conditions are maintained, the CSF1 u_B is estimated as $\leq 1 \cdot 10^{-15}$. The CSF1 results are compiled in Figure 1, together with those of other fountains.

Several comparisons of CSF1 to other fountain clocks took place during the last two years. From Nov. 2002 to Feb. 2003 the team of BNM SYRTE operated their mobile fountain clock FOM next to CSF1 in the clock hall of PTB. A number of frequency comparisons could be performed, with the results and their uncertainty intervals falling into the hatched rectangle in Fig. 2. The other data points in Fig. 2 indicate the results of remote frequency comparisons by GPS and/or TWSTFT, during which the fountain clocks were operated simultaneously in their respective home laboratories. In the table below we list the results of averaging these remote

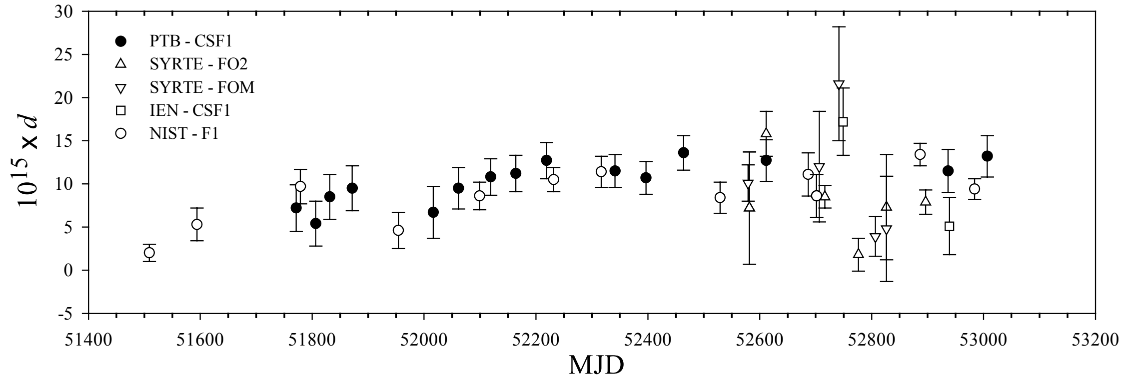

Fig. 1: Contributions of caesium fountain clocks to TAI over the last four years, as given in chapter 4 of BIPM's Circular-T and the BIPM Time Section Annual Report. The vertical axis shows the relative frequency difference y(Fountain – TAI) between the respective fountain clock and TAI, in units of 10^{-15}. The error bars reflect the total uncertainty u.

comparisons of CSF1 with each individual clock. The value y(CSF1-RF) is the average relative frequency difference of CSF1 minus the respective remote fountain. This weighted average was calculated by assigning a combined uncertainty $u_{\mathrm{comb}} = (u_{\mathrm{A}}^2 + u_{\mathrm{B}}^2)^{1/2}$ to each comparison point. A total uncertainty u_{tot} was assigned to the resulting average value y. u_{tot} was obtained by quadratically summing the unweighted average of the individual u_{B} of each data point for this clock pair on the one hand and an overall statistical uncertainty of each data point on the other hand, the latter being obtained in the usual way as the reciprocal of the root of the sum of the individual $1/u_{\mathrm{A}}^2$.

Remote fountain (RF)	***y(CSF1-RF)*** **·10^{15}**	**$u_{\mathrm{tot}}\cdot 10^{15}$**
SYRTE - FO2	0.86	1.89
SYRTE - FOM	3.76	2.08
IEN - CSF1	4.14	2.46
NIST - F1	1.42	1.63
NPL - CSF1	1.82	4.34

Apparently the relative frequency of CSF1 is higher than that of other fountain clocks, by a weighted mean of all remote comparisons of $(2.2 \pm 1.0)\cdot 10^{-15}$. It should be noted, however, that for some data points both GPS and TWSTFT data were available, but sometimes differed by more than $2\cdot 10^{-15}$; the error bars do not include this discrepancy. Furthermore, there are data points from only five other fountain clocks, so the sample is rather small and shows a strong scatter even when the comparison is with one and the same clock at different epochs (see Figure 2). Obviously, the investigation of both the scatter and the apparent frequency differences will have to be continued.

The results of internal and remote comparisons show that any possible CSF1 error lies within the toal uncertainty attributed to CSF1-TAI comparisons which are used for the steering of TAI.

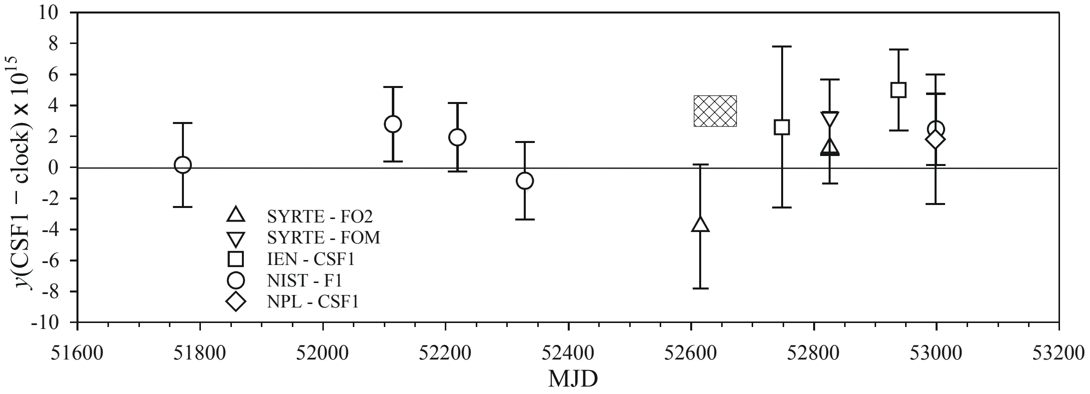

Fig. 2: Direct (hatched rectangle) and indirect (via GPS and/or TWSTFT) comparisons of caesium fountain frequencies. The two data points at MJD = 52826 are preliminary. The uncertainty bars include statistical and systematic uncertainties of both fountain clocks in each comparison, as well as the statistical uncertainty of the remote frequency comparison.

1.2 Thermal beam clocks

The primary clocks CS1 and CS2 have been continuously operated during the last years. Measurements of parameters affecting the clock frequency, like mean atomic velocity, magnetic field, magnetic field homogeneity, cavity phase difference, spectral purity of the microwave interrogation signal, servo electronic offsets, and temperature of the vacuum enclosure, were performed. They supported the validity of the previous estimates of the clock's uncertainties u_B of $7 \cdot 10^{-15}$ and $12 \cdot 10^{-15}$, for CS1 and CS2, respectively [3].

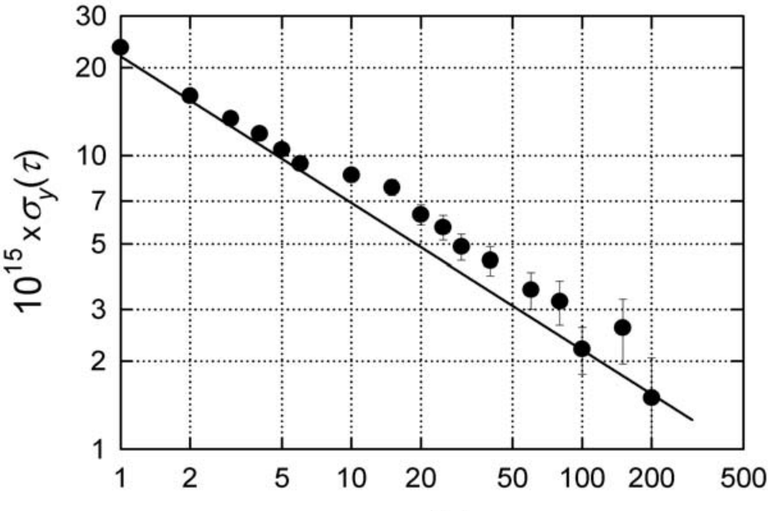

Fig.3 Relative Frequency Instability between CS1 and CS2.

Since the last major refurbishment of CS1 we collected 2200 days (Dec. 1997 to Dec. 2003) of data comparing CS1 and CS2. The mean frequency difference is $y(\mathrm{CS1-CS2}) = -6.05 \cdot 10^{-15}$. The relative frequency instability $\sigma_y(\tau)$ is shown in Figure 3. The "error bars" are calculated based on the number of samples at a given averaging time. To our knowledge this is one of the longest continuous records of a caesium clock comparison available. The solid line is described by $\sigma_y(\tau) = 21.8 \cdot 10^{-15}\ (\tau/\mathrm{d})^{-1/2}$, and is predicted from the properties of the two clocks: signal strength, atomic line Q, and known noise sources. It is not a fit to the data points. One notices slightly excessive noise which can be attributed most likely to CS1 as indicated by comparisons to CSF1 during 2000-2003 (see below).

Comparisons of CS1 and CS2 with CSF1 during 3 years revealed that in case of CS2 the mean departure from CSF1 is only $5 \cdot 10^{-15}$ and is thus much less than u_B(CS2) [4]. The scatter in the data is modelled well by the CS2 short-noise limited frequency instability. This is not perfectly the case for CS1, where the offset is about $10 \cdot 10^{-15}$, and the scatter in the data must be explained with some undetected variations of at least one systematic frequency shift. The results of the internal comparison are compiled in Figure 4.

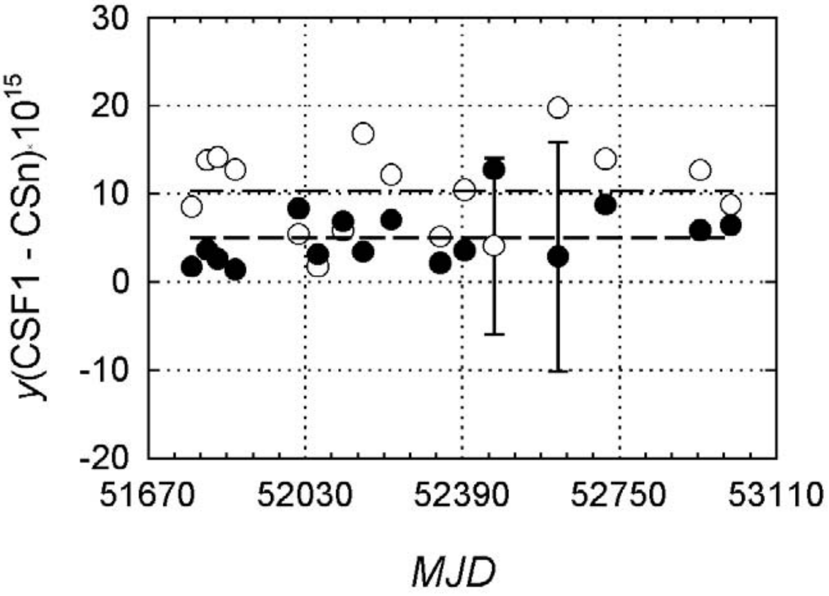

Fig. 4. Relative frequency difference y(CSF1-CSn) obtained between Aug. 2000 and Jan. 2004 for CS1 (O) and CS2 (•). The uncertainty bars (one for each pair of clocks for clarity) represent the combined u_B and u_A due to the measurement time of ≈18 days on average.

In view of the superiority of the fountain type clocks we abandoned operation of CS4 and also do no longer perform uncertainty estimates for CS3 which is now treated like PTB's commercial clocks. We direct most of the resources to the operation of CSF1 and the development of CSF2.

1.3 Fountain clock CSF2

The results obtained on CSF1 demonstrate that it is more important than ever to have a second fountain clock available next to CSF1. Construction of a second caesium fountain, called CSF2, was begun in 2002. It will make use of the (111)-geometry of laser beams in the trapping region and otherwise differs from CSF1 in several details. The vacuum system is now nearing completion, and we are expecting the first cold atoms around the middle of this year. The fountain should become fully operational in early 2005.

2. Time Scales

PTB continues to realise a free atomic time scale TA(PTB) directly from the 1 PPS output of CS2. UTC(PTB) differs from TA(PTB) by a large time offset which has evolved over the decades. The UTC(PTB) rate is adjusted in steps of 0.5 ns/d once per month if required to keep the time scale in close agreement with UTC. The steering values are published in PTB's Time Service Bulletin.

For some time we have studied the possibility and suitability to realise UTC(PTB) based on the output frequency of a hydrogen maser steered towards the frequency of CSF1. Up to now, experimental tests revealed that the availability of fountain data, the stability and predictability of the PTB masers, and the performance of the hardware components did not yield a substantial improvement over the current procedures. These investigations go on.

3. Time and Frequency Comparisons

At present, different GPS common view (CV) time transfer evaluation techniques and Two – Way Satellite Time and Frequency Transfer (TWSTFT) are being employed in the realisation of TAI. In this context PTB provides data of one single-channel, of one multi-channel, and of a geodetic time-oriented GPS receiver as well as TWSTFT data.

PTB is participating in TWSTFT among the institutes BNM SYRTE, IEN, NIST, NPL, OCA, ROA, USNO, and VSL, using a geostationary satellite provided by Intelsat. The up-link and down-link frequencies are in the Ku-band. In August 2003 time comparisons via the satellite IS 706 had to be abandoned since the satellite did no longer provide the required interconnectivity between Europe and America. TWSTFT has been continued using IS 903 which is located at a different position in the sky. The influence of this exchange of satellites on the measurements and the delay changes due to necessary hardware changes were analysed and appropriate corrections were applied to the data.

During 2003, the number of TWSTFT measurements was increased from 3 scheduled sessions per week to 4 sessions per day (7 days a week). In the course of this schedule extension the measurement setup and data processing and distribution was modernised at PTB.

A permanent dedicated TWSTFT link with USNO has become operational in summer 2002 with considerable support by USNO. Currently two hydrogen masers in both institutes are compared nominally 24 times per day for 15 minutes via a military communication satellite (up-link/down-link in X-band) in addition to the established Ku-band link. SATRE modems of TimeTech, Stuttgart, are employed at both sites. They allow the exchange of measurement results obtained with an internal time interval counter among the stations through the transmitted PN-sequence. The data are made available on USNO‘s ftp-server, and after processing by PTB they are sent monthly to the BIPM as a backup to the primary TWSTFT Ku-band link.

For regular time transfer to many timekeeping laboratories, PTB still operates two NIST type single channel C/A code receivers tracking GPS satellites according to the schedule recommended by the BIPM for GPS common view time transfer. The time scale comparison UTC(PTB) – T(GPS) is available on PTB's ftp-server. Since October 2003 the data of the then installed eight-channel GPS receiver TTS-2 have been provided on PTB's ftp site. Since

December 2003 the BIPM uses these data for time transfer between laboratories equipped with multi-channel C/A code receivers.

In April 2000 the German Federal Agency for Cartography and Geodesy (BKG) in Wettzell created a permanent EUREF station using a TurboRogue SNR-8000 receiver. In early 2002 this receiver was replaced by an Ashtec Z12T, and PTB has been included in the IGS Network (station acronym PTBB). Data from PTBB are used in the BIPM TAIP3 study whether geodetic receivers may replace standard C/A code receivers in the production of TAI. In this context the PTBB station was calibrated twice (July 2002, June 2003) by the BIPM.

PTB is involved in the development of the European satellite navigation system Galileo. In 2003 PTB has become part of the experimental ground infrastructure of the Galileo System Testbed (GSTB-V1). Among other elements of the Test-Bed, the time laboratory of IEN, Torino, serves as the Experimental Precision Timing Station (E-PTS), and data from PTB shall be used to steer the time scale generated at IEN to TAI. This collaboration reflects to some extent the future realisation of Galileo System Time. A second geodetic time-oriented Ashtec Z12-T receiver was installed at PTB as a part of the GSTB-V1 Sensor Station network (acronym PTBG). Throughout 2004 it will be used for providing a time link between the E-PTS and PTB through the Orbit Determination and Time Synchronisation process, in parallel with existing standard time comparison links between the two laboratories. The primary time link using TWSTFT between both institutes was calibrated in summer 2003 in the frame of these activities.

Additionally, a Turbo Rogue SNR 12 RM (on loan from NIST) is operated for studies of carrier phase GPS frequency transfer between NIST and PTB [1]. Data were used in the earlier frequency comparisons between NIST-F1 and CSF1 (see Figure 1).

Calibration activities 2002-2003:

GPS:

C/A	Two calibrations using the travelling BIPM receiver in June and August 2003,
TAIP3	Two calibrations with Z12-T from BIPM in the framework of the TAIP3 experiment (July 2002, May/June 2003).

TWSTFT:

USNO-PTB	Link calibrated 2002 and 2003 with a transportable station owned and operated by USNO.
IEN-PTB	Ku-band earth stations calibrated in May/June 2003.

4. References

[1] Bauch, A., Nelson, L., Parker, T., and Weyers. S., Proc. 2003 IEEE Intl. Frequ. Contr. Symp. and 17th EFTF, pp. 217 - 221

[2] S. Weyers, A. Bauch, R. Schröder and Chr. Tamm, *Proc. 6th Symposium on Frequency Standards and Metrology*, St. Andrews, Oct. 2001, pp. 64 - 71

[3] Heindorff T., Bauch A., Hetzel P., Petit G., Weyers S., Metrologia, **38**, 2001, pp. 497-502

[4] Bauch, A., Schröder, R., and Weyers S., Proc. 2003 IEEE Intl. Frequ. Contr. Symp. and 17th EFTF, pp.191 - 199