Physikalisch-Technische Bundesanstalt, Germany

Report on Activities to the 15th Session of the Consultative Committee for Time and Frequency June 2001

This short report covers the activities in the field of time and frequency metrology pursued at PTB,

1. primary clocks,
2. atomic time scales,
3. time and frequency comparisons,
4. optical frequency standards and frequency measurement.

1. Primary clocks

1.1 Status of the clocks using a thermal atomic beam

As an outcome of a detailed evaluation, published in Metrologia in early 1999, the uncertainty (relative quantity, here and in the following) of the primary clock CS1 was stated as $u_B = 7{\cdot}10^{-15}$. For some months the CS1 was used in measurements of the frequency shift due to excitation of the $\Delta F = \pm 1$, $\Delta m_F = \pm 1$ (σ-) transitions which occur simultaneously with the excitation of the clock transition in the cavity. The measurement results were not fully conclusive, but showed that at the routine magnetic flux density in the CS1 the frequency shift is in the low 10^{-15} region. In the clocks' uncertainty budget, an entry of this magnitude was included. 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 $u_B = 12{\cdot}10^{-15}$. The CS3 performance was in some disagreement with the stated uncertainty of $14{\cdot}10^{-15}$. Clock operation was stopped at the beginning of December 1999 for replacement of one empty oven and was resumed by mid February 2000. Unfortunately, over the year 2000 the other oven ran unexpectedly out of caesium as well, and the clock had to be stopped again. Repair was finished at the beginning of March 2001 and the clock uncertainty is currently evaluated.

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 has been common practise for some time. Up to recently, a single line of data for each month or for each time interval during which the standard was operated was published in the CircularT, issued by the BIPM Time Section, and later published in the Annual Report of the BIPM Time Section. This practice was suspected not to fulfil 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,

Hausadresse, Lieferanschrift: Bundesallee 100 38116 Braunschweig Deutschland
Telefon (Zentrale): (05 31) 5 92-0 Telefax (Zentrale): (05 31) 5 92-92 92
Bundeskasse Hannover Postbank 5018-304 (BLZ 250 100 30) Bundeskasse Hannover LZB Hannover 250 01 000 (BLZ 250 000 00)
PTB Berlin-Charlottenburg Abbestraße 2-12, 10587 Berlin PTB Berlin-Friedrichshagen Fürstenwalder Damm 388, 12587 Berlin

- 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 $u_{clock-TAI}$ reflecting the uncertainty in the link to TAI of this contributing clock,
- information on the instability $\sigma_{TAI}(\tau)$ of TAI itself.

In fulfilment of these recommendations two papers were written jointly with colleagues from BIPM, one for the clock results in 1999 and 2000 each.

1.2 Status of the fountain clock CSF1

The development of a Zacharias fountain clock using laser-cooled caesium atoms had started in 1995. First microwave fringes had been observed in 1998. During 1999 it was possible to reduce the frequency instability to the level which is predicted from the local oscillator noise contribution (Dick effect), and the atom number in the detected cloud. In early 2000, the type B uncertainty of CSF1 in the current mode of operation was estimated to be $1.5 \cdot 10^{-15}$. The evaluation was presented at the European Frequency and Time Forum 2000. A second cavity for selection of atoms in the state F=3, $m_F = 0$, after launching and before the passage into the interaction region, was installed later during the year. This caused a break of the normal operation for about three months. The use of this cavity was postponed until early 2001. In the meantime, operational experience was improved by running CSF1 quasi continuously during four intervals, each of 15 days duration. Data with respect to one of PTB's hydrogen maser were collected for periods between BIPM standard dates and submitted to BIPM. In this way, the TAI scale unit could be compared four times to the SI second as realised in CSF1 with a combined uncertainty of $2{,}6 \cdot 10^{-15}$, documented in BIPM CircularT. During April 2001 the first CSF1 run including the state preselection was performed. The frequency instability could be reduced significantly. But, determination of the collisional shift had been hampered by the lack of a suitably stable reference in the laboratory. Therefore the CSF1 standard uncertainty u_B was estimated as $2 \cdot 10^{-15}$ (1 σ) for that particular period. Data have been included in figures 1 and 2.

1.3 Results

In figure 1, the results of comparison between the primary clocks CSF1, CS1, and CS2 and the two hydrogen masers is shown. It can be seen that agreement between CS2 and CSF1 is always well within the overlap of the 1-σ error bars whereas the CS1 frequency was occasionally found slightly too low.

In summary of section 1, in figure 2 all PTB measurement data of the TAI scale interval during the last 24 months have been compiled.

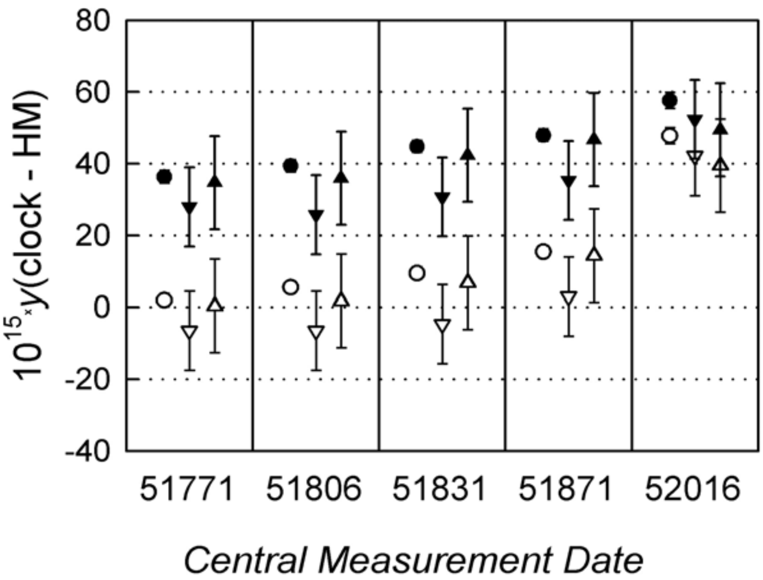

Figure 1. Results of comparison between the primary clocks CSF1 (O), CS1 (∇), CS2 (∆) and the two hydrogen masers, distinguished by open and full symbols, depicted for five 15-day intervals. Each data represents 15-day averages of simultaneous measurements which are displaced horizontally in the plot for clarity. The label on the horizontal axis represents the mid-point of the measurement interval. Error bars (1 σ) reflect the combined uncertainty u_B of the standards, $7 \cdot 10^{-15}$ for the CS1, $12 \cdot 10^{-15}$ for the CS2 and the uncertainty due to white frequency noise dominated performance at 15 days averaging time.

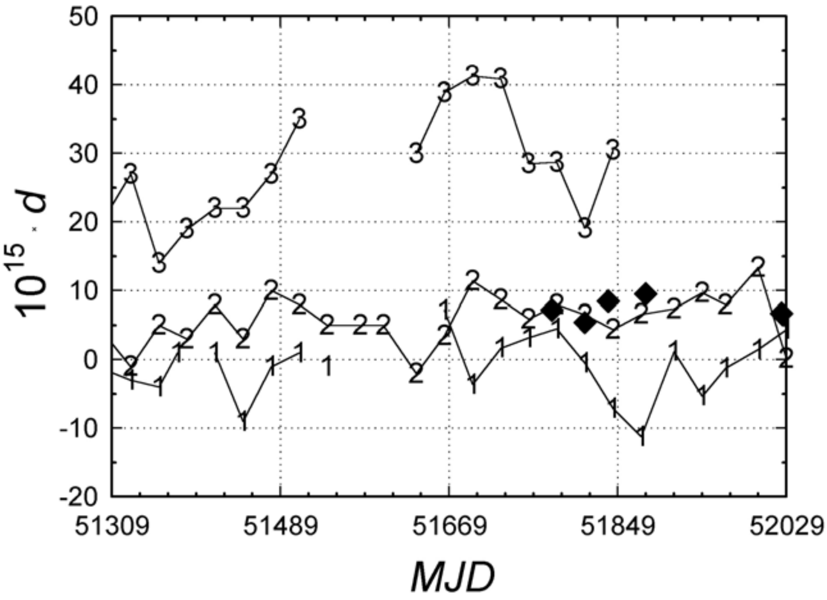

Figure 2. Fractional deviation, *d*, of the duration of the TAI scale interval from the SI second as realised by the clocks CS1(1), CS2(2), CS3(3), and CSF1(♦) during two years. MJD denotes the Modified Julian Date; MJD 52029 corresponds to 2001-04-30. Source: BIPM Circular T issues 137 - 160.

2. PTB Time Scales

PTB continues to realise 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 minimise 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 whose scale unit shall represent the SI second as realised with CSF1 (on the rotating geoid) has been realised and has been given the provisional name TAF(PTB). Its hardware realisation is based on the 5 MHz output signal of an active hydrogen maser HM. Frequency steering in a phase micro stepper (PMS) reflects the results of frequency comparisons CSF1-HM. The PMS output is fed to a divider generating 1 pps which is continuously monitored in PTB's clock comparison routine. Comparison of TAF(PTB) with TAI on one hand, and UTC(USNO) and UTC(NIST) revealed the improved stability of TAF(PTB) compared to UTC(PTB), despite of the problems of realising TAF(PTB) during some weeks of bad performance of the maser. For the time being, it is premature to state an accuracy of 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).

3. Time and Frequency Comparisons

For regular time transfer to the BIPM and other timekeeping laboratories, PTB has operated three NIST type receivers tracking GPS satellites according to the schedule recommended by the BIPM for GPS Common-View Time transfer. The data UTC(PTB)-T(GPS) data are available on PTB's ftp-site.

PTB continues to participate in the TWSTFT using an INTELSAT geostationary satellite at 307°E. The recent synthesizer problems in the transatlantic links caused by the change of the down frequencies from the band 12 GHz range to the lower 11 GHz range could be solved. Thus PTB is able to compare to European as well as to US participating stations. The TWSTFT data are made available on PTB's ftp-site and contribute to the calculation of the BIPM atomic time scales.

At present PTB is establishing an X-band ground station to create a permanent 2-way link via an U.S. military X-band satellite between PTB and USNO. USNO has offered satellite transponder time for such a transatlantic link. It is the aim to get the X-band station running in 2001. In preparation of this undertaking USNO established a provisional X-band link in May 2000 for a few days and verified the feasibility of the link. It was used to perform a calibration experiment of the PTB-USNO KU-band link as the travelling X-band station had been absolutely calibrated after the trip and had been operated simultaneously with the KU-band station. The final evaluation of the data of this calibration trip is in the hands of the USNO.

PTB has been invited to participate in the studies of the GPS carrier phase technique using geodetic receivers for accurate time transfer. Three geodetic receivers have been operated at the PTB and the results of the GPS-CP method have been compared with the results obtained by GPS-CV comparisons and TWSTFT.

a) TourboRogue SNR 12 RM (on loan from NIST) to study the link NIST - PTB using the GPS-CP method. This link was recently used to compare the two fountains, NIST-F1 and PTB CSF1. NIST evaluated the measurement uncertainty due to the link being as low as $6 \cdot 10^{-16}$ for a 15-day measurement interval.

b) GeTT station of the Swiss METAS using Ashtech-Z12 to study the link USNO - PTB

c) In April 2000 the German Federal Agency for Cartography and Geodesy (BKG) in Wettzell created a permanent EUREF station (in the network of geodetic reference stations) at the PTB using at present a TurboRogue SNR-8000 receiver. In addition to the geodetic CP- data once per day the hourly timing data UTC(PTB) - 1PPS/OUT are also sent to the BKG from where they are made available to interested institutions on request. The observed receiver data are available at the ftp-site of the BKG.

4. Optical Frequency Standards

Frequency comb generators based on Kerr-lens mode-locked femtosecond lasers have dramatically simplified optical frequency measurements in units of the SI Hertz. Connecting this technique with lasers stabilised to suitable narrow optical transitions in cold atoms or trapped single ions paves the way for a future optical frequency standard. At PTB such a measurement system has been set-up and successfully employed in measurements of the transition frequency of the calcium intercombination line at λ_{Ca} = 657 nm, and of a transition in $^{171}Yb^{+}$ at λ_{Yb} = 435 nm.

The two recent calcium measurements continued a series of previous measurements using the traditional harmonic frequency chain of PTB. Figure 3 shows the temporal evolution of determinations of the centre frequency and of the uncertainty of these measurements.

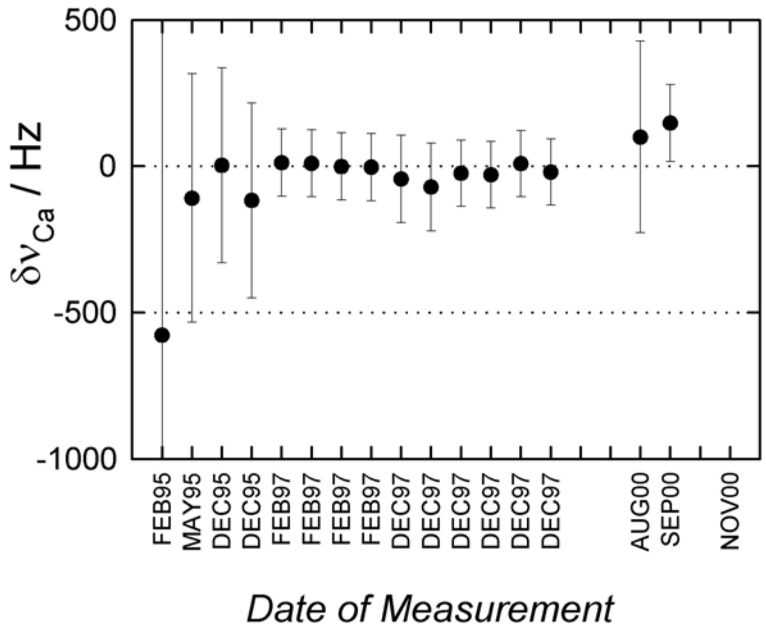

Figure 3. Results of frequency measurements of the Ca intercombination line at λ = 657 nm with PTB's primary clock CS2. The reference value is the CIPM reference value.

The $^2S_{1/2} \rightarrow {}^2D_{3/2}$-transition at λ = 435 nm was observed from a single $^{171}Yb^+$-ion with a linewidth of about 30 Hz, and a frequency-doubled diode laser was stabilised to this transition for hours. The result of the measurement of the transition frequency, 688 358 979 309 312(6) Hz represents one of the most accurate optical frequency measurements ever performed. The uncertainty, about 10^{-14} in relative units, consists of several components which are largely due to the measurement process, the laser stabilisation etc. but which do not reflect the intrinsic accuracy limit of the reference line of the single ion. The more fundamental effects like the sensitivity of the reference transition to AC and DC electric and magnetic fields shall be investigated in measurements using two ion traps in parallel.

Research into optical frequency standards has a very long tradition at the Max Planck Institute for Quantum Optics in Garching. Recent achievements comprise an improved measurement of the transition frequency of the 1s$\rightarrow$2s transition in atomic hydrogen, also using an optical frequency comb. The measurement uncertainty is similar to the one reported above for the ytterbium transition and has been achieved by comparing the hydrogen frequency with the French travelling caesium fountain PHARAO.

In the same institute, measurements of the $5s^2\ {}^1S_0 \rightarrow 5s5p\ {}^3P_0$ transition at λ = 237 nm of a single indium ion with a relative uncertainty of about 1 part in 10^{13} were performed. The indium ion possesses some advantages with respect to the ultimately achievable uncertainty, since some systematic frequency shifting effects which occur e.g. in ytterbium and mercury ions are absent due to the specific electron configuration.