Operation of the PTB primary clocks in 2020

PTB's primary clocks with a thermal beam

During 2020, PTB's primary clocks CS1 and CS2 were operated almost continuously. Time differences UTC(PTB) - clock in the standard ALGOS format were reported to BIPM, so that $u_{l/lab}$ is zero. The mean (MJD 58849 to 59214) relative frequency offset y(CS1 – CS2) amounted to -0.7×10^{-15}, which is compliant with the stated u_B values [1,2].

The clocks' operational parameters were checked periodically and validated to estimate the clock uncertainty. These parameters are the Zeeman frequency, the temperature of the beam tube (vacuum enclosure), the line width of the clock transition as a measure of the mean atomic velocity, the microwave power level, the spectral purity of the microwave excitation signal, and some characteristic signals of the electronics. Using a high-resolution phase comparator, the 5 MHz output signals of both clocks have been continuously compared to 5 MHz of superior frequency instability to assess the frequency instability of CS1 and CS2, respectively. Data analysis has been made based on several 15 to 20-day batches distributed during 2020.

CS1

The CS1 relative frequency instability $\sigma_y(\tau = 5000\ \text{s})$ was found to vary between 69×10^{-15} and 82×10^{-15} during 2020, generally in agreement with the prediction based on the prevailing parameters beam flux, clock transition signal and line width. With reference to TAI, the standard deviation of *d*(CS1) (Circular T Section 3, 12 months) was 6.5×10^{-15}, in agreement with the value $u_A(\tau = 30\ \text{d, CS1}) = 8\times10^{-15}$ stated in Circular T. During the year, two reversals of the beam direction were performed on CS1. No findings call for a modification of the previously stated relative frequency uncertainty u_B, which is 8×10^{-15} for CS1 [2]. This value complies with the mean offset between CS1 and TAI during 2020 (mean of the 12 *d*-values reported in Circular T) of -4.2×10^{-15}.

CS2

The relative CS2 frequency instability of $\sigma_y(\tau = 5000\ \text{s})$ was measured between 52×10^{-15} and 66×10^{-15} during 2020, generally in agreement with the prediction based on the prevailing parameters beam flux, clock transition signal and line width. The standard deviation of the 12 *d*-values reported in Circular T for 2020 amounted to 2.9×10^{-15}. The scatter of data is lower than in previous years and is fully in line with the stated uncertainty contribution $u_A(\tau = 30\ \text{d, CS2}) = 5\times10^{-15}$ reported in Circular T. During the year, two reversals of the beam direction were performed on CS2.The uncertainty estimate as detailed in [1, 2] is considered as still valid, and the CS2 u_B is thus estimated as 12×10^{-15}. This value complies well with the mean offset between CS2 and TAI during 2020 (mean of the 12 *d*-values reported in Circular T) of -3.1×10^{-15}.

PTB's primary caesium fountain clocks

In 2020 both caesium fountain clocks, CSF1 and CSF2, were operated regularly with a high duty cycle. The frequency synthesis for both fountains routinely makes use of an optically stabilized microwave oscillator [3-5] instead of employing quartz based microwave synthesis. Since March 2020 a new more robust frequency comb system, which is primarily dedicated to provide the microwave signal for the two fountain clocks, is in continuous use. In the new setup the microwave signal is obtained directly via a photodetector from the frequency-locked frequency comb. For the generation of UTC(PTB) the data of both fountains were routinely used for the steering of a hydrogen maser output frequency [6]. The steering data was obtained from the weighted average of the data of the two fountains, by taking the systematic and statistical uncertainties of either fountain data into account.

CSF1

In 2020 eleven measurements of the TAI scale unit of 10 (1×), 15 (1×), 25 (1×), 30 (7×) and 35 (1×) days duration were performed and reported to the BIPM. The difference between the mean fractional deviation *d* of the scale interval of TAI from that of TT, measured during 295 days by CSF1, and the mean BIPM estimate of *d* based on all simultaneous Primary and Secondary Frequency Standard measurements was less than 1.0×10^{-16}.

Dead times ranged from 2.5% to 11% of the nominal measurement duration, where about 1.5% dead time is caused by the periodic switching between low and high density operation modes and periodical magnetic field measurements. The resulting clock link uncertainty $u_{l/lab}$ was in the range 0.1×10^{-16} to 0.6×10^{-16}.

The statistical uncertainty of CSF1 measurements was calculated with the assumption of white frequency noise during the measurement intervals. For the eleven TAI contributions in 2020 typically statistical uncertainties $u_A < 1\times10^{-16}$ were achieved.

Below we compile typical frequency biases and the updated type B uncertainty budget of CSF1, valid for TAI scale unit measurements [7].

Physical effect	Bias / 10^{-16}	Type B uncertainty / 10^{-16}
Quadratic Zeeman shift	1078.73	0.10
Black body radiation shift	- 167.09	0.81
Relativistic redshift and Doppler effect	85.56	0.02
Collisional shift	15.0	2.3
Distributed cavity phase shift	0.04	0.93
Microwave lensing	0.4	0.2
AC Stark shift (light shift)		0.01
Rabi and Ramsey pulling		0.013
Microwave leakage		0.01
Electronics		0.1
Background gas collisions		0.4
Total type B uncertainty		2.7

CSF2

In 2020 thirteen measurements of the TAI scale unit of 15 (2×), 25 (1×), 30 (9×) and 35 (1×) days duration were performed and reported to the BIPM. The difference between the mean fractional deviation *d* of the scale interval of TAI from that of TT, measured during 360 days by CSF2, and the mean BIPM estimate of *d* based on all simultaneous Primary and Secondary Frequency Standard measurements was -1.0×10^{-16}.

The dead times of the above measurements were usually between 2%-6% of the nominal measurement duration, where about 1% dead time is caused by the periodic switching between low and high density operation modes and periodical magnetic field measurements. The resulting clock link uncertainty $u_{l/lab}$ was $\leq 0.5\times10^{-16}$.

The statistical uncertainty of CSF2 measurements was calculated with the assumption of white frequency noise for the total measurement intervals and includes a statistical uncertainty contribution from the collisional shift evaluation [7]. For the thirteen TAI contributions in 2020 we arrived at statistical uncertainties u_A between $1.0\text{-}1.5\times10^{-16}$.

Below we compile typical frequency biases and an updated type B uncertainty budget of CSF2, valid for TAI scale unit measurements [7].

Physical effect	Bias / 10^{-16}	Type B uncertainty / 10^{-16}
Quadratic Zeeman shift	999.94	0.10
Black body radiation shift	- 165.93	0.63
Relativistic redshift and Doppler effect	85.45	0.02
Collisional shift	-68.4	0.3
Distributed cavity phase shift	0.28	1.52
Microwave lensing	0.7	0.2
AC Stark shift (light shift)		0.01
Rabi and Ramsey pulling		0.013
Microwave leakage		0.01
Electronics		0.1
Background gas collisions		0.1
Total type B uncertainty		1.7

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