

Operation of the PTB primary clocks in 2019

PTB's primary clocks with a thermal beam

During 2019 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_{lab} is zero. The mean (MJD 58484 to 58849) relative frequency offset $y(\text{CS1} - \text{CS2})$ amounted to -4.3×10^{-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 2019.

CS1

The CS1 relative frequency instability $\sigma_y(\tau = 5000 \text{ s})$ was found to vary between 73×10^{-15} and 97×10^{-15} during 2019, almost 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 $d(\text{CS1})$ (Circular T Section 3, 12 months) was 7.9×10^{-15} , in agreement with the value $u_A(\tau = 30 \text{ d}, \text{CS1}) = 8 \times 10^{-15}$ 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 2019 (mean of the 12 d -values reported in Circular T) of -6.5×10^{-15} .

CS2

The relative CS2 frequency instability of $\sigma_y(\tau = 5000 \text{ s})$ was measured between 54×10^{-15} and 73×10^{-15} during 2019, in reasonable 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 2019 amounted to 6.3×10^{-15} . The scatter of data is larger than in previous years and slightly exceeds the stated uncertainty contribution $u_A(\tau = 30 \text{ d}, \text{CS2}) = 5 \times 10^{-15}$ reported in Circular T. During 2019, the air conditioning system in PTB's clock hall was not always working properly, and CS2 is known to be more susceptible to temperature changes than CS1. 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 2019 (mean of the 12 d -values reported in Circular T) of -1.88×10^{-15} .

PTB's primary caesium fountain clocks

In 2019 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. 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 2019 eight measurements of the TAI scale unit of 10 (1×), 15 (1×), 25 (1×), 30 (4×) 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 205 days by CSF1, and the mean BIPM estimate of d based on all simultaneous Primary and Secondary Frequency Standard measurements was 1.0×10^{-16} .

Due to the performance and reliability of the laser systems, dead times are normally kept between 1%-3% (in three cases between 4%-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 in the range 0.2×10^{-16} to 0.5×10^{-16} .

The statistical uncertainty of CSF1 measurements was calculated with the assumption of white frequency noise during the measurement intervals. For the eight TAI contributions in 2019 typically statistical uncertainties $u_A < 1 \times 10^{-16}$ 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	1078.88	0.10
Black body radiation shift	- 165.80	0.80
Relativistic redshift and Doppler effect	85.56	0.02
Collisional shift	9.3	2.5
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		2.8

CSF2

In 2018 fourteen measurements of the TAI scale unit of 10 (2×), 20 (2×), 25 (2×), 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 355 days by CSF2, and the mean BIPM estimate of d based on all simultaneous Primary and Secondary Frequency Standard measurements was -1.1×10^{-16} .

The dead times of the above measurements were in most cases between 2%-6% (in five cases 6%-8%) 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 $\leq 0.6 \times 10^{-16}$.

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 fourteen TAI contributions in 2019 we arrived at statistical uncertainties u_A between 0.9 - 2.2×10^{-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	1003.99	0.10
Black body radiation shift	- 165.39	0.63
Relativistic redshift and Doppler effect	85.45	0.02
Collisional shift	-73.5	0.4
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

References

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