Evaluation of PTB primary caesium fountain frequency standard CSF1 between MJD 60824 - MJD 60839

PTB's primary caesium fountain frequency standard CSF1 was operated between MJD 60824, 0:00 UTC and MJD 60839, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H9, BIPM code 1400509.

The relative frequency instability of the relative frequency differences y(CSF1-H9) was $11.7\times10^{-14}\cdot(\tau/\mathrm{s})^{-1/2}$ during the 15 days. The actual measurement time amounts to 82.1% of the 15 $\times$ 24 hours. Assuming that white frequency noise is the dominant noise source, this results in a statistical uncertainty $u_A = 0.37\times10^{-15}$, if also the statistical uncertainty of the collisional shift determination (0.35×10^{-15}) is taken into account.

For the statistical uncertainty due to the clock link $u_{A/Lab} = 0.07\times10^{-15}$ is obtained by taking into account the actual measurement time, while the systematic uncertainty due to the clock link $u_{B/Lab}$ is negligible. Finally, the estimated uncertainty for the link to TAI for 15 days is $u_{TAI} = 0.24\times10^{-15}$.

Frequency corrections for the following effects were applied to the raw data:

- Zeeman effect (magnetic field along the atoms' trajectory)
- black body effect (thermal radiation along the atoms' trajectory)
- relativistic redshift and relativistic Doppler effect
- cold collisions effect
- distributed cavity phase effect
- microwave lensing effect

Estimated CSF1 standard uncertainty u_B for the relevant period [1]: 2.4×10^{-16} (1 σ).

<u>Table of results of CSF1 compared to hydrogen maser H9 (1400509)</u>

Interval of evaluation	MJD 60824, 0:00 UTC – MJD 60839, 0:00 UTC
Fractional dead time	17.9%
Resulting frequency difference	y(CSF1 – H9) = 54.25×10^{-15}
Type A uncertainty u_A (1 σ)	0.37×10^{-15}
Type B uncertainty u_B (1 σ)	0.24×10^{-15}
Link to clock $u_{A/Lab}$ (1 σ)	0.07×10^{-15}
Link to clock $u_{B/Lab}$ (1 σ)	0.00×10^{-15}
Link to TAI u_{TAI} (1 σ)	0.24×10^{-15} (15 days)
Combined uncertainty (1 σ)	0.51×10^{-15}

Type A (statistical) uncertainty of CSF1

For the microwave synthesis the previously utilized optically stabilized microwave oscillator [2] has been replaced by a new system for the optical generation of ultra-stable microwave signals. The new system utilizes the same cavity stabilized laser as before, but a new commercial frequency comb system, where the microwave signal is obtained from a photodiode. As before this signal is locked to a hydrogen maser in the long-term and employed as local oscillator for the PTB fountain clocks.

The frequency instability 11.7×10^{-14} $(\tau/s)^{-1/2}$ of the measured relative frequency differences y(CSF1 – Hmaser) is obtained for the combination of low and high density operation. Since the evaluation of the collisional shift is based exclusively on measurements in the reporting interval, the statistical uncertainty of the collisional shift determination (0.35×10^{-15}) is added to the statistical uncertainty obtained from the frequency instability to obtain the overall Type A uncertainty u_A [1].

The optically stabilized microwave system was available during almost 100% of the TAI measurement interval. Alternatively a quartz-based frequency synthesis system was employed.

Type B (systematic) uncertainty of CSF1

In the table below we report the type B uncertainty evaluation results valid for the evaluation at hand. Detailed descriptions of the systematic uncertainty contributions of CSF1 have been published elsewhere [1].

Since the evaluation of the collisional shift is based exclusively on measurements in the reporting interval, the statistical uncertainty of the collisional shift determination is not part of the overall Type B uncertainty u_B [1].

At the 26th CGPM in November 2018, TAI has been newly defined (Resolution 2). As a result the relativistic redshift of a clock contributing to TAI is to be computed with respect to the conventionally adopted equipotential W_0 = 62 636 856.0 m^2s^{-2} of the Earth's gravity potential. The differentiation relating to the uncertainty of the relativistic redshift for the case of TAI contributions of the PTB fountain clocks in [1] is therefore no longer needed, so that a relativistic redshift uncertainty of 0.02×10^{-16} [1] is attributed now and in the future.

Frequency shifts, corrections and type B uncertainties of CSF1 (parts in 10^{16}):

Frequency shift	Correction	Uncertainty
Quadratic Zeeman shift	- 1079.54	0.10
Blackbody radiation shift	165.98	0.81
Relativistic redshift and Doppler effect	- 85.56	0.02
Collisional shift	-19.8	2.0
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		2.4

References

[1] S. Weyers, V. Gerginov, M. Kazda, J. Rahm, B. Lipphardt, G. Dobrev and K. Gibble, Metrologia **55**, pp. 789–805 (2018), https://doi.org/10.1088/1681-7575/aae008

[2] B. Lipphardt, V. Gerginov, S, Weyers, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control **64,** pp. 761–766 (2017), https://ieeexplore.ieee.org/document/7807353