Evaluation of PTB primary caesium fountain frequency standard CSF1 between MJD 59879 - MJD 59909

PTB's primary caesium fountain frequency standard CSF1 was operated between MJD 59879, 0:00 UTC and MJD 59909, 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 $12.0\times10^{-14}\cdot(\tau/s)^{-1/2}$ during the 30 days. The actual measurement time amounts to 96.7% of the 30×24 hours. This results in a statistical uncertainty $u_A = 0.08\times10^{-15}$, assuming that white frequency noise is the dominant noise source.

For the statistical uncertainty due to the clock link $u_{A/Lab} = 0.02\times10^{-15}$ 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 30 days is $u_{TAI} = 0.07\times10^{-15}$.

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

The CSF1 standard uncertainty u_B is estimated as 3.0×10^{-16} (1 σ) for the relevant period [1].

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

Interval of evaluation	MJD 59879, 0:00 UTC – MJD 59909, 0:00 UTC
Fractional dead time	3.3%
Resulting frequency difference	y(CSF1 – H9) = 45.20×10^{-15}
Type A uncertainty u_A (1 σ)	0.08×10^{-15}
Type B uncertainty u_B (1 σ)	0.30×10^{-15}
Link to clock $u_{A/Lab}$ (1 σ)	0.02×10^{-15}
Link to clock $u_{B/Lab}$ (1 σ)	0.00×10^{-15}
Link to TAI u_{TAI} (1 σ)	0.07×10^{-15} (30 days)
Combined uncertainty (1 σ)	0.32×10^{-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For the microwave synthesis the previously utilized optically stabilized microwave oscillator [2] has been replaced by a new system for the optical generation of ultra-stable microwave signals.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 12.0×10^{-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 and gives the statistical measurement uncertainty u_A [1].

The optically stabilized microwave system was available during >99% 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].

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	- 1077.69	0.10
Blackbody radiation shift	164.99	0.80
Relativistic redshift and Doppler effect	- 85.56	0.02
Collisional shift	-22.0	2.7
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		3.0

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