Evaluation of PTB primary caesium fountain frequency standard CSF2 between MJD 59059 - MJD 59089

PTB's primary caesium fountain frequency standard CSF2 was operated between MJD 59059, 0:00 UTC and MJD 59089, 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(CSF2-H9) was $16.2\times10^{-14}\cdot(\tau/\mathrm{s})^{-1/2}$ during the 30 days, where the statistical uncertainty of the collisional shift evaluation is included. The actual measurement time amounts to 97.7% of the 30×24 hours. This results in a statistical uncertainty $u_\mathrm{A} = 0.10\times10^{-15}$, assuming that white frequency noise is the dominant noise source.

For the statistical uncertainty due to the clock link $u_\mathrm{A/Lab} = 0.01\times10^{-15}$ is obtained by taking into account the actual measurement time, while the systematic uncertainty due to the clock link $u_\mathrm{B/Lab}$ is negligible. Finally, the estimated uncertainty for the link to TAI for 30 days is $u_\mathrm{TAI} = 0.07\times10^{-15}$.

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

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

The CSF2 standard uncertainty u_B is estimated as 1.7×10^{-16} (1 σ) for the relevant period [1].

<u>Table of results of CSF2 compared to hydrogen maser H9 (1400509)</u>

Interval of evaluation	MJD 59059, 0:00 UTC - MJD 59089, 0:00 UTC
Fractional dead time	2.3%
Resulting frequency difference	y(CSF2 – H9) = 14.17×10^{-15}
Type A uncertainty u_A (1 σ)	0.10×10^{-15}
Type B uncertainty u_B (1 σ)	0.17×10^{-15}
Stat. link to clock $u_\mathrm{A/Lab}$ (1 σ)	0.01×10^{-15}
Syst. link to clock $u_\mathrm{B/Lab}$ (1 σ)	0.00×10^{-15}
Link to TAI u_TAI (1 σ)	0.07×10^{-15} (30 days)
Combined uncertainty (1 σ)	0.21×10^{-15}

Type A (statistical) uncertainty of CSF2

For the microwave synthesis the previously utilized optically stabilized microwave oscillator [2] has been replaced by a new system for the optical generation of ultra-stable microwave signals.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.

For CSF2 operation at high density, in this measurement the resulting CSF2 frequency instability and the hydrogen maser frequency instability yield an overall instability of $\sigma_y = 4.7\times10^{-14}\ (\tau/1\mathrm{s})^{-1/2}$ for relative frequency difference measurements y(CSF2 – Hmaser). The statistical measurement uncertainty u_A includes the statistical uncertainty of the collisional shift evaluation and is given by the CSF2 frequency instability at high and low density operation, the respective measurement durations and the hydrogen maser frequency instability [1].

The optically stabilized microwave system was available during more than 99% of the TAI measurement interval. Alternatively a quartz-based frequency synthesis system was employed.

Type B (systematic) uncertainty of CSF2

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 CSF2 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 $W_0 = 62\ 636\ 856.0\ \mathrm{m^2s^{-2}}$ 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 CSF2 (parts in 10^{16}):

Frequency shift	Correction	Uncertainty
Quadratic Zeeman shift	-999.62	0.10
Blackbody radiation shift	166.75	0.63
Relativistic redshift and Doppler effect	-85.45	0.02
Collisional shift	71.1	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

[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