# Evaluation of PTB primary caesium fountain frequency standard CSF1 between MJD 59244 - MJD 59269

PTB's primary caesium fountain frequency standard CSF1 was operated between MJD 59244, 0:00 UTC and MJD 59269, 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 $11.3 \times 10^{-14} \cdot (\tau/s)^{-1/2}$ during the 25 days. The actual measurement time amounts to 94.9% of the $25 \times 24$ hours. This results in a statistical uncertainty $u_A = 0.08 \times 10^{-15}$, assuming that white frequency noise is the dominant noise source.

For the statistical uncertainty due to the clock link $u_{A/Lab} = 0.03 \times 10^{-15}$ 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 25 days is $u_{TAI} = 0.08 \times 10^{-15}$.

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 $2.7 \times 10^{-16}$ (1 $\sigma$) for the relevant period [1].

## Table of results of CSF1 compared to hydrogen maser H9 (1400509)

| | |
|---|---|
| Interval of evaluation | MJD 59244, 0:00 UTC – MJD 59269, 0:00 UTC |
| Fractional dead time | 5.1% |
| Resulting frequency difference | $y(CSF1 - H9) = 19.63 \times 10^{-15}$ |
| Type A uncertainty $u_A$ (1 $\sigma$) | $0.08 \times 10^{-15}$ |
| Type B uncertainty $u_B$ (1 $\sigma$) | $0.27 \times 10^{-15}$ |
| Link to clock $u_{A/Lab}$ (1 $\sigma$) | $0.03 \times 10^{-15}$ |
| Link to clock $u_{B/Lab}$ (1 $\sigma$) | $0.00 \times 10^{-15}$ |
| Link to TAI $u_{TAI}$ (1 $\sigma$) | $0.08 \times 10^{-15}$ (25 days) |
| | |
| Combined uncertainty (1 $\sigma$) | $0.29 \times 10^{-15}$ |

## 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For the microwave synthesis the previously utilized optically stabilized microwave oscillator [2] has been replaced by a new system for the optical generation of ultra-stable microwave signals.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 $11.3\times10^{-14}$ $(\tau/s)^{-1/2}$ 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 $\approx$96% 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 $0.02\times10^{-16}$ [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 | - 1078.73 | 0.10 |
| Blackbody radiation shift | 166.05 | 0.81 |
| Relativistic redshift and Doppler effect | - 85.56 | 0.02 |
| Collisional shift | -16.0 | 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 |

**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