

## Evaluation of PTB primary caesium fountain frequency standard CSF1 between MJD 59269 - MJD 59304

PTB's primary caesium fountain frequency standard CSF1 was operated between MJD 59269, 0:00 UTC and MJD 59304, 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  $y(\text{CSF1-H9})$  was  $11.3 \times 10^{-14} \cdot (\tau/\text{s})^{-1/2}$  during the 35 days. The actual measurement time amounts to 92.6% of the  $35 \times 24$  hours. This results in a statistical uncertainty  $u_A = 0.07 \times 10^{-15}$ , assuming that white frequency noise is the dominant noise source.

For the statistical uncertainty due to the clock link  $u_{A/\text{Lab}} = 0.05 \times 10^{-15}$  is obtained by taking into account the actual measurement time, while the systematic uncertainty due to the clock link  $u_{B/\text{Lab}}$  is negligible. Finally, the estimated uncertainty for the link to TAI for 35 days is  $u_{\text{TAI}} = 0.06 \times 10^{-15}$ .

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 59269, 0:00 UTC – MJD 59304, 0:00 UTC
Fractional dead time	7.4%
Resulting frequency difference	$y(\text{CSF1} - \text{H9}) = 20.79 \times 10^{-15}$
Type A uncertainty $u_A$ ( $1 \sigma$ )	$0.07 \times 10^{-15}$
Type B uncertainty $u_B$ ( $1 \sigma$ )	$0.27 \times 10^{-15}$
Link to clock $u_{A/\text{Lab}}$ ( $1 \sigma$ )	$0.05 \times 10^{-15}$
Link to clock $u_{B/\text{Lab}}$ ( $1 \sigma$ )	$0.00 \times 10^{-15}$
Link to TAI $u_{\text{TAI}}$ ( $1 \sigma$ )	$0.06 \times 10^{-15}$ (35 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For the microwave synthesis the previously utilized optically stabilized microwave oscillator [2] has been replaced by a new system for the optical generation of ultra-stable microwave signals.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  $11.3 \times 10^{-14} (\tau/s)^{-1/2}$  of the measured relative frequency differences  $y(\text{CSF1} - \text{Hmaser})$  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  $\approx 95\%$  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 26<sup>th</sup> 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  $W_0 = 62\,636\,856.0 \text{ m}^2\text{s}^{-2}$  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  $0.02 \times 10^{-16}$  [1] is attributed now and in the future.

**Frequency shifts, corrections and type B uncertainties of CSF1 (parts in 10<sup>16</sup>):**

Frequency shift	Correction	Uncertainty
Quadratic Zeeman shift	- 1078.76	0.10
Blackbody radiation shift	166.23	0.81
Relativistic redshift and Doppler effect	- 85.56	0.02
Collisional shift	-12.6	2.4
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>