Evaluation of PTB primary caesium fountain frequency standard CSF2 between MJD 54839 - MJD 54854

PTB's primary caesium fountain frequency standard CSF2 was operated between MJD 54839, 0:00 UTC and MJD 54854, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H6, BIPM code 1400506, using a 5 MHz phase comparator.

The relative short-term frequency instability of CSF2 was $3.8 \cdot 10^{-13} \cdot (\tau/\mathrm{s})^{-1/2}$ during the 15 days. As has been demonstrated by internal comparisons with PTB-CSF1 the assumption of white frequency noise for the calculation of the statistical measurement uncertainty of CSF2 is valid at least down to $u_\mathrm{A} = 0.70 \cdot 10^{-15}$ at 130000 s measurement time. Currently we take this number as an upper limit for the statistical uncertainty of the whole measurement interval of CSF2.

The frequency comparison over the 15 day average is made with a statistical uncertainty - due to the instrumentation - of below $0.1 \cdot 10^{-15}$. In total 12829 comparison data points for intervals of 100 s duration were obtained, corresponding to 99.0% of the 15 x 24 hours. The very small amount of dead time was entirely due to voluntary time-outs for laser checks.

From these numbers an uncertainty due to the clock link $u_\mathrm{Lab} < 0.60 \cdot 10^{-16}$ is obtained. The estimated uncertainty for the link to TAI is $u_\mathrm{TAI} = 0.25 \cdot 10^{-15}$.

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

- Zeeman effect (magnetic field along the atoms' trajectory),
- AC Stark effect (thermal radiation along the atoms' trajectory),
- cold collisions effect,
- gravitational red-shift effect.
- systematic correction due to the frequency measurement instrumentation.

The CSF2 standard uncertainty u_B is estimated as $0.67 \cdot 10^{-15}$ ($1\ \sigma$) for the relevant period.

Table of results of CSF2 compared to hydrogen maser H6 (1400506)

Interval of evaluation	MJD 54839, 0:00 UTC - MJD 54854, 0:00 UTC
Fractional dead time	< 1.1%
Resulting frequency difference	$y(\mathrm{CSF2} - \mathrm{H6}) = -36.09 \cdot 10^{-15}$
Type A uncertainty u_A (1 σ)	$0.70 \cdot 10^{-15}$
Type B uncertainty u_B (1 σ)	$0.67 \cdot 10^{-15}$
Link to clock u_Lab (1 σ)	$0.06 \cdot 10^{-15}$
Link to TAI u_TAI (1 σ)	$0.25 \cdot 10^{-15}$ (15 days)
Combined uncertainty (1 σ)	$1.01 \cdot 10^{-15}$

Type A (statistical) uncertainty of CSF2

For CSF2 we use an optical molasses configuration for loading the atoms, with orthogonal linear polarizations for each laser beam pair. The launch direction of the atoms has been aligned with <1mrad precision using the atoms as a sensor. Because of the alignment of the launch direction and because the atomic cloud temperature is below 10^{-6}K, 30% of the atoms are detected after the second Ramsey interaction. For normal operation for TAI scale unit measurements, CSF2 is operated with the optimum short-term instability conditions with $3 \cdot 10^{4}$ detected atoms. Such operation typically results in an instability of $2.5 \cdot 10^{-13} \cdot (\tau/\mathrm{s})^{-1/2}$. The short-term instability ($3.8 \cdot 10^{-13}$) was somewhat higher during the reported interval because of a drift in the locking point of the detection laser.

The frequency synthesis of CSF2 is the same as the one described in the evaluation of the first fountain standard CSF1 at PTB [1]. By an internal frequency comparison between CSF1 and CSF2, where the Allan standard deviation was dominated by the white frequency noise of CSF2, a $\tau^{-1/2}$-dependence down to $7 \cdot 10^{-16}$ at 130000 s averaging time could be demonstrated. Therefore we use $u_\mathrm{A} = 0.70 \cdot 10^{-15}$ as an estimate for the statistical uncertainty of CSF2.

Type B (systematic) uncertainty of CSF2

A detailed description of the PTB fountain CSF2 has been accepted for publication in a peer reviewed journal [2]. Below we report the type B uncertainty evaluation results valid for the evaluation at hand. For this evaluation we observed a systematic frequency shift due to the employed phase comparator. We found that this frequency shift is proportional to the actual frequency difference between CSF2 and the reference maser H6. Based on these findings a frequency correction of $(0.30 \pm 0.10) \cdot 10^{-15}$ has to be applied to the measured frequency difference CSF2-H6.

Frequency shifts, corrections and type B uncertainties of CSF2 (parts in 10^{15}):

Frequency shift	Correction	Uncertainty
Quadratic Zeeman shift	-100.14	0.06
Blackbody radiation shift	16.56	0.06
Gravity+relativistic Doppler effect	-8.567	0.006
Collisional shift	-0.16	0.45
Frequency measurement instrumentation	0.30	0.10
Cavity phase shift		0.15
AC Stark shift (light shift)		0.001
Majorana transitions		0.0001
Rabi pulling		0.0002
Ramsey pulling		0.001
Electronics		0.20
Microwave leakage		0.10
Microwave power dependence		0.40
Background pressure		0.05
Total type B uncertainty		0.67

References

[1] S. Weyers, U. Hübner, R. Schröder, Chr. Tamm, A. Bauch, Metrologia **38** (4), pp. 343–352 (2001)

[2] V. Gerginov, N. Nemitz, S. Weyers, R. Schröder, D. Griebsch, R. Wynands, accepted for publication in Metrologia