Evaluation of PTB primary caesium fountain frequency standard CSF2 between MJD 55244 - MJD 55259

PTB's primary caesium fountain frequency standard CSF2 was operated between MJD 55244, 0:00 UTC and MJD 55259, 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 $1.6 \cdot 10^{-13} \cdot (\tau/s)^{-1/2}$ 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 $u_A = 0.70 \cdot 10^{-15}$ 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, 12931 comparison data points for intervals of 100 s duration were obtained, corresponding to 99.8% 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 $u_{Lab} < 0.02 \cdot 10^{-15}$ is obtained. The estimated uncertainty for the link to TAI for 15 days is $u_{TAI} = 0.24 \cdot 10^{-15}$.

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.

The CSF2 standard uncertainty u_B is estimated as $0.60 \cdot 10^{-15}$ (1 σ) for the relevant period.

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

Interval of evaluation	MJD 55244, 0:00 UTC - MJD 55259, 0:00 UTC
Fractional dead time	< 0.3%
Resulting frequency difference	$y(CSF2 – H6) = 61.87 \cdot 10^{-15}$
Type A uncertainty u_A (1 σ)	$0.70 \cdot 10^{-15}$
Type B uncertainty u_B (1 σ)	$0.60 \cdot 10^{-15}$
Link to clock u_{Lab} (1 σ)	$0.02 \cdot 10^{-15}$
Link to TAI u_{TAI} (1 σ)	$0.24 \cdot 10^{-15}$ (15 days)
Combined uncertainty (1 σ)	$0.96 \cdot 10^{-15}$

Type A (statistical) uncertainty of CSF2

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, 20% of the atoms are detected after the second Ramsey interaction. Since January 2010 we use a Low-Velocity Intense Atom Source (LVIS) [3] for loading of atoms in CSF2. With the new atom source, we detect $9 \cdot 10^4$ atoms at 250 ms loading time. As a result the measured short-term instability of the fountain is $1.6 \cdot 10^{-13}$/s.

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 $u_A = 0.70 \cdot 10^{-15}$ as an estimate for the statistical uncertainty of CSF2.

Type B (systematic) uncertainty of CSF2

A detailed description of the systematic uncertainty contributions of the PTB fountain CSF2 has been published elsewhere [2].

The only relevant change is the utilization of the LVIS for loading atoms, which enables a more efficient determination of the collisional shift at lower statistical uncertainty levels than before: To estimate the collisional shift of the output frequency of CSF2, before and after the evaluation the fountain is operated for 24 hours with 750 ms total loading time, with alternating low and high atomic density regimes every 1000 seconds. For the low atomic density regime, the atom source lasers are switched off during the first 500 ms of the total 750 ms loading time. For the high-density regime, the slow beam source lasers are on for the total 750 ms loading time. The measured atomic densities of both regimes differ by a factor of 10. The statistical uncertainty of the collisional shift correction is determined to be less than $0.2 \cdot 10^{-15}$ in each 24-hour measurement. The collisional shift correction and its uncertainty valid for the actual evaluation period are calculated as a weighted average of the collisional shift determinations using the statistical uncertainties of the two 24-hour measurements as weights. For the total collisional shift correction uncertainty, a 10% of the collisional shift correction is added in quadrature to the weighted statistical uncertainty of the two measurements. The 10% systematic uncertainty accounts for possible deviations between the measured fluorescence signal and the actual atomic density (see also [2]).

Below we report the type B uncertainty evaluation results valid for the evaluation at hand.

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

Frequency shift	Correction	Uncertainty
Quadratic Zeeman shift	-99.58	0.06
Blackbody radiation shift	16.57	0.06
Gravity+relativistic Doppler effect	-8.567	0.006
Collisional shift	1.04	0.34
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		0.60

References

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