Evaluation of PTB primary caesium fountain frequency standard CSF2 between MJD 55694 - MJD 55709

PTB's primary caesium fountain frequency standard CSF2 was operated between MJD 55694, 0:00 UTC and MJD 55709, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H5, BIPM code 1400590, using a 5 MHz phase comparator.

The relative frequency instability of CSF2 was $1.99{\cdot}10^{-13}{\cdot}(\tau/s)^{-1/2}$ during the 15 days. This results in a statistical uncertainty of $0.18{\cdot}10^{-15}$ assuming that white frequency noise is the dominant noise source. Because the frequency comparison over the 15 days is made with an uncertainty - due to the instrumentation - of below $0.09{\cdot}10^{-15}$ the resulting total statistical uncertainty is given by u_A (τ = 15 d) = $0.20{\cdot}10^{-15}$.

In total, 12788 comparison data points for intervals of 100 s duration were obtained, corresponding to 98.67% of the 15 x 24 hours. From these numbers an uncertainty due to the clock link $u_{Lab} < 0.03{\cdot}10^{-15}$ 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)
- blackbody effect (thermal radiation along the atoms' trajectory)
- gravitational red-shift and relativistic Doppler effect
- cold collisions effect
- cavity phase effect
- microwave lensing effect

The CSF2 standard uncertainty u_B is estimated as $0.42{\cdot}10^{-15}$ (1 σ) for the relevant period.

Table of results of CSF2 compared to hydrogen maser H5 (1400590)

Interval of evaluation	MJD 55694, 0:00 UTC - MJD 55709, 0:00 UTC
Fractional dead time	< 1.4%
Resulting frequency difference	y(CSF2 – H5) = $-42.30 \cdot 10^{-15}$
Type A uncertainty u_A (1 σ)	$0.20 \cdot 10^{-15}$
Type B uncertainty u_B (1 σ)	$0.42 \cdot 10^{-15}$
Link to clock u_{Lab} (1 σ)	$0.03 \cdot 10^{-15}$
Link to TAI u_{TAI} (1 σ)	$0.24 \cdot 10^{-15}$ (15 days)
Combined uncertainty (1 σ)	$0.53 \cdot 10^{-15}$

Type A (statistical) uncertainty of CSF2

For the TAI scale unit measurement at hand the atoms were loaded from the background gas into the molasses. The replacement of the master laser diode and a better profile adjustment and intensity balancing of the cooling laser beams resulted in an improved performance with respect to the loaded atom number and the achievable signal-to-noise ratio. The resulting frequency instability of CSF2 was measured to be $1.99 \cdot 10^{-13} \cdot (\tau/\mathrm{s})^{-1/2}$.

In 2010 the same new microwave frequency synthesis setup [1] as utilized in the fountain PTB-CSF1 has been introduced in the CSF2 electronics setup. Because it had been demonstrated that the new synthesis setup is capable of providing instabilities below the 10^{-16} level, the statistical uncertainty of CSF2 frequency measurements is no more limited at the 7×10^{-16}-level as before.

For these reason the statistical uncertainty of the current TAI scale unit measurement was calculated with the assumption of white frequency noise for the total measurement interval and taking into account a $0.09 \cdot 10^{-15}$ uncertainty contribution due to the measurement instrumentation. The resulting total statistical uncertainty is calculated to be u_A (τ = 15 d) = $0.20 \cdot 10^{-15}$.

Type B (systematic) uncertainty of CSF2

A detailed description of the systematic uncertainty contributions of the PTB fountain CSF2 has been published elsewhere [2]. Below we report some type B uncertainty contributions, which are now treated in a different way or were newly addressed since the last publication of the CSF2 uncertainty budget [2].

1) Distributed cavity phase

The systematic uncertainty contribution due to the distributed cavity phase has been thoroughly reevaluated based on the theory presented in Refs. [3], [4]. A publication about the details of the new evaluation is in preparation.

Major findings are that the previously attributed uncertainty contribution due to an observed power dependence can be omitted. It could be demonstrated that the reason for the power dependence are longitudinal phase variations in the microwave cavity, which cause very small frequency shifts at normal optimum microwave power operation. The dominant uncertainty contribution results from transverse m=1 phase variations, which have been experimentally evaluated by tilting the launch direction of the atoms in CSF2. Another small uncertainty contribution is caused by transverse m=2 phase variations, which can produce frequency shifts, if the atom cloud does not traverse the cavity on the cavity symmetry axis or if the detection is inhomogeneous.

Altogether a correction of $-0.044 \cdot 10^{-15}$ with an uncertainty of $0.134 \cdot 10^{-15}$ is now applied due to distributed cavity phase shift.

2) Cold collisions

The value of the collisional shift correction and its uncertainty were calculated from four collisional shift evaluations. The last two of these measurements were performed before and after the present fountain evaluation.

The number of atoms contributing to the signal – and in this way the density – was changed by changing the microwave amplitude in the state selection cavity. An electronics switches automatically between two microwave amplitudes of the state selection cavity every 1000 s coherently with the data taking of the 5 MHz phase comparator. In this way a differential measurement of the collisional shift is performed, eliminating the effect of the frequency drifts of the hydrogen maser reference. The results of these evaluations are slope factors which give – multiplied with the actual number of atoms – the collisional frequency shift correction [2]. For the correction of the TAI scale unit measurement the weighted average slope value obtained from the last four collisional shift evaluations was taken.

As described in Ref. [2] the uncertainty of the collisional shift correction is composed of the statistical uncertainty and a 10% systematic uncertainty because of a potentially imperfect proportionality between the measured actual number of atoms and the effective density.

3) Microwave lensing

It has been pointed out that transverse dipole forces in the microwave cavity affect the phase of the atomic dressed states in a way that leads to frequency shifts in the presence of apertures along the atoms' trajectory and because of the non-uniform detection in a fountain [5]. Following the treatment in [6], an evaluation of this effect results in a correction of $-0.083 \cdot 10^{-15}$ when the experimental parameters of CSF2 are taken into account. For the uncertainty half of this value ($0.042 \cdot 10^{-15}$) is taken.

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	-100.596	0.059
Blackbody radiation shift	16.457	0.076
Gravity+relativistic Doppler effect	-8.567	0.006
Collisional shift	0.947	0.296
Cavity phase shift	-0.044	0.134
Microwave lensing	-0.083	0.042
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
Background pressure		0.05
Total type B uncertainty		0.42

References

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