Evaluation of PTB primary caesium fountain frequency standard CSF2 between MJD 55859 - MJD 55879

PTB's primary caesium fountain frequency standard CSF2 was operated between MJD 55859, 0:00 UTC and MJD 55879, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H8, BIPM code 1400508, using a 5 MHz phase comparator.

The relative frequency instability of CSF2 was $2.04 \cdot 10^{-13} \cdot (\tau/\mathrm{s})^{-1/2}$ during the 20 days. This results in a statistical uncertainty of $0.16 \cdot 10^{-15}$ assuming that white frequency noise is the dominant noise source. Because the frequency comparison over the 20 days is made with an uncertainty -due to the instrumentation- of $0.06 \cdot 10^{-15}$, the resulting total statistical uncertainty is given by u_A (τ = 20 d) = $0.17 \cdot 10^{-15}$.

In total, 17191 comparison data points for intervals of 100 s duration were obtained, corresponding to 99.48% of the 20 x 24 hours. From these numbers an uncertainty due to the clock link $u_\mathrm{Lab} = 0.06 \cdot 10^{-15}$ is obtained. The estimated uncertainty for the link to TAI for 20 days is $u_\mathrm{TAI} = 0.19 \cdot 10^{-15}$.

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 $0.56 \cdot 10^{-15}$ (1 σ) for the relevant period.

<u>Table of results of CSF2 compared to hydrogen maser H8 (1400508)</u>

Interval of evaluation	MJD 55859, 0:00 UTC - MJD 55879, 0:00 UTC
Fractional dead time	< 0.52%
Resulting frequency difference	y(CSF2 – H8) = $-63.37 \cdot 10^{-15}$
Type A uncertainty u_A (1 σ)	$0.17 \cdot 10^{-15}$
Type B uncertainty u_B (1 σ)	$0.56 \cdot 10^{-15}$
Link to clock u_Lab (1 σ)	$0.06 \cdot 10^{-15}$
Link to TAI u_TAI (1 σ)	$0.19 \cdot 10^{-15}$ (20 days)
Combined uncertainty (1 σ)	$0.62 \cdot 10^{-15}$

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 $2.04 \cdot 10^{-13} \cdot (\tau/s)^{-1/2}$.

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 $0.06 \cdot 10^{-15}$ uncertainty contribution due to the measurement instrumentation. The resulting total statistical uncertainty is calculated to be u_A (τ = 20 d) = $0.17 \cdot 10^{-15}$.

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]. The results of this reevaluation will be published soon [5].

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 $0.133 \cdot 10^{-15}$ is now applied due to distributed cavity phase shift.

2) Cold collisions

To prepare the fountain for future evaluations at increased atomic density, a new method to measure the collisional shift has been implemented using rapid adiabatic passage [6]. The required microwave pulses are applied in the state selection cavity. By switching from the full microwave pulse to a pulse that is cut off at the exact pulse center, it is possible to reduce the density of the atomic cloud to 50% of its original value at any point in the atomic cloud, leaving the relative distribution unchanged [6].

Switching between full and half density is performed every 1000 s by an electronic circuit that is synchronized with the data acquisition of the phase comparator. This differential measurement of the collisional shift eliminates the effect of the frequency drifts of the hydrogen maser reference. The result of this evaluation is a slope factor which gives – multiplied with the actual number of atoms – the collisional frequency shift correction [2].

In fact, we calculate the collisional shift based on the measured atom number of the TAI scale unit measurement and a slope factor obtained during the same measurement interval and additional 10 days of measurement time. A 10% systematic uncertainty has therefore again been included to cover the effects of possible changes in the density distribution before and after the TAI scale unit measurement interval. This is assumed to be a conservative estimate and will be reevaluated once more data (and experience) is available for fountain operation using rapid adiabatic passage. In total we obtain a collisional shift uncertainty of $0.49 \cdot 10^{-15}$.

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 [7]. Following the treatment in [8], 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 [5]. 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	-100.203	0.058
Blackbody radiation shift	16.522	0.057
Gravity+relativistic Doppler effect	-8.567	0.006
Collisional shift	0.61	0.49
Cavity phase shift	-0.044	0.133
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		0.56

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