Evaluation of PTB primary caesium fountain frequency standard CSF2 between MJD 56729- MJD 56739

PTB's primary caesium fountain frequency standard CSF2 was operated between MJD 56729, 0:00 UTC and MJD 56739, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H6, BIPM code 1400506.

The relative frequency instability of CSF2 was $1.52\times10^{-13}\,(\tau/\mathrm{s})^{-1/2}$ during the 10 days. The actual measurement time amounts to 98.97% of the 10 × 24 hours. This results in a statistical uncertainty $u_\mathrm{A} = 0.16\times10^{-15}$ assuming that white frequency noise is the dominant noise source.

For the uncertainty due to the clock link $u_\mathrm{Lab} = 0.02\times10^{-15}$ is obtained by taking into account the actual measurement time. Finally, the estimated uncertainty for the link to TAI for 10 days is $u_\mathrm{TAI} = 0.18\times10^{-15}$.

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 0.35×10^{-15} ($1\ \sigma$) for the relevant period.

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

Interval of evaluation	MJD 56729, 0:00 UTC - MJD 56739, 0:00 UTC
Fractional dead time	1.03%
Resulting frequency difference	$y(\mathrm{CSF2} - \mathrm{H6}) = 226.14 \times 10^{-15}$
Type A uncertainty u_A ($1\ \sigma$)	0.16×10^{-15}
Type B uncertainty u_B ($1\ \sigma$)	0.35×10^{-15}
Link to clock u_Lab ($1\ \sigma$)	0.02×10^{-15}
Link to TAI u_TAI ($1\ \sigma$)	0.18×10^{-15} (10 days)
Combined uncertainty ($1\ \sigma$)	0.43×10^{-15}

Operation mode of CSF2

Formerly CSF2 was operated in an autonomous mode by steering a quartz oscillator to the atomic resonance frequency and measuring the frequency difference between the quartz oscillator and the hydrogen maser with a commercial phase comparator [1]. Since 2011 CSF2 is operated in a non-autonomous mode: As in other fountains, for this purpose the quartz oscillator is locked to the hydrogen maser. The microwave signal for the fountain is synthesized based on the quartz oscillator and a DDS synthesizer locked to the quartz oscillator. The output frequency of the DDS synthesizer is digitally steered to the atomic resonance frequency by evaluating the caesium transition probability measured by the fountain. The frequency difference between CSF2 and the hydrogen maser is thus obtained from the monitored synthesizer frequency settings.

For the TAI scale unit measurement at hand we deviated from this setup. For the first time for such measurement the quartz oscillator based microwave synthesis was replaced by a synthesis which makes use of an optically stabilized microwave oscillator [2-4]. In the new setup the short term stability of the microwave oscillator is provided by a 1.5 μm cavity stabilized fiber laser via a commercial femto-second frequency comb. In the long-term the microwave oscillator is locked to the hydrogen maser to enable the fountain frequency measurement with respect to the maser. In this setup the instability contribution of the microwave oscillator via the Dick-effect becomes negligible and the overall instability is mostly caused by the quantum projection noise.

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 frequency instability was reduced by ~25% due to the utilization of the optically stabilized microwave oscillator and measured to be 1.52×10^{-13} $(\tau/\mathrm{s})^{-1/2}$.

In 2010, a new microwave frequency synthesis setup [5] identical to the one used 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 [1].

For this 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.

Type B (systematic) uncertainty of CSF2

Detailed descriptions of the systematic uncertainty contributions of the PTB fountain CSF2 have been published elsewhere [1], [6]. Here we only report some details about the current methods for evaluating the quadratic Zeeman shift and the collisional shift because they differ from our previously employed and described methods. We also briefly comment on the reduced uncertainty due to the electronics.

The average value of the quadratic Zeeman shift is determined by automated periodic measurements of the frequency of the (F=3, m= −1) → (F=4, m= −1) transition during the relevant period. Therefore the uncertainty of the quadratic Zeeman correction is now dominated by the statistical measurement uncertainty and amounts to 0.010×10^{-15}.

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 [7,8]. 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 position in the atomic cloud, leaving the relative distribution unchanged.

During the present evaluation, the fountain was alternately operated at high (300 shots) and low density (400 shots) using the rapid adiabatic passage method for the density variation. The collisional shift was thus evaluated online during the fountain evaluation while the differential measurement eliminates the effect of frequency drifts of the hydrogen maser reference. As in previous evaluations, the result of this evaluation is a slope factor which gives – multiplied with the actual number of atoms – the collisional frequency shift correction [1].

For the present evaluation we calculate the collisional shift based on the measured relative atom numbers during the present evaluation and a slope factor, which is the weighted average of slope factors obtained during the present evaluation and during the two previous evaluations. The collisional shift uncertainty is given by the statistical measurement uncertainty of the slope factors. In total we obtain a collisional shift uncertainty of 0.28×10^{-15}.

The new microwave frequency synthesis setup [5] provides a better suppression of sidebands compared to the previously employed synthesis. The dominating 50 Hz sidebands are 65 dB below the carrier with an asymmetry of much less than 10%. Therefore the current conservative estimate of the uncertainty due to the electronics amounts to 0.1×10^{-15}.

In the table 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	-100.140	0.010
Blackbody radiation shift	16.566	0.057
Gravity+relativistic Doppler effect	-8.567	0.006
Collisional shift	1.11	0.28
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		0.10
Microwave leakage		0.10
Background gas collisions		0.05
Total type B uncertainty		0.35

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