Evaluation of PTB primary caesium fountain frequency standard CSF2 between MJD 57934 - MJD 57954

PTB's primary caesium fountain frequency standard CSF2 was operated between MJD 57934, 0:00 UTC and MJD 57954, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H10, BIPM code 1400510.

The actual measurement time amounts to 98.1% of the 20×24 hours. Assuming that white frequency noise is the dominant noise source, a statistical uncertainty $u_A = 0.24\times10^{-15}$ is obtained, which includes the statistical uncertainty of the collisional shift evaluation.

For the uncertainty due to the clock link $u_{Lab} = 0.02\times10^{-15}$ is obtained by taking into account the actual measurement time. Finally, the estimated uncertainty for the link to TAI for 20 days is $u_{TAI} = 0.19\times10^{-15}$.

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 0.20×10^{-15} (1 σ) for the relevant period.

<u>Table of results of CSF2 compared to hydrogen maser H10 (1400510)</u>

Interval of evaluation	MJD 57934, 0:00 UTC - MJD 57954, 0:00 UTC
Fractional dead time	1.9%
Resulting frequency difference	y(CSF2 – H10) = -11.32×10^{-15}
Type A uncertainty u_A (1 σ)	0.20×10^{-15}
Type B uncertainty u_B (1 σ)	0.24×10^{-15}
Link to clock u_{Lab} (1 σ)	0.02×10^{-15}
Link to TAI u_{TAI} (1 σ)	0.19×10^{-15} (20 days)
Combined uncertainty (1 σ)	0.37×10^{-15}

Operation mode of CSF2

For the TAI scale unit measurement at hand, solely the quartz oscillator based microwave synthesis was employed since the synthesis which makes use of an optically stabilized microwave oscillator [1-3] was out of operation for maintenance work

Type A (statistical) uncertainty of CSF2

In CSF2, atoms are loaded from a slow atom beam source [4]. For CSF2 operation at high density, in this measurement the resulting CSF2 frequency instability and the hydrogen maser frequency instability yield an instability of $\sigma_y = 10.3\times10^{-14}\ (\tau/1s)^{-1/2}$ for relative frequency difference measurements y(CSF2 – Hmaser). For the calculation of the statistical uncertainty u_A this instability and the corresponding instability for low density operation is taken into account with the assumption of white frequency noise for the total measurement interval. Additionally the statistical uncertainty of the collisional frequency shift measurement (see below) is included.

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 [6].

Type B (systematic) uncertainty of CSF2

Detailed descriptions of the systematic uncertainty contributions of CSF2 have been published elsewhere [6-7]. Here only some details about the current methods for evaluating the quadratic Zeeman shift and the collisional shift are reported, because they differ from our previously employed and described methods. We also briefly comment on the reduced uncertainty due to the electronics and other minor changes.

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 amounts to 0.01×10^{-15} only.

To reduce the systematic uncertainty of the collisional frequency shift determination, the necessary atom density variation is performed by rapid adiabatic passage in the state selection cavity [8-9]. 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 (200 shots) and low cloud density (400 shots) modes of operation. 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. In contrast to previous measurements [6], the known factor of two between the high and low cloud densities, and the frequency values for both high and low density modes of operation were used to determine a collisional shift correction. The statistical uncertainty of this collisional shift correction is now part of the statistical uncertainty of the frequency measurement (see above). The systematic uncertainty of the collisional shift correction is calculated as 0.5% of the collisional shift correction, as described in [9].

As an additional check, an evaluation of the measured atom numbers for high and low density modes of operation was used to calculate a slope factor which gives – multiplied with the measured number of atoms – another value for the collisional frequency shift correction [6]. This value was compared with the value obtained from the frequency measurements described above. The two values are consistent within the systematic uncertainty of the collisional shift correction.

The new microwave frequency synthesis setup [5] provides a better suppression of sidebands compared to the previously employed synthesis. From the dominating 50 Hz sidebands at 65 dB below the carrier with an asymmetry of much less than 10% we estimate the uncertainty due to the electronics to 0.01×10^{-15}.

Because atoms are now loaded from a slow atom beam, the frequency shifts caused by the cavity phase [7] and microwave lensing [7],[10] were both reevaluated.

Rabi and Ramsey pulling have also been reevaluated theoretically and experimentally using more elaborate methods than before [11]. The resulting combined uncertainty is 0.0013×10^{-15}.

A reevaluation of the frequency shift due to background gas collisions has been performed by measuring the loss of atoms during the Ramsey interrogation time [12].

Finally within the European EMRP project “Times scales with optical clocks” (JRP55 ITOC) [13] the gravity potential was newly determined with respect to the conventional zero potential W_0(IERS2010) = 62 636 856.0 m^2s^{-2} at the sites of the European metrology institutes INRIM(Italy), NPL (UK), SYRTE (France) and PTB (Germany). As a result of these investigations the gravitational redshift correction of CSF2 is changed by $+2.2\times10^{-17}$. While the uncertainty of the new CSF2 gravitational redshift correction is at the level of 2×10^{-18} only, an uncertainty of 3×10^{-17} is taken into a ccount in the CSF2 uncertainty budget, as at present there is no exact and internationally accepted geoid definition, i.e. agreed zero potential value.

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	-100.173	0.010
Blackbody radiation shift	16.506	0.057
Gravity+relativistic Doppler effect	-8.545	0.03
Collisional shift	8.33	0.04
Cavity phase shift	-0.032	0.15
Microwave lensing	-0.067	0.034
AC Stark shift (light shift)		0.001
Majorana transitions		0.0001
Rabi and Ramsey pulling		0.0013
Electronics		0.01
Microwave leakage		0.10
Background gas collisions		0.01
Total type B uncertainty		0.20

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