# Evaluation of PTB primary caesium fountain frequency standard CSF2 between MJD 57459 - MJD 57474

PTB's primary caesium fountain frequency standard CSF2 was operated between MJD 57459, 0:00 UTC and MJD 57474, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H9, BIPM code 1400509.

The actual measurement time amounts to 84.43% of the 15 × 24 hours. Assuming that white frequency noise is the dominant noise source, this results in a statistical uncertainty $u_A = 0.15\times10^{-15}$, 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 15 days is $u_{TAI} = 0.12\times10^{-15}$.

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 $0.20\times10^{-15}$ (1 σ) for the relevant period.

**Table of results of CSF2 compared to hydrogen maser H9 (1400509)**

| | |
|---|---|
| Interval of evaluation | MJD 57459, 0:00 UTC - MJD 57474, 0:00 UTC |
| Fractional dead time | 15.57 % |
| Resulting frequency difference | $y(\text{CSF2} - \text{H9}) = 119.63 \times 10^{-15}$ |
| Type A uncertainty $u_A$ (1 σ) | $0.15 \times 10^{-15}$ |
| Type B uncertainty $u_B$ (1 σ) | $0.20 \times 10^{-15}$ |
| Link to clock $u_{Lab}$ (1 σ) | $0.02 \times 10^{-15}$ |
| Link to TAI $u_{TAI}$ (1 σ) | $0.12 \times 10^{-15}$ (15 days) |
| | |
| Combined uncertainty (1 σ) | $0.28 \times 10^{-15}$ |

## Operation mode of CSF2

The quartz oscillator based microwave synthesis was replaced by a synthesis which makes use of an optically stabilized microwave oscillator [1-2]. The short term frequency stability of the microwave oscillator is provided by a 1.5 μm cavity stabilized fiber laser via a commercial femtosecond 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 of CSF2 and the frequency instability of the hydrogen maser.

During the 15 day TAI measurement interval no significant failures of the optically stabilized microwave system occurred. In total approximately 0.3% of data are missing due to short-term malfunctions of the optically stabilized microwave system.

## Type A (statistical) uncertainty of CSF2

In CSF2, atoms are loaded from a slow atom beam source [3]. For CSF2 operation at high density, the resulting quantum projection noise and the hydrogen maser frequency instability yield an instability of $\sigma_y = 5.5\times10^{-14}\ (\tau/1\mathrm{s})^{-1/2}$ for relative frequency difference measurements y(CSF2 – Hmaser). For the calculation of the statistical uncertainty $u_\mathrm{A}$ 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 [4] 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 $7\times10^{-16}$-level as before [5].

## Type B (systematic) uncertainty of CSF2

Detailed descriptions of the systematic uncertainty contributions of CSF2 have been published elsewhere [5-6]. 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 $0.01\times10^{-15}$ 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 [7-8]. 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 (40 shots) and low cloud density (120 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 [5], 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 [8].

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 [5]. 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 [4] 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 $0.01\times10^{-15}$.

Because atoms are now loaded from a slow atom beam, the frequency shifts caused by the cavity phase [6] and microwave lensing [6],[9] were both reevaluated.

Rabi and Ramsey pulling have also been reevaluated theoretically and experimentally using more elaborate methods than before [10]. The resulting combined uncertainty is $0.0013\times10^{-15}$.

Finally 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 [11].

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 | -100.556 | 0.010 |
| Blackbody radiation shift | 16.523 | 0.056 |
| Gravity+relativistic Doppler effect | -8.567 | 0.006 |
| Collisional shift | 8.62 | 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 |

## References

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