Evaluation of PTB primary caesium fountain frequency standard CSF1 between MJD 54369 - MJD 54384

PTB's primary caesium fountain frequency standard CSF1 was operated between MJD 54369, 0:00 UTC and MJD 54384, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H5, BIPM code 400590, using a 5 MHz phase comparator.

The relative frequency instability of CSF1 was $3.0 \cdot 10^{-13} \cdot (\tau/\mathrm{s})^{-1/2}$ during the 15 days. Until better proof of the CSF1 frequency instability at averaging times τ > 1 day is at hand, u_A (τ = 15 d) = $1 \cdot 10^{-15}$ is used, even if this might be a too pessimistic estimate.

The frequency comparison over the 15 day average is made with a statistical uncertainty - due to the instrumentation - of below $0.1 \cdot 10^{-15}$. In total 12926 comparison data points for intervals of 100 s duration were obtained, corresponding to 99.74% of the 15·24 hours. The very small amount of dead time was entirely due to voluntary time-outs for laser and C-field checks.

From these numbers an uncertainty due to the clock link u_{Lab} < $0.1 \cdot 10^{-15}$ is obtained. The estimated uncertainty for the link to TAI is $u_{TAI} = 0.2 \cdot 10^{-15}$.

Frequency corrections for the following effects were applied to the raw data:

- Zeeman effect (magnetic field along the atoms' trajectory),
- AC Stark effect (thermal radiation along the atoms' trajectory),
- cold collisions effect,
- gravitational red-shift effect.

The CSF1 standard uncertainty u_B is estimated as $1.0 \cdot 10^{-15}$ (1 σ) for the relevant period.

<u>Table of results of CSF1 compared to hydrogen maser H5 (400590)</u>

Interval of evaluation	MJD 54369, 0:00 UTC - MJD 54384, 0:00 UTC
Fractional dead time	< 0.3%
Resulting frequency difference	y(CSF1 – H5) = $-12.3 \cdot 10^{-15}$
Type A uncertainty u_A (1 σ)	$1.0 \cdot 10^{-15}$
Type B uncertainty u_B (1 σ)	$1.0 \cdot 10^{-15}$
Link to clock u_{Lab} (1 σ)	$0.1 \cdot 10^{-15}$
Link to TAI u_{TAI} (1 σ)	$0.2 \cdot 10^{-15}$ (15 days)
Combined uncertainty (1 σ)	$1.4 \cdot 10^{-15}$

Type B (systematic) uncertainty of CSF1

A detailed description of the PTB fountain CSF1 is given in Refs. [1] and [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 CSF1 uncertainty budget [2]. The main change is an additional uncertainty contribution, issue (7), that currently has to be taken into account because of the observation of a frequency shift when CSF1 is operated at elevated microwave power levels.

Furthermore, the present evaluation of CSF1 is the first one which was performed with a pure optical molasses without utilisation of a magneto-optical trap.

1) AC Stark shift

Recently the frequency shifting effect due to the electric field of the ambient temperature radiation has been reevaluated [3]. The outcome for the corresponding frequency shift $\delta\nu_{BB}$ confirms most of the former results and amounts to

$$\delta\nu_{BB} = k_0 E_{300}^2 \left(\frac{T}{300}\right)^4 \left(1 + \varepsilon \left(\frac{T}{300}\right)^2\right)$$

with the ambient temperature T, E_{300} = 831.9 V/m, and the coefficients k_0 = -2.282(4) × 10^{-10} Hz/(V/m)^2 and ε = 0.013. We use this most up-to-date result for the correction of the AC stark shift.

Without utilisation of a magneto-optical trap the observed temperature gradients along the vacuum tube of CSF1 are within the uncertainty of the employed PT100 resistances (0.11 K). During the reported 15 days time interval the temperature indicated by each single PT100 resistance remained the same within the limits of ± 0.1 K. However, for the AC Stark shift correction the calculated average temperature is used. Based on these findings we now assume an uncertainty of this temperature of 0.2 K, which gives an uncertainty contribution of < $0.1\cdot10^{-15}$, also taking into account the given uncertainty of k_0.

2) Cold collisions

The collisional frequency shift of CSF1 in the pure molasses operation mode was evaluated before and after the TAI scale unit measurement at hand for 34 and 10 days, respectively. The number of atoms contributing to the signal – and in this way the density – was changed by varying the loading time of the molasses.

The results of these evaluations are slope factors which give – multiplied with the actual number of atoms – the collisional frequency shift correction [1], [2]. For the correction of the TAI scale unit measurement the weighted average slope value obtained from both collisional shift evaluations was taken.

As described in Refs. [1] and [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) Gravitational red shift

The “Institut für Geodäsie und Photogrammetrie” of the Technical University of Braunschweig has newly determined the height above the geoid of a reference point inside PTB’s clock hall. As a result, the gravitational red shift correction has changed by $0.1 \cdot 10^{-15}$ with respect to the value given in [1] and has a reduced uncertainty of well below $0.1 \cdot 10^{-15}$.

4) Majorana transitions

In November 2004 during a frequency comparison campaign [4] between several European fountain clocks relative frequency variations of CSF1 of the order of 10^{-14} became apparent. These frequency variations could be traced back to Majorana transitions caused by unintended changes of the properties of the magnetic shield [5]. By proper current settings of correction coils located close to the lower shield caps the problem could be remedied. The related extensive investigations led to a deeper understanding of the effect of Majorana transitions in fountain clocks and hence enabled us to take further measures in order to avoid such transitions in CSF1. In particular the spatial structure of the magnetic field below the magnetic shield surrounding the C-field region is now better characterised and controlled. Therefore our former estimate of the uncertainty contribution due to Majorana transitions ($< 0.1 \cdot 10^{-15}$) could be recovered.

5) Microwave leakage

Recently extended investigations of the effect of microwave leakage in CSF1 were performed [6]. The related results together with the absence of potential leakage fields at the level of –145 dBm lead to an uncertainty contribution due to potential microwave leakage fields of $< 0.1 \cdot 10^{-15}$.

6) Light shift

Extended investigations of a possible frequency shift due to the interaction of the atoms during their ballistic flight with residual light from one of the laser beams used for cooling or detection resulted in a reduced uncertainty estimate of this effect of $< 0.1 \cdot 10^{-15}$. For these investigations several mechanical shutters were put out of action with the result that no relative frequency shift at the low 10^{-15} level was observed.

7) Microwave power dependence: $1\pi/2$-pulses, $3\pi/2$-pulses

It has become a standard procedure to test primary fountain frequency standards at elevated microwave powers in order to check for potential frequency shifts. Usually such tests are performed at odd multiples of $\pi/2$ microwave pulse area, where the microwave power is adjusted to these values typically by maximising the contrast of the central Ramsey fringe. During the past two years we investigated shifts of the CSF1 output frequency – exceeding the formerly stated type B uncertainty – that occurred when the main cavity was operated at increased microwave power. Many possible sources of this effect were investigated, with some concentration on Majorana transitions [5] and microwave leakage [6], and could be excluded.

Recently it has been pointed out that under certain conditions the overall collisional shift significantly depends on the clock state composition after the first interaction with the microwave field in the Ramsey cavity, i.e., the ratio of the atom numbers in the clock states (F = 4, m_F = 0) and (F = 3, m_F = 0) [7]. Notably in the case of a small initial atom cloud size associated with the use of a magneto-optical trap (like in PTB-CSF1), the expansion of the cloud during its ballistic flight results in position-momentum correlations, which in turn lead to decreasing relative atom velocities in a collision. At these low collisional energies the collisional cross-section is markedly different for atoms in the two clock states [7]. The overall collisional shift therefore depends on the composition of the atomic state after the first Ramsey interaction.

It has been experimentally demonstrated that in this case for different multiples of $\pi/2$ pulse area a varying clock state composition after the first Ramsey interaction can be obtained, if the average microwave power seen by the expanding atom cloud is different during the first and the second transition through the Ramsey cavity [8]. In the presence of a clock state composition dependent collisional shift, this effect gives rise to different collisional shifts for operation at different multiples of $\pi/2$ pulse area.

Taking this into account we are able to explain the major part – if not all – of the peculiarities found in PTB-CSF1 at multiple $\pi/2$ pulse area operation, as confirmed by experiment. In the case of pure molasses operation, the currently observed remaining frequency difference for operation at $1\pi/2$ pulse area and $3\pi/2$-pulse area is $(1.3 \pm 0.4)\cdot 10^{-15}$. In order to take this difference into account we have added a conservative uncertainty contribution of half of the measured frequency difference (i.e., $0.7\cdot 10^{-15}$) to the uncertainty budget for the normal mode of operation at $1\pi/2$ pulse area.

Frequency biases and type B uncertainties of CSF1:

Physical effect	Bias / 10^{-15}	Type B uncertainty / 10^{-15}
Second order Zeeman shift	46.6	0.1
AC Stark shift	- 16.5	0.1
Cold collisions	- 0.25	0.3
Gravitational red shift	8.6	0.1
Cavity phase		0.5
Majorana transitions		0.1
Rabi and Ramsey pulling		0.1
Microwave leakage		0.1
Electronics		0.2
Light shift		0.1
Background gas collisions		0.1
Microwave power dependence		0.7
Total type B uncertainty		1.0

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