Evaluation of PTB primary caesium fountain frequency standard CSF1 between MJD 54644 - MJD 54669

PTB's primary caesium fountain frequency standard CSF1 was operated between MJD 54644, 0:00 UTC and MJD 54669, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H6, BIPM code 1400506, using a 5 MHz phase comparator.

The relative frequency instability of CSF1 was $1.4\cdot10^{-13}\cdot(\tau/\mathrm{s})^{-1/2}$ during the 25 days. This results in a statistical uncertainty u_A ($\tau = 25$ d) = $0.1\cdot10^{-15}$ assuming that white frequency noise is the dominant noise source.

The frequency comparison over the 25 day average is made with a statistical uncertainty - due to the instrumentation - of below $0.1\cdot10^{-15}$. In total 21571 comparison data points for intervals of 100 s duration were obtained, corresponding to 99.87% of the 25 x 24 hours. The very small amount of dead time was entirely due to voluntary time-outs for laser checks.

From these numbers an uncertainty due to the clock link $u_{\mathrm{Lab}} < 1\cdot10^{-17}$ is obtained. The estimated uncertainty for the link to TAI is $u_{\mathrm{TAI}} = 0.2\cdot10^{-15}$.

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 $0.9\cdot10^{-15}$ (1 σ) for the relevant period.

Table of results of CSF1 compared to hydrogen maser H6 (1400506)

Interval of evaluation	MJD 54644, 0:00 UTC - MJD 54669, 0:00 UTC
Fractional dead time	< 0.14%
Resulting frequency difference	y(CSF1 – H6) = $79.4 \cdot 10^{-15}$
Type A uncertainty u_A (1 σ)	$0.1 \cdot 10^{-15}$
Type B uncertainty u_B (1 σ)	$0.9 \cdot 10^{-15}$
Link to clock u_{Lab} (1 σ)	$0.0 \cdot 10^{-15}$
Link to TAI u_{TAI} (1 σ)	$0.2 \cdot 10^{-15}$ (25 days)
Combined uncertainty (1 σ)	$0.9 \cdot 10^{-15}$

Type A (statistical) uncertainty of CSF1

Recent improvements of the setup for the detection of the atoms, the master laser frequency stabilisation and the timing of the fountain cycle resulted in significant improvements of the signal-to-noise ratio. It is now quantum projection noise limited up to the maximum currently achievable detected atom number. For normal operation for TAI scale unit measurements, where CSF1 is operated with reduced atom number, the improvements result in an instability of $1.4\cdot10^{-13}\cdot(\tau/\mathrm{s})^{-1/2}$, if a magneto-optical trap is used for loading the atoms.

For the TAI scale unit measurement at hand a new microwave frequency synthesis [1] was used for the first time. Before, it had been demonstrated that this new synthesis setup is capable to provide instabilities below the 10^{-16} level [1]. Also in parallel to the TAI scale unit measurement a measurement of the single ytterbium ion clock transition frequency was performed. As a result the Allan standard deviation dominated by the white frequency noise of CSF1 exhibits a $\tau^{-1/2}$-dependence down to $4\cdot10^{-16}$ at 100000 s averaging time.

For these reasons we decided, in contrast to previous TAI scale unit measurement using CSF1, to calculate the statistical uncertainty with the assumption of white frequency noise for the total measurement interval arriving at an statistical uncertainty u_A ($\tau = 25$ d) = $0.1\cdot10^{-15}$.

Type B (systematic) uncertainty of CSF1

A detailed description of the PTB fountain CSF1 is given in Refs. [2] and [3]. 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 [3]. 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.

1) AC Stark shift

Recently the frequency shifting effect due to the electric field of the ambient temperature radiation has been reevaluated [4]. The outcome for the corresponding frequency shift $\delta\nu_{BB}$ confirms most of the former results and amounts to

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

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

During the reported 25 days time interval the observed temperature gradients along the vacuum tube of CSF1 were within the uncertainty of the employed PT100 resistances (0.11 K). At the same time 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 assume an uncertainty of this temperature of 0.2 K, which gives an uncertainty contribution of $< 0.1 \cdot 10^{-15}$, also taking into account the given uncertainty of k_0.

2) Cold collisions

The collisional frequency shift of CSF1 was evaluated before and after the TAI scale unit measurement at hand for 5.3 and 4.9 days, respectively. The number of atoms contributing to the signal – and in this way the density – was changed by changing the microwave amplitude in the state selection cavity. An electronics switches automatically between two microwave amplitudes of the state selection cavity every 1000 s coherently with the data taking of the 5 MHz phase comparator. In this way a differential measurement of the collisional shift is performed, getting rid of the frequency drifts of the hydrogen maser that were the limiting factor of former evaluations.

The results of these evaluations are slope factors which give – multiplied with the actual number of atoms – the collisional frequency shift correction [2], [3]. 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. [2] and [3] 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 [2] and has a reduced uncertainty of well below $0.1 \cdot 10^{-15}$.

4) Majorana transitions

In November 2004 during a frequency comparison campaign [5] 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 [6]. 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 [7]. The related results together with the absence of potential leakage fields at the level of –153 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: 1π/2-pulses, 3π/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 [6] and microwave leakage [7], 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 ($F = 3$, $m_F = 0$) [8]. 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 [8]. 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. The currently observed remaining frequency difference for operation at $1\pi/2$ pulse area and $3\pi/2$-pulse area is $(1.1 \pm 0.5) \cdot 10^{-15}$. In order to take this difference into account we have added a conservative uncertainty contribution of half of the measured frequency difference (i.e., $0.6 \cdot 10^{-15}$) 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	46.2	0.1
AC Stark shift	- 16.6	0.1
Cold collisions	- 1.8	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		0.6
Total type B uncertainty		0.9

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