Evaluation of PTB primary caesium fountain frequency standard CSF1 between MJD 54079 - MJD 54094

PTB's primary caesium fountain frequency standard CSF1 was operated between MJD 54079, 0:00 UTC and MJD 54094, 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 typically $2.4 \cdot 10^{-13} \cdot (\tau/\mathrm{s})^{-1/2}$ 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 12872 comparison data points for intervals of 100 s duration were obtained, corresponding to 99.3% of the 15·24 hours. 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 $u_{TAI} = 0.4 \cdot 10^{-15}$.

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 $1.1 \cdot 10^{-15}$ (1 σ) for the relevant period.

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

Interval of evaluation	MJD 54079, 0:00 UTC - MJD 54094, 0:00 UTC
Fractional dead time	0.7%
Resulting frequency difference	y(CSF1 – H5) = $91.0 \cdot 10^{-15}$
Type A uncertainty u_A (1 σ)	$1.0 \cdot 10^{-15}$
Type B uncertainty u_B (1 σ)	$1.1 \cdot 10^{-15}$
Link to clock u_{Lab} (1 σ)	$0.1 \cdot 10^{-15}$
Link to TAI u_{TAI} (1 σ)	$0.4 \cdot 10^{-15}$ (15 days)
Combined uncertainty (1 σ)	$1.6 \cdot 10^{-15}$

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 (6), 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) Cold collisions

Unlike former evaluations of the collisional frequency shift of CSF1, where the number of atoms contributing to the signal – and in this way the density – was changed by varying the loading time of the magneto-optical trap (MOT), for the TAI scale unit measurement at hand the number of atoms was changed by changing the microwave amplitude in the state selection cavity. A newly developed electronics enables us to switch 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.

Such collisional shift evaluations were performed during 5.0 days before and during 8.8 days after the TAI scale unit measurement at hand. The results of such 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. The fact that the slope factors obtained by the new method fit well with the slope factors obtained previously with the traditional method of changing the MOT-loading time (see also Ref. [2]) supports the validity of this approach within the resulting error bars.

2) 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 $0.1 \cdot 10^{-15}$.

3) Majorana transitions

In November 2004 during a frequency comparison campaign [3] 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 [4]. 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.

4) Microwave leakage

Recently extended investigations of the effect of microwave leakage in CSF1 were performed [5]. 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 $< 0.1 \cdot 10^{-15}$.

5) 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.

6) 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 [4] and microwave leakage [5], 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 ($F = 3$, $m_F = 0$) [6]. 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 [6]. 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 [7]. 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 $(1.4 \pm 0.6)\cdot 10^{-15}$. 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 operation mode at $1\pi/2$ pulse area.

<u>Frequency biases and type B uncertainties of CSF1:</u>

Physical effect	Bias / 10^{-15}	Type B uncertainty / 10^{-15}
Second order Zeeman shift	46.1	0.1
AC Stark shift	- 16.5	0.2
Cold collisions	- 3.54	0.42
Gravitational red shift	8.6	0.1
Cavity phase		0.5
Majorana transitions		0.1
Rabi pulling		0.1
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		1.1

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