Evaluation of PTB primary caesium fountain frequency standard CSF1 between MJD 53914 - MJD 53923

PTB's primary caesium fountain frequency standard CSF1 was operated between MJD 53914, 0:00 UTC and MJD 53924, 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 10 days. Until better proof of the CSF1 frequency instability at averaging times τ > 1 day is at hand, u_A (τ = 10 d) = $1 \cdot 10^{-15}$ is used, even if this might be a too pessimistic estimate.

The frequency comparison over the 10 day average is made with a statistical uncertainty - due to the instrumentation - of below $0.1 \cdot 10^{-15}$. In total 8596 comparison data for intervals of 100 s duration were obtained, corresponding to 99.5% of the 10·24 hours. From these numbers an uncertainty due to the clock link $u_{Lab} = 0.1 \cdot 10^{-15}$ is obtained. The uncertainty for the link to TAI is obtained from $u_{TAI} = 30 \cdot 10^{-15}/\tau$ where τ is the interval of the report in days.

Frequency corrections due to 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 $2.6 \cdot 10^{-15}$ (1 σ) for the relevant period.

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

Interval of evaluation	MJD 53914, 0:00 UTC - MJD 53924, 0:00 UTC
Fractional dead time	0.5%
Resulting frequency difference	$y(\mathrm{CSF1} - \mathrm{H5}) = 19.7 \cdot 10^{-15}$
Type A uncertainty u_A (1 σ)	$1.0 \cdot 10^{-15}$
Type B uncertainty u_B (1 σ)	$2.6 \cdot 10^{-15}$
Link to clock u_{Lab} (1 σ)	$0.1 \cdot 10^{-15}$
Link to TAI u_{TAI} (1 σ)	$3.0 \cdot 10^{-15}$ (10 days)
Combined uncertainty (1 σ)	$4.1 \cdot 10^{-15}$

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]. An additional uncertainty contribution, issue (6), has currently to be taken into account because of the occurrence 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 7.2 days before and during 7.5 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 $0.1 \cdot 10^{-15}$ 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 about the effect of microwave leakage in CSF1 were performed [5]. The related results together with sensitive detection 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: pi/2-pulses, 3pi/2-pulses

No CSF1 measurements of the TAI scale unit have been submitted to BIPM for more than two years. Instead, we investigated the issue that a shift of the fountain output frequency – exceeding the formerly stated type B uncertainty – occurred when the main cavity was operated at increased microwave power (applying e.g. $3\pi/2$-pulses to the atoms instead of $1\pi/2$-pulses). Many possible sources of this effect were investigated with some concentration on Majorana transitions [4] and microwave leakage [5].

In order to take this effect into account we have added to u_B an additional uncertainty contribution of $2.5 \cdot 10^{-15}$. This value is based on measurements using hydrogen masers or the $^{171}Yb^+$-clock transition as references. Taking into account this additional uncertainty contribution we have performed two frequency measurements of the $^{171}Yb^+$-clock transition, in summer 2005 and in summer 2006. In connection with the latter measurement we have operated CSF1 as a primary frequency standard for the 10 days reported here.

Only in the last few days results were obtained which indicate that the observed frequency difference is due to a modification of the collisional shift at increased microwave power levels. If this finding is confirmed by our ongoing investigations, the additional contribution to the type B uncertainty of CSF1 could be omitted. For the time being we keep this additional uncertainty contribution in the uncertainty budget for the CSF1 measurement of the TAI scale unit reported here.

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	- 16.5	0.2
Cold collisions	- 4.1	0.5
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		2.5
Total type B uncertainty		2.6

References

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