Evaluation of PTB primary caesium fountain frequency standard CSF1 between MJD 58114 - MJD 58134

PTB's primary caesium fountain frequency standard CSF1 was operated between MJD 58114, 0:00 UTC and MJD 58134, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H10, BIPM code 1400510. Maser H10 failed during day 58134 and no clock data could be provided for the rest of the month. The CSF1 data were thus referred to maser H6, BIPM code 1400506, after the fact.

All PTB masers are continuously monitored one against the other. During the reported 20-days interval, the mean frequency difference y(H10-H6) was -9.52×10^{-15}, based on 1 PPS time comparisons at 0:00 UTC of the two days. The sigma of the individual hourly measurements recorded during the 20 days is 70 ps. Therefore an additional "Link to clock" uncertainty is estimated as 70 ps/20 d $\times$ $2^{1/2}$ = 0.06×10^{-15} as two measurements at the start and the end of the interval are involved.

The relative frequency instability of CSF1 was $9.6\times10^{-14}\cdot(\tau/s)^{-1/2}$ during the 20 days. The actual measurement time amounts to 97.4% of the 20 $\times$ 24 hours. This results in a statistical uncertainty $u_A = 0.07\times10^{-15}$ assuming that white frequency noise is the dominant noise source.

For the uncertainty due to the clock link $u_{Lab}=[(0.04\times10^{-15})^2 + (0.06\times10^{-15})^2]^{1/2}=0.07\times10^{-15}$ is obtained by taking into account the actual measurement time and the link to H6. Finally, the estimated uncertainty for the link to TAI for 20 days is $u_{TAI} = 0.19\times10^{-15}$.

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

- Zeeman effect (magnetic field along the atoms' trajectory),
- black body effect (thermal radiation along the atoms' trajectory),
- gravitational red-shift and relativistic Doppler effect,
- cold collisions effect.

The CSF1 standard uncertainty u_B is estimated as 0.39×10^{-15} (1 σ) for the relevant period.

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

Interval of evaluation	MJD 58114, 0:00 UTC – MJD 58134, 0:00 UTC
Fractional dead time	2.6%
Resulting frequency difference	y(CSF1 – H6) = -31.39×10^{-15}
Type A uncertainty u_A (1 σ)	0.07×10^{-15}
Type B uncertainty u_B (1 σ)	0.39×10^{-15}
Link to clock u_{Lab} (1 σ)	0.07×10^{-15}
Link to TAI u_{TAI} (1 σ)	0.19×10^{-15} (20 days)
Combined uncertainty (1 σ)	0.44×10^{-15}

Operation mode of CSF1

The quartz oscillator based microwave synthesis was replaced by a synthesis which makes use of an optically stabilized microwave oscillator [1-3]. 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 CSF1 and the frequency instability of the hydrogen maser.

During the 20 day TAI measurement interval the optically stabilized microwave system was operated almost continuously (~100%) of the time.

Type A (statistical) uncertainty of CSF1

For the TAI scale unit measurement at hand, the frequency instability of CSF1 was measured to be $9.6\times10^{-14}\,(\tau/\mathrm{s})^{-1/2}$. Previously, it had been demonstrated that the employed synthesis setup is capable of providing instabilities below the 10^{-16} level [4]. Using CSF1 for a measurement of the single ytterbium ion clock transition frequency, where the Allan standard deviation was dominated by the white frequency noise of CSF1, a $\tau^{-1/2}$-dependence down to 4×10^{-16} at 100000 s averaging time could be demonstrated some time ago.

For these reasons the statistical uncertainty of the current TAI scale unit measurement was calculated with the assumption of white frequency noise for the total measurement interval.

Type B (systematic) uncertainty of CSF1

A detailed description of the PTB fountain CSF1 is given in Refs. [5] and [6]. Here we report on type B uncertainty contributions, which are treated in a different way or were newly addressed since the last publication of the CSF1 uncertainty budget [6].

1) Quadratic Zeeman shift

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 less than 0.10×10^{-15}.

2) Black body radiation shift

For calculating the frequency shifting effect due to the electric field of the ambient temperature radiation we use the results of the most recent evaluation [7]. 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 $\varepsilon = 0.013$.

During the reported 20 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 ± 0.15 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 $< 0.1\times10^{-15}$, also taking into account the given uncertainty of k_0.

3) Gravitational red shift

Within the European EMRP project “Times scales with optical clocks” (JRP55 ITOC) [8,9] the gravity potential was newly determined with respect to the conventional zero potential W_0(IERS2010) = 62 636 856.0 m^{2}s^{-2} at the sites of the European metrology institutes INRIM(Italy), NPL (UK), SYRTE (France) and PTB (Germany). As a result of these investigations the gravitational redshift correction of CSF1 is changed by $+2.4\times10^{-17}$. While the uncertainty of the new CSF1 gravitational redshift correction is at the level of 2×10^{-18} only, an uncertainty of 3×10^{-17} is taken into account in the CSF1 uncertainty budget, as at present there is no exact and internationally accepted geoid definition, i.e. agreed zero potential value.

4) Collisional shift

For evaluating the collisional frequency shift, CSF1 is alternately operated at high (200 shots) and low density (200 shots). The number of atoms contributing to the signal – and in this way the density – is changed by changing the microwave amplitude in the state selection cavity. In this way, a differential measurement of the collisional shift is performed, eliminating the effect of the frequency drifts of the hydrogen maser reference. The results of such measurements are slope factors which give – multiplied with the actual number of atoms – the collisional frequency shift correction [5], [6].

For the present evaluation we calculate the collisional shift based on the measured relative atom numbers during the present evaluation and a slope factor, which is obtained from slope factor measurements during the last month.

As described in Refs. [5] and [6] 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. In the measurement at hand the systematic uncertainty contribution is zero, since the collisional shift correction is zero.

5) Cavity phase shift

A new comprehensive evaluation of cavity phase gradients has been performed in line with Refs. [10-13]. Details of the evaluation, including frequency measurements at fountain tilts, will be presented in a publication about a new comprehensive uncertainty evaluation of CSF1, which is in preparation.

The major finding is that related frequency shifts are at the 0.01×10^{-15}-level and that the overall uncertainty is below 0.1×10^{-15}. Previously it has already been confirmed that the observed microwave power dependence of the CSF1 frequency [14] is well explained by the presence of longitudinal cavity phase gradients [15]. Because of the new cavity phase evaluation, the previous microwave power dependence entry in the uncertainty budget becomes obsolete.

6) AC Stark shift (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 $< 0.1\times10^{-15}$. 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) Majorana transitions

In November 2004 during a frequency comparison campaign [16] 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 [17]. 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 ($< 0.1\times10^{-15}$) could be recovered.

8) Electronics

The new microwave frequency synthesis setup [4] provides a better suppression of sidebands compared to the previously employed synthesis. The dominating 50 Hz sidebands are 65 dB below the carrier with an asymmetry of much less than 10%. Therefore, the current conservative estimate of the uncertainty due to the electronics amounts to 0.1×10^{-15}.

9) Microwave leakage

Extended investigations of the effect of microwave leakage in CSF1 were performed [18]. 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 $< 0.1\times10^{-15}$.

Frequency shifts, corrections and type B uncertainties of CSF1 (parts in 10^{15}):

Frequency shift	Correction	Uncertainty
Quadratic Zeeman shift	- 107.97	0.10
Black body radiation shift	16.58	0.10
Gravity+relativistic Doppler effect	- 8.556	0.03
Collisional shift	0.00	0.25
Cavity phase shift		0.10
AC Stark shift (light shift)		0.10
Majorana transitions		0.10
Rabi and Ramsey pulling		0.10
Electronics		0.10
Microwave leakage		0.10
Background gas collisions		0.10
Total type B uncertainty		0.39

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