

Evaluation of PTB primary caesium fountain frequency standard CSF2 between MJD 55629 - MJD 55644

PTB's primary caesium fountain frequency standard CSF2 was operated between MJD 55629, 0:00 UTC and MJD 55644, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H5, BIPM code 1400590, using a 5 MHz phase comparator.

The relative short-term frequency instability of CSF2 was $2.07 \cdot 10^{-13} \cdot (\tau/s)^{-1/2}$ during the 15 days. This results in a statistical uncertainty of $0.19 \cdot 10^{-15}$ assuming that white frequency noise is the dominant noise source. Because the frequency comparison over the 15 days is made with a statistical uncertainty - due to the instrumentation - of below $0.07 \cdot 10^{-15}$ the resulting total statistical uncertainty is given by $u_A (\tau = 15 \text{ d}) = 0.21 \cdot 10^{-15}$.

In total, 12921 comparison data points for intervals of 100 s duration were obtained, corresponding to 99.7% of the 15 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 $u_{\text{Lab}} < 0.02 \cdot 10^{-15}$ is obtained. The estimated uncertainty for the link to TAI for 15 days is $u_{\text{TAI}} = 0.24 \cdot 10^{-15}$.

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 CSF2 standard uncertainty u_B is estimated as $0.54 \cdot 10^{-15}$ (1σ) for the relevant period.

Table of results of CSF2 compared to hydrogen maser H5 (1400590)

Interval of evaluation	MJD 55629, 0:00 UTC - MJD 55644, 0:00 UTC
Fractional dead time	0.3%
Resulting frequency difference	$y(\text{CSF2} - \text{H5}) = -57.53 \cdot 10^{-15}$
Type A uncertainty u_A (1σ)	$0.21 \cdot 10^{-15}$
Type B uncertainty u_B (1σ)	$0.54 \cdot 10^{-15}$
Link to clock u_{Lab} (1σ)	$0.02 \cdot 10^{-15}$
Link to TAI u_{TAI} (1σ)	$0.24 \cdot 10^{-15}$ (15 days)
Combined uncertainty (1σ)	$0.63 \cdot 10^{-15}$

Type A (statistical) uncertainty of CSF2

For the TAI scale unit measurement at hand the atoms were loaded from the background gas into the molasses. The replacement of the master laser diode and a better profile adjustment and intensity balancing of the cooling laser beams resulted in an improved performance with respect to the loaded atom number and the achievable signal-to-noise ratio. The resulting frequency instability of CSF2 was measured to be $2.07 \cdot 10^{-13} \cdot (\tau/s)^{-1/2}$.

In 2010 the same new microwave frequency synthesis setup [1] as utilized in the fountain PTB-CSF1 has been introduced in the CSF2 electronics setup. Because it had been demonstrated that the new synthesis setup is capable of providing instabilities below the 10^{-16} level, the statistical uncertainty of CSF2 frequency measurements is no more limited at the 7×10^{-16} -level as before.

For these reason the statistical uncertainty of the current TAI scale unit measurement was calculated with the assumption of white frequency noise for the total measurement interval and taking into account a $0.07 \cdot 10^{-15}$ uncertainty contribution due to the measurement instrumentation. The resulting total statistical uncertainty is calculated to be $u_A (\tau = 15 \text{ d}) = 0.21 \cdot 10^{-15}$.

Type B (systematic) uncertainty of CSF2

A detailed description of the systematic uncertainty contributions of the PTB fountain CSF2 has been published elsewhere [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 CSF2 uncertainty budget [2].

1) Distributed cavity phase

The systematic uncertainty contribution due to the distributed cavity phase has been thoroughly reevaluated based on the theory presented in Refs. [3], [4]. A publication about the details of the new evaluation is in preparation.

Major findings are that the previously attributed uncertainty contribution due to an observed power dependence can be omitted. It could be demonstrated that the reason for the power dependence are longitudinal phase variations in the microwave cavity, which cause very small frequency shifts at normal optimum microwave power operation. The dominant uncertainty contribution results from transverse $m=1$ phase variations, which have been experimentally evaluated by tilting the launch direction of the atoms in CSF2. Another small uncertainty contribution is caused by transverse $m=2$ phase variations, which can produce frequency shifts, if the atom cloud does not traverse the cavity on the cavity symmetry axis or if the detection is inhomogeneous.

Altogether an uncertainty of $0.12 \cdot 10^{-15}$ due to the distributed cavity phase shift is obtained from the new evaluation.

2) *Cold collisions*

The collisional frequency shift of CSF2 was evaluated before and after the TAI scale unit measurement at hand for 7.6 and 9.2 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, eliminating the effect of the frequency drifts of the hydrogen maser reference.

The results of these evaluations are slope factors which give – multiplied with the actual number of atoms – the collisional frequency shift correction [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 Ref. [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.

Below we report the type B uncertainty evaluation results valid for the evaluation at hand.

Frequency shifts, corrections and type B uncertainties of CSF2 (parts in 10^{15}):

Frequency shift	Correction	Uncertainty
Quadratic Zeeman shift	-100.89	0.059
Blackbody radiation shift	16.52	0.076
Gravity+relativistic Doppler effect	-8.567	0.006
Collisional shift	1.03	0.455
Cavity phase shift		0.12
AC Stark shift (light shift)		0.001
Majorana transitions		0.0001
Rabi pulling		0.0002
Ramsey pulling		0.001
Electronics		0.20
Microwave leakage		0.10
Background pressure		0.05
Total type B uncertainty		0.54

References

[1] A. Sen Gupta, R. Schröder, S. Weyers and R. Wynands, 21st European Frequency and Time Forum (EFTF), Geneva, pp. 234–237 (May/June 2007)

[2] V. Gerginov, N. Nemitz, S. Weyers, R. Schröder, D. Griebisch, R. Wynands, *Metrologia*, **47**(1), 65-79 (2010)

[3] R. Li and K. Gibble, *Metrologia* **41**(6), 376-386 (2004)

[4] R. Li and K. Gibble, *Metrologia* **47**(5), 534-551 (2010)