Evaluation of PTB primary caesium fountain frequency standard CSF1 between MJD 59849 - MJD 59879

PTB's primary caesium fountain frequency standard CSF1 was operated between MJD 59849, 0:00 UTC and MJD 59879, 0:00 UTC. Frequency comparisons were made with respect to PTB hydrogen maser H9, BIPM code 1400509.

The relative frequency instability of the relative frequency differences \(y(\text{CSF1-H9})\) was \(11.6 \times 10^{-14} \text{(s)}^{-1/2}\) during the 30 days. The actual measurement time amounts to 97.7% of the \(30 \times 24\) hours. This results in a statistical uncertainty \(u_A = 0.07 \times 10^{-15}\), assuming that white frequency noise is the dominant noise source.

For the statistical uncertainty due to the clock link \(u_A/\text{Lab} = 0.01 \times 10^{-15}\) is obtained by taking into account the actual measurement time, while the systematic uncertainty due to the clock link \(u_B/\text{Lab}\) is negligible. Finally, the estimated uncertainty for the link to TAI for 30 days is \(u_{\text{TAI}} = 0.07 \times 10^{-15}\).

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)
- relativistic redshift and relativistic Doppler effect
- cold collisions effect
- distributed cavity phase effect
- microwave lensing effect

The CSF1 standard uncertainty \(u_B\) is estimated as \(3.1 \times 10^{-16}\) (1 \(\sigma\)) for the relevant period [1].

### Table of results of CSF1 compared to hydrogen maser H9 (1400509)

<table>
<thead>
<tr>
<th>Interval of evaluation</th>
<th>MJD 59849, 0:00 UTC – MJD 59879, 0:00 UTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fractional dead time</td>
<td>2.3%</td>
</tr>
<tr>
<td>Resulting frequency difference</td>
<td>(y(\text{CSF1-H9}) = 44.50 \times 10^{-15})</td>
</tr>
<tr>
<td>Type A uncertainty (u_A) (1 (\sigma))</td>
<td>(0.07 \times 10^{-15})</td>
</tr>
<tr>
<td>Type B uncertainty (u_B) (1 (\sigma))</td>
<td>(0.31 \times 10^{-15})</td>
</tr>
<tr>
<td>Link to clock (u_{A/\text{Lab}}) (1 (\sigma))</td>
<td>(0.01 \times 10^{-15})</td>
</tr>
<tr>
<td>Link to clock (u_{B/\text{Lab}}) (1 (\sigma))</td>
<td>(0.00 \times 10^{-15})</td>
</tr>
<tr>
<td>Link to TAI (u_{\text{TAI}}) (1 (\sigma))</td>
<td>(0.07 \times 10^{-15}) (30 days)</td>
</tr>
<tr>
<td>Combined uncertainty (1 (\sigma))</td>
<td>(0.33 \times 10^{-15})</td>
</tr>
</tbody>
</table>
**Type A (statistical) uncertainty of CSF1**

For the microwave synthesis the previously utilized optically stabilized microwave oscillator [2] has been replaced by a new system for the optical generation of ultra-stable microwave signals. The new system utilizes the same cavity stabilized laser as before, but a new commercial frequency comb system, where the microwave signal is obtained from a photodiode. As before this signal is locked to a hydrogen maser in the long-term and employed as local oscillator for the PTB fountain clocks.

The frequency instability $11.6 \times 10^{-14} (\tau/s)^{1/2}$ of the measured relative frequency differences $y(\text{CSF1} – \text{Hmaser})$ is obtained for the combination of low and high density operation and gives the statistical measurement uncertainty $\mu_A$ [1].

The optically stabilized microwave system was available during >99% of the TAI measurement interval. Alternatively a quartz-based frequency synthesis system was employed.

**Type B (systematic) uncertainty of CSF1**

In the table below we report the type B uncertainty evaluation results valid for the evaluation at hand. Detailed descriptions of the systematic uncertainty contributions of CSF1 have been published elsewhere [1].

At the 26th CGPM in November 2018, TAI has been newly defined (Resolution 2). As a result the relativistic redshift of a clock contributing to TAI is to be computed with respect to the conventionally adopted equipotential $W_0 = 62 636 856.0 \text{ m}^2\text{s}^{-2}$ of the Earth’s gravity potential. The differentiation relating to the uncertainty of the relativistic redshift for the case of TAI contributions of the PTB fountain clocks in [1] is therefore no longer needed, so that a relativistic redshift uncertainty of $0.02 \times 10^{-16}$ [1] is attributed now and in the future.
### Frequency shifts, corrections and type B uncertainties of CSF1 (parts in $10^{16}$):

<table>
<thead>
<tr>
<th>Frequency shift</th>
<th>Correction</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadratic Zeeman shift</td>
<td>-1077.68</td>
<td>0.10</td>
</tr>
<tr>
<td>Blackbody radiation shift</td>
<td>165.19</td>
<td>0.80</td>
</tr>
<tr>
<td>Relativistic redshift and Doppler effect</td>
<td>-85.56</td>
<td>0.02</td>
</tr>
<tr>
<td>Collisional shift</td>
<td>-23.1</td>
<td>2.8</td>
</tr>
<tr>
<td>Distributed cavity phase shift</td>
<td>-0.04</td>
<td>0.93</td>
</tr>
<tr>
<td>Microwave lensing</td>
<td>-0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>AC Stark shift (light shift)</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Rabi and Ramsey pulling</td>
<td></td>
<td>0.013</td>
</tr>
<tr>
<td>Microwave leakage</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Electronics</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>Background gas collisions</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Total type B uncertainty</td>
<td></td>
<td>3.1</td>
</tr>
</tbody>
</table>

### References
