Evaluation of the METAS-FOC2 primary frequency standard
Period 59149-59179

The Swiss primary frequency standard METAS-FOC2 was operated between MJD 59149, 0:00 UTC and MJD 59179, 0:00 UTC. The frequency comparison was made with respect to the METAS Hydrogen Maser (BIPM clock code: 1405701).

The standard was measured continuously during 30 days with 9 dead-times (total 34.7 %). The frequency instability of the standard over the period of measurement was $11.5 \times 10^{-14} (\tau/\text{s})^{-1/2}$. For a 30-days integration time, this yields a statistical uncertainty $u_A = 0.09 \times 10^{-15}$.

A frequency correction of $68.72 \times 10^{-15}$ was applied to the raw data to obtain the relative frequency offset $y(\text{FOC2-HM})$. This correction is the sum of all the frequency shifts reported in the uncertainty budget (Table 1). This correction includes the following effects:
- Second-order Zeeman
- Gravitational red shift
- Second-order Doppler
- Blackbody radiation
- Light shifts (from source and from detection parts)
- Ramsey pulling
- End-to-end
- Collisional Cs-Cs

The combined standard uncertainty of the standard is $u_B = 1.36 \times 10^{-15}$.

**Summary of results**

<table>
<thead>
<tr>
<th>Evaluation period</th>
<th>$u_A$</th>
<th>$u_B$</th>
<th>$u_A/\text{lab}$</th>
<th>$u_B/\text{lab}$</th>
<th>$y(\text{FOC2} - \text{HM})$</th>
<th>Uptime (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>59149-59179</td>
<td>0.09</td>
<td>1.36</td>
<td>0.26</td>
<td>0.04</td>
<td>-17.01</td>
<td>65.3</td>
</tr>
</tbody>
</table>

All uncertainties are given with $k = 1$ standard uncertainties and are expressed in $10^{-15}$ unit.
**Operation**

METAS-FOC2 was operated continuously with 9 dead-times during the period of measurement. The microwave signal used to interrogate the atoms is generated by a commercial synthesizer, which uses the 5 MHz maser output as external reference. Due to its continuous interrogation scheme, the frequency stability of METAS-FOC2 is not limited by the Dick effect but by the atomic shot noise \[1\].

The relative frequency offset \( y(FOC2-HM) \) is estimated from the average correction applied to the synthesizer. For this period of measurement, we obtained:

\[
y(FOC2 - HM) = -17.01 \times 10^{-15}
\]

**Uncertainties**

1. \( u_A \) uncertainty

During this period of measurement, the Allan deviation is \( \sigma_y(\tau) = 11.5 \times 10^{-14}(\tau/s)^{-1/2} \) for the relative frequency difference \( y(FOC2-HM) \). For a 30-day integration time, this leads to the value:

\[
u_A = 0.09 \times 10^{-15}
\]

2. \( u_B \) uncertainty

The detailed evaluation of the uncertainty budget of METAS-FOC2 was published in \[2\] and \[3\].

A new evaluation of the second order Zeeman shift was realized. The related uncertainty takes into account the long-term drift of the magnetic field. We consider that the result of this evaluation is valid for the whole reported period.

The collisional shift dependence was also reevaluated at the beginning of this year and is consistent with the value reported in \[2\]. All the other effects are assumed to be the same as in \[2\], leading to a total uncertainty of:

\[
u_B = 1.36 \times 10^{-15}
\]

In table 1, we report the updated total uncertainty budget valid for this evaluation period.

3. \( u_{A/lab} \) uncertainty

This uncertainty comes from statistical fluctuations including the uncertainty due to the dead-time. A total dead-time of 898 782 s was accumulated during the period of measurement which represents 34.7 % of the 30 days. By using a dead-time model that takes into account the actual master clock stability, we calculated the relative frequency uncertainty:

\[
u_{A/lab} = 0.26 \times 10^{-15}
\]
4. \( u_{B/\text{lab}} \) uncertainty

This uncertainty comes from systematic effects in the link between the fountain and the hydrogen maser using as a transfer standard. A worst-case estimation of the uncertainty in local phase comparisons is \( \pm 100 \) ps leading to the fractional frequency uncertainty:

\[
u_{B/\text{lab}} = 0.04 \times 10^{-15}\]

Uncertainty budget

<table>
<thead>
<tr>
<th>Physical effect</th>
<th>Frequency shift</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second-order Zeeman</td>
<td>24.02</td>
<td>0.20</td>
</tr>
<tr>
<td>Gravitational</td>
<td>59.72</td>
<td>0.02</td>
</tr>
<tr>
<td>Second-order Doppler</td>
<td>-0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Blackbody radiation</td>
<td>-16.68</td>
<td>0.04</td>
</tr>
<tr>
<td>Microwave spectrum purity</td>
<td>0.00</td>
<td>0.05</td>
</tr>
<tr>
<td>Light shift from source</td>
<td>-0.16</td>
<td>0.04</td>
</tr>
<tr>
<td>Cavity pulling</td>
<td>0.00</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Rabi pulling</td>
<td>0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>Ramsey pulling</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>End-to-end</td>
<td>2.17</td>
<td>0.27</td>
</tr>
<tr>
<td>Collisional Cs-Cs</td>
<td>-0.29</td>
<td>0.16</td>
</tr>
<tr>
<td>Light shift from detection</td>
<td>-0.10</td>
<td>0.41</td>
</tr>
<tr>
<td>RF leakage</td>
<td>0.00</td>
<td>0.47</td>
</tr>
<tr>
<td>Majorana transitions</td>
<td>0.00</td>
<td>0.50</td>
</tr>
<tr>
<td>DCPS</td>
<td>--</td>
<td>1.03</td>
</tr>
<tr>
<td>Total</td>
<td>68.72</td>
<td>1.36</td>
</tr>
</tbody>
</table>

*Table 1: Frequency shifts and uncertainty budget of METAS-FOC2 during the period 59149-59179 (in \( 10^{-15} \) unit).*

References