FREQUENCY COMPARISON (H_MASER 140 0810) - (LNE-SYRTE-FO2)
For the period MJD 59579 to MJD 59609

The primary frequency standard LNE-SYRTE-FO2 has been compared to the hydrogen maser 140 0810 of the laboratory, during a measurement campaign between MJD 59579 and 59609 (31st December 2021 – 30th January 2022). The fountain operation covered 90.5 % of the period.

The mean frequency difference at the middle date of the interval is given in the following table:

Period (MJD)	**Date of the estimation**	**y(HMaser$_{140\ 0810}$– FO2Cs)**	u_A	u_B	$u_{A/lab}$	$u_{B/lab}$
59579 – 59609	**59594**	**-1003.5**	**2.0**	**2.1**	**0.5**	**0.0**

Table 1: Results of the comparison in 1 × 10^{-16}.

The FO2 fountain was operated in the same mode during all the period: the interrogating signal is based on the down conversion to 9.192 GHz of a 11.98 GHz signal provided by a cryogenic oscillator phase locked to the maser 140 0810. A synthesizer is used to lock the microwave signal to the atomic resonance. The frequency difference between this maser and the fountain is deduced from the average correction applied to the synthesizer.

Average value and statistical uncertainty

The frequency data are averaged over 0.2 day intervals. We then perform a linear unweighted fit to the average data points to determine the average frequency at the middle date of the period, as given in Table 1. The statistical uncertainty u_A is estimated using the Allan variance of the frequency residuals, after removing the drift. We estimate a conservative statistical uncertainty u_A of 2.0 × 10^{-16}.

We verified the result by applying a second method. We calculated the accumulated phase by integrating the data points, assuming a constant frequency during each segment, and during the dead times of the fountain operation. The average frequency is then obtained by dividing the total accumulated phase by the calibration period duration. The processing has been performed with segments of 0.01, 0.1 and 1 day duration. The results are in agreement with the values given in Table 1 within 0.7 × 10^{-16} which is consistent with the estimation of the statistical uncertainty u_A and the uncertainty due to the link.

Accuracy

The frequency is corrected from the quadratic Zeeman, the black body radiation, the cold collisions (+ cavity pulling), the distributed cavity phase shift and the microwave lensing shifts, and at last the redshift. The cold collision correction is based on alternating measurements at full density for 50 cycles and at half density for 100 cycles, using adiabatic passage in the state selection cavity. The uncertainty in this correction accounts for both a statistical uncertainty and a systematic uncertainty taken as 3×10^{-3} of the average correction over full and half density measurements. The following table summarizes the budget of the systematic corrections and their associated uncertainties. The accuracy is the quadratic sum of all the systematic uncertainties.

	Correction (10^{-16})	**Uncertainty (10^{-16})**
Quadratic Zeeman effect	-1936.85	0.30
Black body radiation	174.40	0.80
Cold collisions and cavity pulling	108.76	0.93
Distributed cavity phase shift	-0.90	1.00
Microwave lensing	-0.70	0.70
Microwave spectral purity&leakage	0	< 0.50
Ramsey & Rabi pulling	0	< 0.10
Second order Doppler effect	0	< 0.10
Background gas collisions	0	<1.00
Total	-1655.29	2.09
Redshift	- 65.54	0.25
Total with redshift	**-1720.83**	**2.10**

Table 2: Budget of systematic effects and uncertainties for SYRTE-FO2 fountain for the MJD 59579 – 59609 period

$$u_B = \mathbf{2.1 \times 10^{-16}}$$

Uncertainty of the link

The statistical uncertainty of the link $u_{A/lab}$ is the quadratic sum of 2 terms:
-A possible effect of phase fluctuations introduced by the cables that connect the primary standard to the maser. A new characterization of the signal distribution leads to a still conservative value of 0.5×10^{-16}.
-The uncertainty due to the dead times of the frequency comparison.
We have updated the estimation of this contribution, applying the method described in *Metrologia*, vol. 44, pp 91-96, 2007, as we did for the initial calibration reports of the LNE-SYRTE Strontium SFS. The maser noise model includes a white frequency noise component of 5×10^{-16} at 1 d and a flicker frequency noise component of 5×10^{-16} at 1 d, which is pessimistic especially for short averaging periods. We applied the method to the dead times longer than 600 s and obtained a stability degradation of 0.2×10^{-16}.

In the signal distribution chain between the maser and the fountain, all the intermediate oscillators are phase locked using proportional/integrator phase lock loops. The comparison between the maser and UTC(OP) is performed using a time interval counter. Therefore, the systematic uncertainty of the link $u_{B/lab}$ is expected to be negligible.

Fountain uptime

According to the guidelines for reporting PSFS data for TAI calibrations recently adopted by the WG on PSFS and published on the BIPM website [1], the method for estimating the value of the uptime of FO2 has been updated. Starting January 2022, this value is obtained by dividing the effective time when the clock is locked to the hydrogen maser (ie number of clock cycles times the cycle time) divided by the estimation period duration. For this January 2022 calibration, the uptime value is 90.5%.
In the previous reports, we accounted only for downtime period larger than 600 s. This was applied because the fountain operation includes sequences for checking the parameters: measurements of the magnetic field, temperature, optical power of the laser beams (duration ~140 s every 2h), optimization of the interrogation microwave power (duration ~60 s every 9000 cycles), a few cycles are discarded after each alternation between full and half atomic density to avoid possible transient effects. These short sequences used to access in real time the accuracy of the fountain have a negligible impact on the dead time uncertainty. With this method, the uptime value would have been 97.1% for January 2022 FO2 calibration.
For estimating the time of "normal operation" of the clock, we added the duration elapsed for checking and optimizing the parameters to the effective time when the clock is locked to the reference maser. This leads to an uptime of 96.% for the January 2022 period, in good agreement with the previous value.
This shows that our previous method gave a good estimation of the downtime of the fountain due to failure of a subsystem. With the new method, the maximum uptime of FO2 operation will be about 90% given its sequential operation.

[1] guidelines-psfs-reports.pdf, available at https://webtai.bipm.org/database/guidelines.html