FREQUENCY COMPARISON (H_MASER 140 0809) - (LNEOP-FO2)
For the period MJD 60704 to MJD 60734

The primary frequency standard LNEOP-FO2 has been compared to the hydrogen maser 140 0809 of the laboratory, during a measurement campaign between MJD 60704 and 60734 (29^{th} January 2025 – 28^{th} February 2025). The fountain operation covered 60.4 % 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$_{140\ 0809}$– FO2Cs)**	u_A	u_B	$u_{A/lab}$	$u_{B/lab}$
60704 – 60734	**60719**	**-3082.6**	**2.0**	**2.3**	**1.0**	**0.0**

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

During the period, the interrogating signal of the FO2 fountain was based on a 11.98 GHz signal generated from an optical frequency comb locked to an ultrastable laser stabilised to an optical cavity. The microwave signal from the comb is phase locked to the maser 140 0809. 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 2.9×10^{-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 20 cycles and at half density for 40 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 $3x10^{-3}$ 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	-1940.82	0.30
Black body radiation	169.17	0.80
Cold collisions and cavity pulling	74.59	1.25
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	-1698.66	2.25
Redshift	- 65.54	0.25
Total with redshift	**-1764.20**	**2.26**

Table 2: Budget of systematic effects and uncertainties for LNEOP-FO2 fountain for the MJD 60704 – 60734 period

$$\boxed{u_B = \mathbf{2.3 \times 10^{-16}}}$$

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 60 s and obtained a stability degradation of 0.9×10^{-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.