

**FREQUENCY COMPARISON (H_MASER 140 0810) - (LNE-SYRTE-FO2)
For the period MJD 58664 to MJD 58694**

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 58664 and 58694 (30th June 2019 – 30th July 2019). The fountain operation covered 45.1% of the period.

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

Period (MJD)	Date of the estimation	$y(\text{HMaser}_{140\ 0810} - \text{FO2})$	u_A	u_B	$u_{\text{link/maser}}$
58664 – 58694	58679	-6823.5	2.0	2.4	1.6

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.

During the second half of the period, in addition to the usual full/half atomic density measurements for real time cold collisions evaluation, additional configurations were regularly interspersed for tests. This reduced the effective uptime of the maser calibration despite the tracking of the maser was almost continuous.

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 2.0×10^{-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	-1935.95	0.30
Black body radiation	173.55	0.80
Cold collisions and cavity pulling	118.68	1.41
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	-1645.32	2.34
Redshift	- 65.54	0.25
Total with redshift	-1710.86	2.35

Table 2: Budget of systematic effects and uncertainties for SYRTE-FO2 fountain for the MJD 58664 – 58694 period

$$u_B = 2.4 \times 10^{-16}$$

Uncertainty of the link

The uncertainty of the link 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. Because test measurements were regularly interspersed with the maser calibration during the second half of the period, we had to account for repeated short dead times with typical duration of 600 s. Therefore we performed the computation of the dead time uncertainty for shorter dead time durations than usual. We obtained the same value of 1.5×10^{-16} for dead time durations longer than 100 s or 200 s, as compared with 1.2×10^{-16} for dead times longer than 600 s.